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Transpired solar collectors for ventilation air heating

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Transpired solar collectors (TSCs) improve the environmental performance of buildings by preheating incoming ventilation air using solar energy, substituting the need to use fossil fuels. TSCs have been used successfully in the USA and Canada over the past 20 years and have been shown to achieve economic payback of between 2 and 10 years. The economic performance is achieved through a combination of high thermal efficiency and the low cost of the solar collector, which is in the form of a single perforated steel sheet. In 2006, the first installation of a TSC in the UK was on a single-storey industrial building in County Durham and during its first year of operation, the TSC provided around 20% of the building's heating demand. This paper presents a review of the research into TSC technology, examining its thermal performance, the different construction types, annual energy performance, and international experiences. The evidence from the UK-based research performance investigations suggest that the success of TSCs in the USA and Canada could be replicated in the UK.

Notation

A	area of the perforated absorber (m^2)
C_p	specific heat of air (J/kg.K)
G_T	tilted solar irradiance (W/m^2)
h_{rad}	linearised radiation heat transfer coefficient ($W/m^2.K$)
$\dot{m}$	mass flow rate (kg/s)
n_i	instantaneous thermal efficiency
T_{amb}	ambient air temperature (K)
T_{col}	perforated absorber temperature (K)
T_{out}	outlet air temperature (K)
v	suction-face velocity (m/s)
α	solar absorbance
ε_{HX}	heat exchange effectiveness
ρ_{air}	density of air (kg/m^3)

1. Introduction

In Europe, the operational energy use of buildings is around 40% of total energy consumption. In 2002, the European Union (EU) adopted the energy performance of buildings directive (EPBD), which aims to reduce the EU's energy dependency and reduce emissions of greenhouse gases by reducing the energy consumption of buildings (Ekins and Lees, 2008; EU, 2010). In the UK, operational energy use of buildings is estimated to be 39% of total energy consumption, with roughly 50% of the energy used in buildings due to the provision of heating, ventilation and air conditioning (HVAC) services (Pérez-Lombard *et al.*, 2008).

One method of providing the heating component of HVAC services that both reduces energy dependency and results in lower greenhouse gas emissions is through the use of solar thermal systems, which convert solar radiation into thermal energy (Kalogirou, 2004). This paper describes a solar thermal system known as a transpired solar collector (TSC), which uses an unglazed perforated absorber as the solar-collecting component (Figure 1). TSCs can be used to preheat the ventilation air supply to buildings using solar radiation as its energy source.

2. Transpired solar collectors

TSCs were invented in the mid-1980s by John Hollick and Rolf Peter as a method of using solar radiation to preheat ventilation

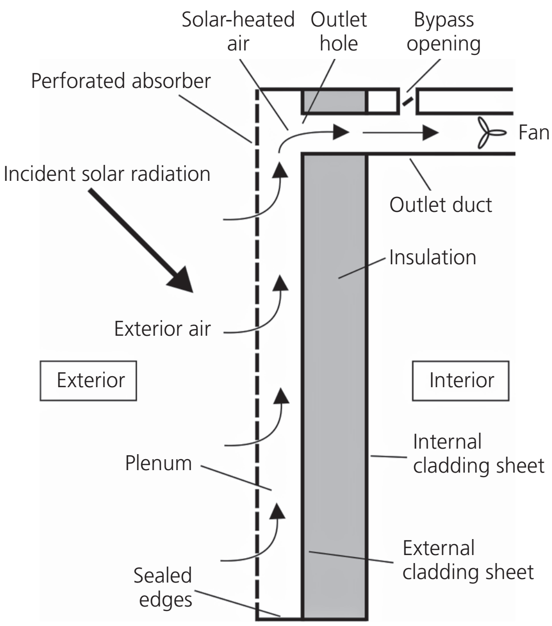

Figure 1. Schematic illustration of a transpired solar collector

air for buildings (Hollick, 1994; Kutscher, 1996). Since the first commercial installation of a TSC on the Ontario (Canada) Ford Motor Company assembly plant in 1990 (CEI, 2009a), over 1000 TSCs have been installed in more than 30 countries (CEI, 2009b). The first TSC system in the UK was installed in 2006 on the south wall of a single-storey industrial building (CA Group, 2009) and since then a number of TSCs have been installed and are now operating around the UK (see Table 1).

TSCs are constructed by fixing a solar absorbing perforated metallic sheet to the envelope of a building. This creates an air gap between the perforated sheet and the building envelope (plenum). Using a fan, exterior air is drawn into the plenum through thousands of evenly spaced perforations that cover the surface of the absorber. As the air passes over the front surface of the perforated sheet, heat is transferred by convection from the sheet to the air (Kutscher *et al.*, 1993). The solar heated air is then drawn out of the plenum through the outlet hole, where it can be ducted towards its application (see Figure 1). When solar-heated air is not required, TSCs have a bypass opening so that the ventilation air stream can circumvent the perforated absorber (Kutscher, 1996). To direct the air to flow through the perforations, the plenum is sealed around all the edges. For large TSCs, the perforated absorber is usually profiled for structural rigidity.

Early on in their development, TSCs were shown to be competitive in many applications (Christensen *et al.*, 1990); they combine instantaneous thermal efficiencies of over 70% (Brunger *et al.*, 1999) with low capital investment costs. These two factors create the potential of simple economic payback of less than 2 years for large installations (Brewster, 2010; CEI, 2009a).

3. Basic TSC energy balance equation

The instantaneous thermal efficiency (n_i) of a TSC can be described using the standard flat-plate solar collector efficiency equation (Duffie and Beckman, 2006: p. 292), which is the energy transferred to the outlet air stream divided by the total solar radiation incident on the perforated absorber

$$1.\quad n_\mathrm{i} = \frac{\dot{m}C_\mathrm{p}(T_\mathrm{out} - T_\mathrm{amb})}{AG_\mathrm{T}}$$

where C_p is the specific heat of ambient air (ambient air is the term used in the solar thermal literature for exterior air (ASHRAE, 2010)), A is the projected area of the perforated absorber, $\dot{m}$ is the mass flow rate though the perforated absorber, T_out is the air leaving the perforated absorber, G_T is the total solar irradiance incident on the perforated absorber and T_amb is the exterior air temperature. Equation 1 can be rearranged to find the temperature of the air leaving the TSC (Duffie and Beckman, 2006: pp. 278–289).

Similar to flat-plate solar collectors, the instantaneous thermal efficiency required by Equation 1 to find T_out can be determined by performing an energy balance of the perforated absorber

Project	Location	TSC area: m^2	Predicted energy savings: kWh/year
Jaguar/Land Rover	Leamington Spa	268	80 530
Beaconsfield Services	Beaconsfield	255	99 235
Premier Park	Winsford, Cheshire	580	130 000
Sainsbury's Distribution	Pineham	947	256 093
CA Group Rollforming Mill	Evenwood	1211	299 000
International Paints	Felling, Gateshead	100	31 169
Royal Mail	Swan Valley	800	233 396

Table 1. UK commercial installations of TSCs (Brewster, 2010; CA Group, 2010)

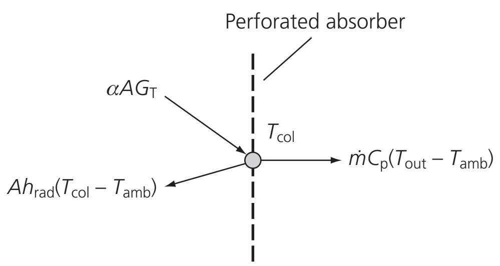

Figure 2. Simple energy balance on the perforated absorber

(Duffie and Beckman, 2006: p. 239). This energy balance is illustrated in Figure 2 and shown mathematically as

$$2. \quad \dot{m}C_p(T_{out} - T_{amb}) = \alpha AG_T - Ah_{rad}(T_{col} - T_{amb})$$

where α is the absorptance of the perforated absorber (Duffie and Beckman, 2006: pp. 174–177), T_{col} is the temperature of the perforated absorber and h_{rad} is the linearised radiation heat transfer coefficient (linearising the radiation heat transfer coefficient is an effective means of converting the temperature to the power of 4 as described by the Stefan–Boltzmann law to a linear formula over a narrow temperature range). Equation 2 assumes that the TSC is large and wind heat loss can be considered negligible (Gawlik and Kutscher, 2002).

Given that the energy transferred to the outlet air stream is a function of the design of the perforated absorber, a heat exchange effectiveness (HEE) ratio (ε_{HX}) is used to describe the relationship between the actual temperature rise against the maximum possible temperature rise

$$3. \quad \varepsilon_{HX} = \frac{(T_{out} - T_{amb})}{(T_{col} - T_{amb})}$$

where the HEE is determined experimentally (Brunger *et al.*, 1999: p. 109). By rearranging Equation 3 for T_{out} and substituting into Equation 2, Equation 2 is transformed into

$$4. \quad mC_p\varepsilon_{HX}(T_{col} - T_{amb}) = \alpha AG_T - Ah_{rad}(T_{col} - T_{amb})$$

Equation 4 can then be rearranged for AG_T and substituted into Equation 1 to relate the characteristics of the perforated absorber and the mass flow rate to the instantaneous thermal efficiency. To simplify the result of substituting Equation 4 into Equation 1, the mass flow rate is expressed in terms of the suction-face velocity v, which is defined as the velocity of air if it were to travel though whole surface area of the absorber

$$5. \quad v = \frac{\dot{m}}{A\rho_{air}}$$

where ρ_{air} is the density of ambient air. Once these steps have been followed, the following equation for instantaneous thermal efficiency is obtained (Brunger *et al.*, 1999: p. 102; Carpenter *et al.*, 1999; Kutscher *et al.*, 1991)

$$6. \quad n_i = \frac{\alpha}{[1 + (h_{rad}/\varepsilon_{HX}\rho_{air}C_p v)]}$$

Equation 6 shows that the efficiency of the TSC is proportional to its absorptivity. Broadly speaking, absorptivity is higher in darker colours and as TSCs tend to cover large sections of the building's south wall, careful design is required to balance aesthetics and thermal efficiency. Depending upon the application, colours such as blue, red, green and grey can be considered as having good solar absorptance characteristics (Corus Colors, 2010).

Figure 3 shows Equation 6 modelled for suction-face velocities between 0·001 and 0·06 m/s, and demonstrates that TSCs are able to achieve instantaneous efficiency of over 70% when operating at suction-face velocities above 0·02 m/s. Operating a TSC at suction-face velocities below 0·02 m/s results in lower instantaneous thermal efficiencies but higher air temperature rises.

Suction-face velocities of 0·04–0·05 m/s are recommended for field installations to ensure wind heat loss and 'outflow' do not compromise the performance of the TSC (Gawlik and Kutscher, 2002; Kutscher *et al.*, 2003). Outflow is where the heated air in the plenum exits through a section of the TSC absorber, thus losing the heat generated. Gunnewiek *et al.* (2002) identified that if the site wind speed reached 5 m/s, which would not be a typical wind speed for built-up sites in the UK, outflow would be prevented if the TSC were operating with suction-face velocities of

- 0·0125 m/s under typical operating conditions
- 0·017 m/s for long buildings facing into the wind
- 0·026 m/s for cubical buildings with the collector facing the wind
- 0·039 m/s for cubical buildings with the wind incident on the collector at 45°.

4. Types of TSCs

4.1 Basic construction types

TSCs come in three basic construction types – stand-alone, on a south-facing wall and rooftop-mounted. A stand-alone TSC is one where both the perforated absorber and the non-perforated sheets (see Figure 1) are exposed to the ambient environment and the TSC is supported independently of the building. This type of TSC is used for commercial drying applications (Leon and Kumar, 2007).

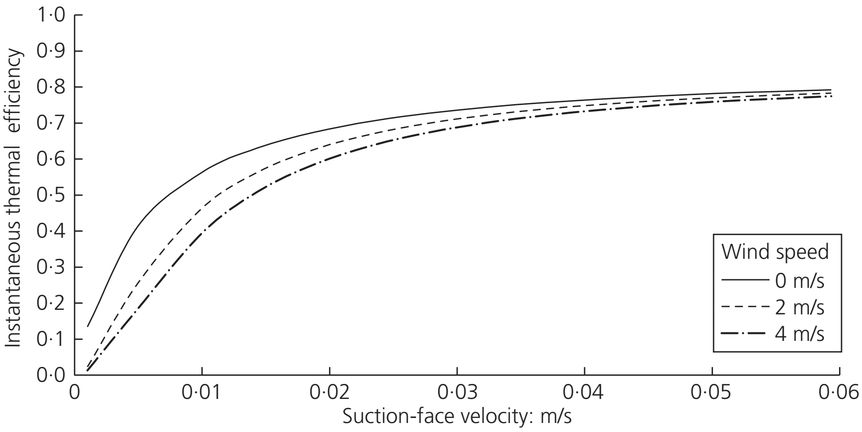

Figure 3. Instantaneous thermal efficiency against flow rate for three wind velocities (based on the assumptions in solar air heating project model (SAHPM) (Carpenter and Meloche, 2002) and using an absorptivity of 0·9)

Figure 4 shows a south-facing wall type of TSC, also known as an envelope-mounted TSC (Kozubal *et al*., 2008). In this construction type, the perforated absorber is fixed to the building façade of either a new or existing building. As the TSC is incorporated onto the existing façade, the additional components of the TSC are a single metal sheet (the perforated absorber) and the spacer system. In new-build applications, the same construction team can install both the building cladding system and the TSC.

The rooftop-mounted TSC (CEI, 2010a) sits on the roof of the building and can be used when there is no suitable south-facing wall area. This construction type has the potential to achieve higher energy yields than the south wall type due to the greater freedom to optimise the tilt, orientation and coating of the absorber (Kozubal *et al*., 2008).

4.2 Photovoltaic TSCs

Similar to other solar thermal systems, TSCs can also be combined with photovoltaic (PV) modules to create a hybrid photovoltaic/solar thermal panel (PV/T) (Hollick, 2000a) – that is, a PV/TSC. The aim of creating a hybrid PV/TSC system is to develop a device that can simultaneously convert solar radiation into economical heat and electricity when available collector area is at a premium (Charalambous *et al*., 2007), or simply to improve the economic performance of the PV system by cooling the PV cells (Naveed *et al*., 2006). There are two broad types of PV/TSC

- bonded type – PV cells/modules are bonded directly to the absorber (Delisle, 2008; Hollick, 1998)
- fixed type – PV modules are fixed to the absorber (CEI, 2010b; Naveed *et al*., 2006).

Figure 4. Commercial TSCs installed on the south wall of Beaconsfield service station (UK), where the TSC preheats ventilation air for the food court

The bonding of PV cells directly onto the TSC perforated sheet has been researched by Hollick (1998) and Delisle (2008). They have been able to verify that the PV/TSC was able to lower the temperature of the PV cells, but the PV cells also resulted in a reduction in the thermal efficiency when compared with a standard TSC. The effect was attributed in part to the reduced absorptivity of the PV cells compared with the absorber. When bonding PV cells to a corrugated absorber, an important consideration is the location of the PV cells on the corrugations. When investigating the effect of two potential PV cell configurations (bonding just on the ridge or across the whole sheet), Delisle (2008) was able to conclude that there would be shading of the PV cells if bonded over the whole surface of the sheet. Thus, careful design of the PV cell configuration would be required. Currently, there is no commercial PV/TSC of the bonded type; this is thought to be primarily due to the difficulty in manufacturing suitable PV cells that can be economically bonded to the absorber.

The fixed-type PV/TSC, where conventional PV modules are fixed to the absorber, has been commercialised in both the south-facing wall form and modular form (CEI, 2010b; Hollick and Barnes, 2007). In one study, the forced ventilation of polycrystalline silicone PV modules using a TSC system was able to reduce the operating temperature of the PV modules by 3–9°C. This cooling of the PV modules resulted in a reduction in simple economic payback time from 23 years (PV without TSC) to 15 years (PV/TSC) (Naveed *et al.*, 2006).

5. TSC systems

5.1 System types

The most common application of a TSC is for preheating ventilation air, where the ventilation air supply is heated as it passes through the TSC perforated sheet. The heated air is then generally heated further as it passes through the building's HVAC system to reach the desired delivery temperature. In summer, when there may be no requirement to heat the ventilation air supply, TSC systems have a means of bypassing the absorber (Figure 1). Guidelines for the design of TSCs for ventilation preheating have been outlined previously (Brunger *et al.*, 1999; Hollick, 2000b; Kutscher, 1996). A number of alternative system types have been explored, with various degrees of success.

(*a*) Cooling ventilation air (Hollick, 2007): at night, the temperature of the TSC absorber will be lower than the ambient air temperature due to radiant heat losses to the sky, thus enabling the TSC absorber to cool ambient air at night (Summers, 1995).
(*b*) Preheating water for a district heating network: TSC-heated air is passed over an air-to-water heat exchanger (Frank *et al.*, 2006).
(*c*) Hot water preheating (e.g. the correctional facility at Inuvik and the WIWOG Wohnbaugesellschaft, Germany (CEI, 2009a).
(*d*) Desiccant regeneration for cooling applications (Pesaran and Wipke, 1992).
(*e*) Diurnal cycle energy storage (e.g. at St Lawrence College, excess heated air is ducted through a hypocaust energy storage radiant flooring system (CEI, 2009a)).
(*f*) Drying of agricultural products (e.g. chicken manure, cocoa and tea) (Leon and Kumar, 2007).

5.2 Integrated performance of systems

The predicted integrated environmental and economic performance of TSCs is primarily determined using either RETScreen® V3.1 solar air heating project model (SAHPM) (CEI, 2009b) or, in the UK, the simplified building energy model (SBEM) 2010 (version 4.0.a onwards) for Building Regulations Part L compliance (Hall, 2010).

RETScreen SAHPM is a free secure Microsoft Office Excel spreadsheet application designed to model preheating of industrial, commercial, residential ventilation air and for preheating process air. It uses Nasa (National Aeronautics and Space Administration) surface meteorology and solar energy weather data to calculate energy savings on a monthly average timestep using an efficiency equation similar to Equation 6, which takes into account the dominant variables of absorptivity, airflow rate and wind speed. The energy saving calculated is the sum of the active absorber solar gain and wall heat recapture (heat loss through the wall is recaptured into the air stream). SAHPM has been validated against SWift™, which is a free dynamic simulation model for TSCs (Carpenter and Meloche, 2002; Carpenter *et al.*, 1999). The two models showed good agreement in all the available TSC system types. While SAHPM can be used in the UK to model the performance of TSCs, SWift cannot be used as the software only includes North American weather files.

A comparison of the US National Renewable Energy Laboratory (NREL) TRNSYS TSC model with SAHPM found that the NREL model predicted 14% less delivered energy than SAHPM. The rationale was that the SAHPM is 'based on product offerings no longer available' (Kozubal *et al.*, 2008: p. 4), which is likely to be referring to the observation that some manufacturers are using more extreme profiles than those originally studied for SAHPM and using slits rather than circular holes (Kutscher *et al.*, 2003).

A TSC energy yield model is included in the UK Part L compliance SBEM (Hall, 2010). This model uses efficiency algorithms researched in the IEA solar heating and cooling programme task 14 (Brunger *et al.*, 1999) and can model ventilation air preheating for most building types. TSC energy yield models are, however, not currently included in many of the building energy dynamic simulation software packages. Crawley *et al.* (2008) reviewed the capability of whole-building energy modelling software in 2008 and found that TSCs were only included in the EnergyPlus simulation engine (EnergyPlus, 2009) and the research tool TRNSYS (Langensiepen and Morhenne, 2010; Summers, 1995).

Table 2 compiles the principal findings of detailed performance investigations on existing TSC installations or models of potential TSC installations. Internationally, TSCs appear to be able to generate economic payback periods (i.e. the number of years required to pay back capital costs) of around 2–10 years (CEI, 2009a) depending upon the application, with less than 1 year needed to pay back their embodied greenhouse gas emissions (IEA, 2000).

UK-based integrated performance investigations are providing evidence to suggest that the performance of TSCs experienced in the USA and Canada over the past 20 years could be replicated in the UK. In 2007, a post-occupancy evaluation (POE) was undertaken to determine the actual first-year integrated performance of a TSC installation in County Durham (Pearson and Anderson, 2007). The POE found that the TSCs delivered

Study	Location	TSC system type	Principal findings
Christensen *et al*. (1990)	USA: Denver, Madison, Miami	Retrofit envelope-mounted TSC for ventilation air preheat	■ TSCs are nearly cost competitive with natural gas heating ■ The absorber area is much larger than alternative solar thermal systems ■ TSCs installed on new buildings have a lower capital cost than TSCs retrofitted to existing buildings ■ Energy performance of TSC system sensitive to length of heating season
Pesaran and Wipke (1992)	USA	Desiccant cooling systems regenerated with a TSC	■ TSCs could not use the heat recovered by the sensible heat exchanger in the desiccant cooling system ■ TSCs required 64% more absorber area than an equivalent glazed absorber based system ■ Relative to glazed absorber based systems, TSCs are cost-effective ■ Natural gas based systems are more cost-effective than TSC based systems ■ Emissivity plays an important role when the TSC system is required to generate high output temperatures (greater than 50°C) ■ Simple economic payback of around 10 years ■ The TSC vertical tilt required for winter operation is not ideal for summer desiccant regeneration
Summers (1995)	USA: Bismarck, Buffalo, Denver, Madison, Washington	South wall TSC for ventilation and air preheating	■ At night, the absorber's temperature can be lower than the ambient air temperature due to radiation losses to the sky ■ Automatically opening the bypass damper at night leads to increased energy performance, except when the wall is poorly insulated ■ The amount of time that the ambient temperature is below the summer bypass set temperature is a significant climate variable ■ Additional fan power is less than 2% of energy saved ■ Significant energy savings can be achieved in industrial buildings if high indoor temperatures are required and there is a high fresh air requirement ■ Absorptivity and absorber area are important variables in energy savings ■ TSCs are only cost competitive when compared with electric heating systems
Brown (2003)	USA: Various Air Force bases	South wall TSC for ventilation air preheating	■ Simple economic payback between 4 and 14 years ■ Internal rate of return between 6 and 30% ■ TSCs were economically beneficial for all of the Air Force bases investigated ■ Fuel cost, capital cost and seasonal efficiency variables are the most import determinants of economic performance

Table 2. Principal findings from integrated building energy and environmental performance investigations

Study	Location	TSC system type	Principal findings
Maurer (2004)	USA: North Carolina	South wall ventilation heating	■ Results suggest that the presence of the collector can increase the temperature of the building fabric in the summer (more research is required) ■ TSCs are economical in North Carolina even though it has a short heating season ■ Suggest separating the TSC mode in TRNSYS from the whole building model
Naveed *et al*. (2006)	South Korea: Daejeon	TSC/PV (modular type) 3 kW PV modules fixed in a 50 m^2 TSC	■ TSCs reduced the temperature of the PV modules by 3–9°C ■ Requires three less 75 W modules than a system without the TSC ■ PV/TSC requires 50 m^2 whereas a PV and TSC would require 70 m^2 to generate the same output ■ Simple economic payback for the PV/TSC system reduced from 23 to 15 years (given 50% government subsidy for the PV modules)
Ashley (2007)	USA: New York	South wall TSC for high-rise residential ventilation preheating	■ Optimal control strategy would allow for varying set temperatures throughout the year ■ TSCs perform optimally at vertical tilts ■ Substantial wall recapture is possible in poorly insulated buildings
Battle McCarthy (2007)	UK	Envelope-mounted TSC for ventilation preheating	■ TSCs can contribute 10–20% of overall energy demand of low-energy distribution centres ■ TSCs can make significant contributions to heated or poorly managed low-rise buildings ■ In single-storey industrial buildings that only require frost protection, TSCs cannot be used as a substitute for frost protection and are unlikely to make significant energy savings (due to the low demand for heated ventilation air)
Kozubal *et al*. (2008)	USA	Rooftop-mounted modular and south wall TSCs for ventilation preheating	■ Selective coatings (high absorptivity and low emissivity) can increase energy savings made by TSCs ■ Higher absorptivity coating can be used for modular designs because they are not within the view of people ■ A modular design enables optimisation of the absorber's tilt ■ Modular absorbers have a 28–37% higher capital cost compared with south wall designs ■ South wall absorbers can achieve 10% or greater internal rates of return in DOE climate zones 4A–8
DSAE (2008)	UK	Envelope-mounted TSC for ventilation preheating	■ To provide 10% of the building energy demand from renewable energy would require 595 m^2 of TSC absorber and costs significantly less than other potential renewable energy alternatives

Table 2. Continued

21% of the total heating demand of the building in the first full year of operation (2006–2007). A comparison of a range of renewable energy technologies for use on a building in the UK indicated that the TSC option could meet a 10% renewable energy planning policy requirement at a capital cost significantly lower than the alternatives (DSAE, 2008). Finally, a study of typical and low energy distribution centres reported that TSCs can make a 'significant contribution' to the operational energy demand of these types of buildings (Battle McCarthy, 2007: p. 9).

6. Avoiding known international design problems

There is considerable international experience of installing TSCs and, while the vast majority of these systems appear to be installed without issue, there are a few installations that have been the subject of POEs that aim to mitigate some form of design problem. The following design lessons can be derived from these international POEs.

(*a*) Warehouses with large doors that are open for a significant duration of time may lose the benefit of heat generated by TSCs (Deru *et al.*, 2005).
(*b*) Distributing TSC heat from high-level fabric ducts in large spaces can be ineffective because the heat tends to stay near the ceiling and is unable to heat the occupied space. To resolve this problem, some method of destratification is required (Brown, 2003; Deru *et al.*, 2005; Maurer, 2004).
(*c*) Where heating of a building's ventilation air is generally not required all year round, a means of bypassing the TSC is required (Maurer, 2004).
(*d*) TSCs operating with low suction-face velocities (below 0·02 m/s) can result in low solar conversion efficiencies and are vulnerable to wind heat loss effects (Fleck *et al.*, 2002; Kozubal *et al.*, 2008; Kutscher *et al.*, 2003; Maurer, 2004).
(*e*) Since TSCs are driven by a fan, occupant exposure to fan noise should be considered (e.g. the installation of silencers may be required) (Brown, 2003).
(*f*) TSCs that are not integrated with a building's fire alarm systems can be problematic as the rate of combustion can be increased if fresh heated ventilation air is delivered during a fire (Brown, 2003).
(*g*) The performance of a TSC can be reduced in buildings with an early-morning dominated heating demand since a large proportion of the heating demand is at a time when there is no solar radiation available (Pearson and Anderson, 2007).
(*h*) Maintenance personnel require training to understand TSC technology so that if issues arise they are able to solve them without having to resort to switching the system off (Maurer, 2004).
(*i*) Air quality adjacent to the absorber needs to be considered. For example, a car park directly adjacent to a TSC could result in car exhaust fumes being brought into the building (Brown, 2003).
(*j*) TSCs operating without auxiliary heating of the output air (not preheating) should consider the thermal comfort implications of delivering cool ventilation air to the building space (Meier, 2000).
(*k*) Some TSCs are not accompanied by a standard controller unit; sites with multiple TSCs may therefore have multiple controller units, making facility management more difficult (Brown, 2003).
(*l*) If water coils are present in air handling units being served by the TSC, when the ambient temperature is below freezing the air handling units will not draw from the TSC to avoid coil freezing, even if the heat from the TSC can bring the temperature of the air above freezing (Kozubal *et al.*, 2008).

If the system is designed for ventilation preheating and space heating, then the design must take into account the facts that

(*a*) the collector area may be oversized for times when only ventilation preheating is required, resulting in very low suction flow rates and thus very low efficiencies (Kozubal *et al.*, 2008)
(*b*) as TSCs are once-through systems, the air temperature rise from ambient to the return temperature does not offset gas use. This must be accounted for when calculating energy savings (Kozubal *et al.*, 2008).

By using the knowledge gained through the experiences of installing TSCs in the USA and Canada over the past 20 years, these potential design problems can easily be avoided in the UK.

7. Strengths and limitations of TSCs

7.1 Strengths

(*a*) Long life of the absorber (>40 years depending upon the quality of the coating) (CA Group, 2009).
(*b*) High efficiencies (wind having a negligible impact on the performance if the system is well designed) (Kutscher *et al.*, 2003).
(*c*) Potential for heat recovery as heated indoor air passes into the plenum through the existing cladding (Summers, 1995).
(*d*) Can be applied to any building that requires heated air or fresh ventilation (single-storey commercial, offices, multi-residential, agriculture, process heating, etc.) (Hollick, 2000b).
(*e*) As the TSC absorber is an additional component to the building envelope, TSCs can be incorporated onto new and existing buildings.

(*f*) Good aesthetic qualities (generally indistinguishable from a conventional metal cladding sheet and a wide range of colours can provide high absorption performance) (Munari Probst and Roecker, 2007).

7.2 Limitations

(*a*) The large size of the collector can limit applications to the tilt and orientation defined by the building envelope (mitigated to a degree with modular designs).
(*b*) Generally not suitable for high temperature rise applications (30°C over ambient air temperature) (Leon and Kumar, 2007).
(*c*) The large size of the collector means that the absorber needs to fit in with the building's aesthetic (the colour desired for aesthetic characteristics may not always be the ideal colour for a solar absorber) (Munari Probst and Roecker, 2007).

8. Conclusions

TSCs have been used successfully in the USA and Canada to provide preheating of ventilation air for buildings and the evidence suggests that they can compete against other renewable technologies. The incorporation of a simplified TSC energy yield model into the simplified building energy model will enable building energy practitioners to assess the performance of TSCs for Building Regulations Part L compliance. However, there is still a need to widen the uptake of TSC energy yield models within dynamic building modelling software. This paper has highlighted some potential design pitfalls that can be avoided if practitioners are aware of them. Overall, TSC technology appears to be a promising means of providing economically competitive renewable energy to a wide range of buildings in the UK.

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