The potential of Concrete Solar Thermal Collectors for Energy Savings

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Abstract: Solar thermal collectors manufactured from concrete offer a cheap alternative to the standard range of solar thermal collectors. Concrete is also inherently durable, maintenance free and exhibits good thermal storage qualities given its high specific heat capacity and density. Also, considering the wide range of concrete, textures and surface finishes now achievable, concrete solar thermal collectors may offer greater potential as a façade integrated solar technology. Research into concrete solar collectors has presented the challenge in attaining the high output temperatures needed for domestic hot water (DHW) applications. Optimising the conductivity and absorptivity of a 1m^2 concrete solar collector yields maximum outlet water temperatures of approximately 25°C for winter and 35°C for summer months. Similar to unglazed flat plate collectors which are also characterised by low temperature outputs, supplementary heating of the water may be required to bring the water to DHW temperatures. This study evaluates the real feasibility of concrete solar thermal collectors. Specifically, it assesses the potential for energy saving by reducing the energy requirement of the heating system by supplying input water at temperatures 5-20 °C above mains temperature. The energy and cost payback is calculated for the maritime climate of Ireland. Concrete solar thermal collectors are shown to have good potential for energy saving and should be considered among the range of solar thermal technologies, particularly for building integration.

1. Introduction

Concrete Solar Collectors (CSCs) are a type of solar thermal collector that use a thick concrete layer as their absorber in place of a thin metallic plate, typical of standard solar thermal collectors (D'Antoni and Saro, 2012). They offer a unique solution to the building integrated solar thermal market for buildings with concrete facades (O'Hegarty et al., 2016b). These exposed concrete surfaces are designed to harness the energy of the sun which in turn is used to provide for the building's energy requirements.

Concrete solar collectors have been investigated for optimal inclination angles and in high temperature climates such as India (Chaurasia, 2000; Keste and Patil, 2012; Krishnavel et al., 2014), Tunisia (Hazami et al., 2005, 2010) and Thailand (Sarachitti et al., 2011). However, the potential of CSCs in colder climates is so far limited to simulation studies. D'Antoni and Saro (2013) used a 1D transient model to show that CSCs could offer significant energy savings when employed as part of a heat pump system. One of the limitations of standard solar thermal systems for Irish climates is their poor payback (Gill et al., 2016). The high capital costs of solar thermal panels are largely associated to the expensive materials used in manufacturing these. CSCs use cheap, locally sourced materials and can be manufactured with significantly greater ease. Outlined in this paper is a method to quantify the CSCs cost benefit and energy potential using simple calculation methods.

2. Experimental setup

This study uses an experimental system set-up to quantify the potential energy savings of 1m^2 of concrete solar collectors connected to a 65L storage tank.

2.1. Concrete collector development

Pipe embedment depth, concrete conductivity and absorptivity are influential performance parameters (O'Hegarty et al., 2016a). The CSC, tested on the roof of Trinity College Dublin, is constructed within the practical limits of these parameters.

Practical limits in relation to lifting these CSCs onto the roof restricted the use of one single 1m2 collector. Three 0.6 m^2 collectors are instead connected in series to make up approximately $1m^2$ of collection area. The construction of the collector itself followed the process described below and is depicted in Figure 1.

- Formwork is made of plywood and screwed together (a).
- 10 mm diameter copper pipe is cut into the required lengths and welded together with copper elbows to form the heat exchanger.
- The heat exchanger is placed into the formwork, resting on two small concrete placers (b).
- The concrete is mixed and superplasticiser is added to ensure good workability and therefore a good bond with the pipe.
- The concrete is poured in place (c).
- The concrete collector is left to cure for 2 weeks before being lift to the roof.
- Formwork is removed (d)
- The collectors are painted black and connected using flexible plastic pipe.
- The collectors are orientated vertically and insulated to simulate a façade installation

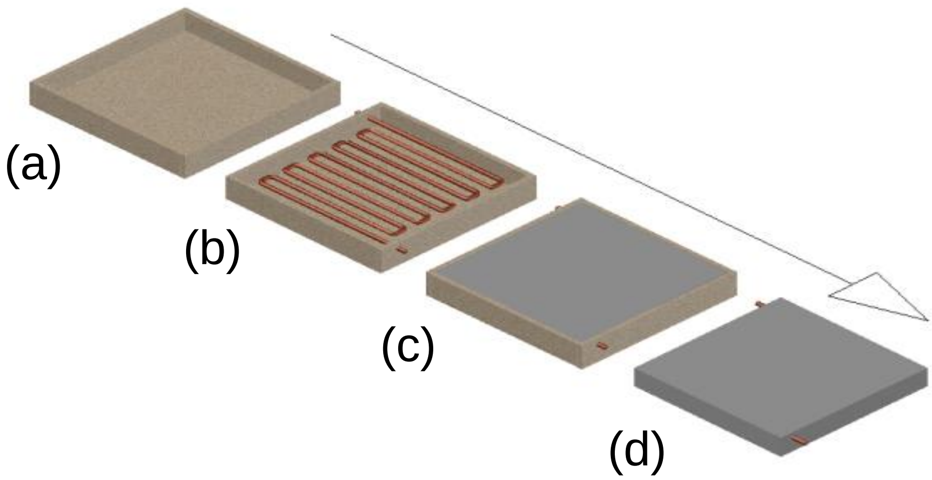

Figure 1. Concrete solar collector construction process (left to right)

Copper is chosen over PEX as the choice of pipe material as it allowed for narrower bends (hence closer spaced pipes and a greater length of pipe). For real applications with larger available surface areas PEX piping would be preferable due to the risks of corrosion with copper.

2.2. System description

The closed loop experimental system (Figure 2) is setup in such a way to minimize maintenance and allow for a continuously flow of water throughout the year. The continuous flow of water means the tank is charged during the day and discharged at night without the need for a hot water load. It is assumed that the minimum temperature reached at night time is representative of the mains water temperature. This assumption is validated by comparing minimum tank temperatures with average mains water temperatures from Gill et al. (2016).

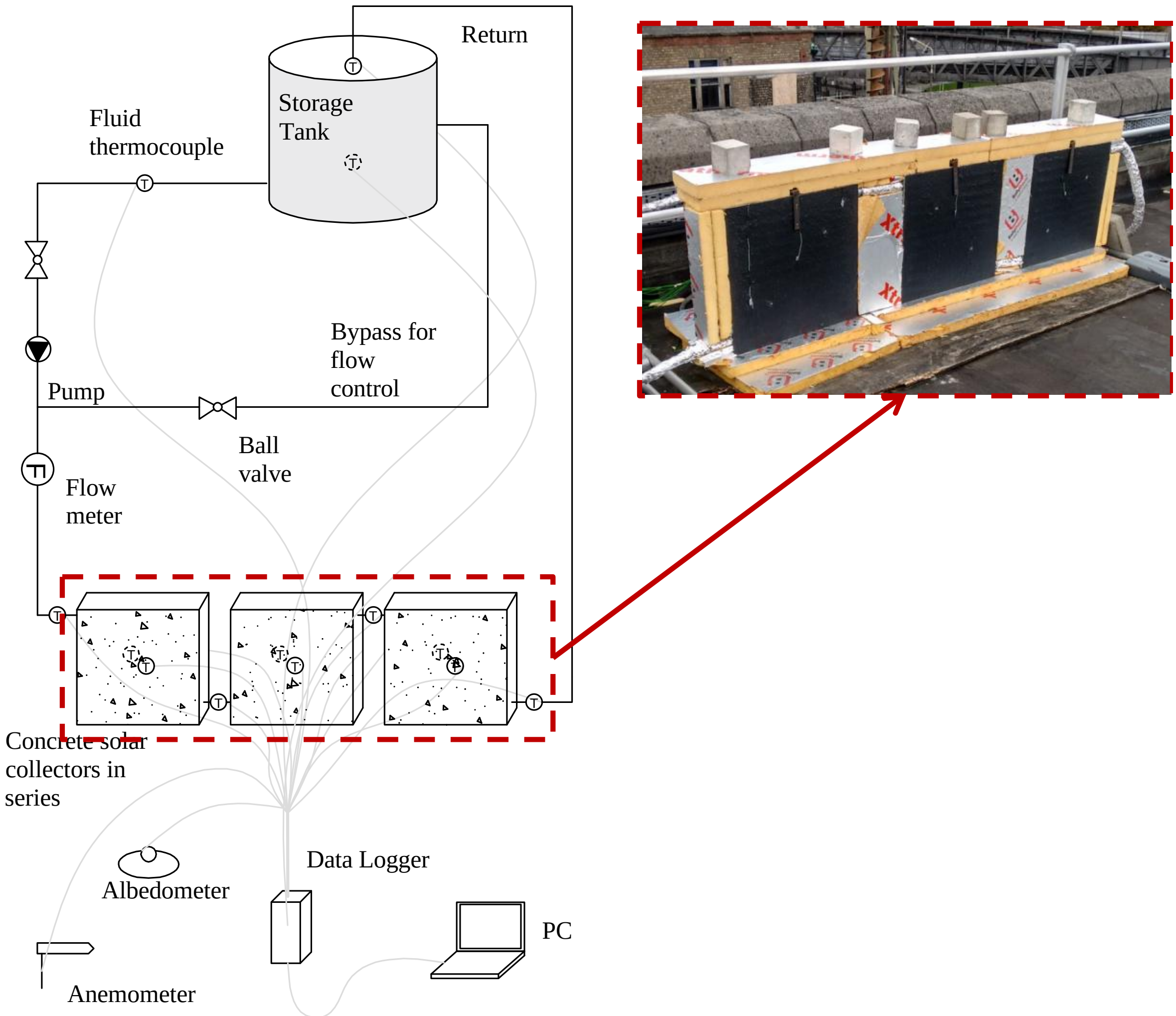

Figure 2. Experimental set-up of the concrete solar collectors (Dublin, Ireland).

A 65L insulated storage tank (located indoors) is connected to the CSCs using insulated PEX pipe. An aluminium coating is also wrapped around the pipe to minimize heat transfer between the surroundings and fluid in the pipe. The panels are connected in series to make up a 1m^2 surface area and then connected back to the storage tank to finish the continuous loop.

The pump is left on and a bypass in the system allows for flow control. A flow rate of 0.03 L/s is set and is also recorded electronically. In addition, fluid temperatures are recorded at the inlet and outlet of the CSC as well as at different levels in the tank. The temperature recordings in the tank showed negligible difference; therefore, the assumption of an un-stratified, fully mixed tank is reasonable. Surface temperatures are recorded on the front and back of the panels. Wind speed, solar irradiance and ambient temperatures are also recorded by the National instruments Data Logger.

The arrangement of the experiment means that the water in the tank is cooled down over night and this temperature can be used to approximate the water mains temperature in the morning. The energy output can be approximated according to Equation 1.

$$Q = m_{tank} c_f (T_{tank,max} - T_{tank,min}) \quad \text{(Eq. 1)}$$

Where Q is the energy output per day, m_{tank} is the mass of the fluid in the tank and c_f is the specific heat capacity of the fluid. The morning water temperature, $T_{tank,min}$ is subtracted maximum temperature of the tank for a given day, $T_{tank,max}$, to give the temperature difference for a given day. It is worth noting that quantifying the energy potential for a CSC using this system under-estimates the potential. A controller would improve the efficiency of the system but is not used as the authors are interested in how the system reacts to sharp drops in solar irradiance.

3. Results

The energy output of a CSC is ultimately determined by the solar irradiance. The performance and weather data for three different days in Dublin Ireland are illustrated in Figure 3.

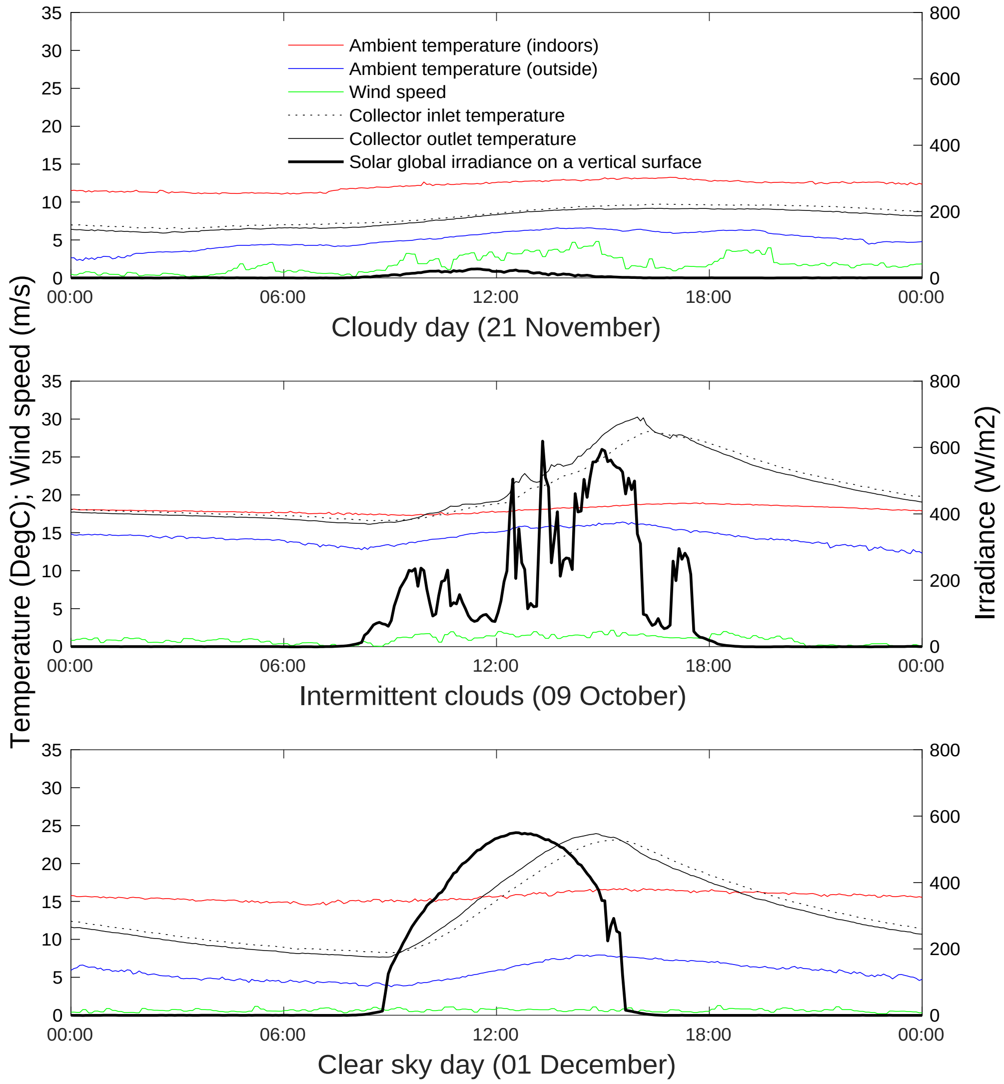

Figure 3. Concrete solar collector inlet and outlet temperatures for three example days

A cloudy day with only diffuse radiation, an intermittent cloudy day and a clear sky day all display different performance curves.

- The cloudy day recordings show how the ambient temperature becomes the main driving force on the outlet temperature. The energy output, as calculated by Equation 1, is almost negligible.
- The intermittent cloudy day shows some drops in the outlet water temperature during the heat up phase during the day. These drops would be eradicated with the inclusion of a controller. The greatest outlet water temperatures are observed for the intermittent cloudy day in October, because of the longer hours of sunlight in October compared with December, as well as the higher ambient and mains water temperatures.
- The clear sky day in December shows the greatest temperature difference of the 3 days where water temperatures of 25 °C are attainable, even though ambient temperature is as low as 5 °C.

4. Energy assessment

Based on the data available, conservative estimates are made on the potential energy savings of a $1m^2$ vertically installed CSC in Ireland. Several assumptions are made in calculating both the energy savings and payback of the CSC. Daily energy outputs are displayed in Figure 4.

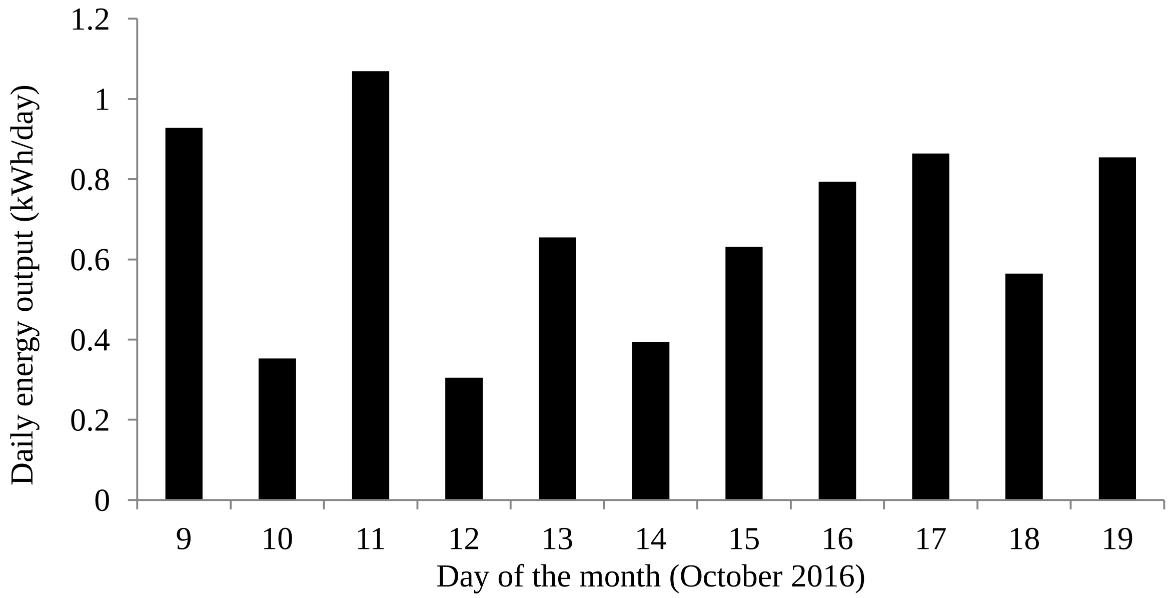

Figure 4. Daily Energy Outputs for a run of 10 days in Ocotber

The following assumptions are made in calculating the energy and cost savings:

- An average day in October is representative of the whole year as this is halfway between Winter and Summer.
- The energy savings are calculated for a simplified heating system represented by Eq 1 and described in Section 2.2.

- A 1 m^2 concrete solar collector costs approximately 45 € (majority of the cost is for the copper pipe which could be replaced by a PEX pipe, given a greater available surface area).

- Fuel costs taken for Ireland (SEAI, 2016).

The average tank temperature difference between daily maxima and minima is 8°C for October and ranges from 13°C on a clear day to 3°C on a cloudy day. Based on this average temperature difference and a simple hot water system the energy savings can be approximated as 225 kWh/year (Eq 1 multiplied by 365 days). Further analysis can be used to approximate the simple payback as displayed in Table 1.

Table 1. Cost savings and simple payback period

System	€/kWh (SEAI)	Cost savings €/year	Simple Payback (Years)
Oil	0.055 - 0.071	12.3 – 15.9	3.66 - 2.83
Gas	0.061 - 0.073	13.63 – 16.3	3.3 – 2.76
Electricity	0.17 - 0.405	38 – 90.5	1.18 – 0.5

The payback periods vary depending on the auxiliary energy type, but in general are significantly lower than payback periods for the standard higher efficiency solar thermal systems, such as flat plate or evacuated tube systems.

The figures are calculated based on a low maintenance experimental system. The aim is of this paper is to portray value for these concrete solar collectors as building integrated renewable technology components in a northern maritime climate. The potential energy output can be further explored through collector and system optimization. Three proposed system alternatives for concrete solar collectors are described below and displayed in Figure 5.

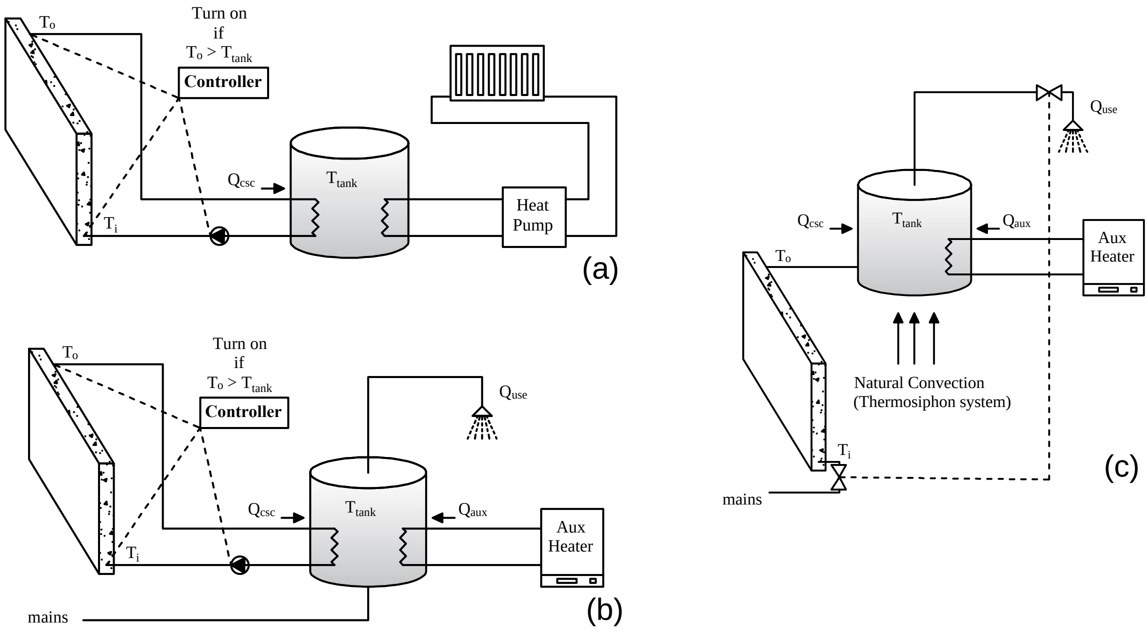

Figure 5. Heating systems suitable for concrete solar collectors.

- System (a) would use the concrete solar collector in conjunction with a buffer storage tank and a heat pump to supply space heating to the building via radiators or under floor heating.

- System (b) is most like the experimental setup with the addition of a load, controller, auxiliary heater and heat exchangers.
- For system (c), a pump is not required and the tank (raised above the concrete solar collectors) is heated up by thermosiphonic action. The water entering from the mains to the dwelling is split into a normal cold tap and a hot water tap which first travels through the concrete solar collector before reaching the storage tank.

Different systems offer advantages for different heating requirements and may be selected based on a building's needs.

5. Conclusion

An outdoor experiment of a concrete solar collector has been set up on a roof in Dublin, Ireland. The collectors are installed vertically and insulated at the back to mimic a building integrated system. The research has found that, while these collectors can't reach the high temperatures achievable by other solar thermal collectors, they do offer several advantages.

- Concrete solar collectors are easy to manufacture and don't require any specialist equipment or materials. They can even be constructed on site.
- The materials used can be sourced locally.
- The inherent durability of concrete offers an advantage, particularly for building integrated systems, where durability is a key requirement.
- $1m^2$ of concrete solar collectors, optimised within practical and economic limits, can increases the mains by 15°C on a winters day.
- Outlet water temperatures as high as 25°C and 32°C have been recorded for winter and autumn months respectively.
- For the system described in this paper conservative calculations showed energy savings of approximately 225 kWh/year
- Payback periods range from 6 months to 3.5 years depending on the auxiliary energy used.

The results are in general promising but work can still be done on improving how these concrete solar collectors are integrated as part of a building's heating system. Some ideas are presented in this paper and the authors have begun investigations into these, through CFD simulation based studies.

References

Chaurasia, P.B.L., 2000. Solar water heaters based on concrete collectors. Energy 25, 703–716. doi:10.1016/S0360-5442(99)00091-2

D'Antoni, M., Saro, O., 2013. Energy potential of a Massive Solar-Thermal Collector design in European climates. Sol. Energy 93, 195–208. doi:10.1016/j.solener.2013.04.011

D'Antoni, M., Saro, O., 2012. Massive Solar-Thermal Collectors: A critical literature review. Renew. Sustain. Energy Rev. 16, 3666–3679. doi:10.1016/j.rser.2012.02.076

Gill, L., Mac Mahon, J., Ryan, K., 2016. The performance of an evacuated tube solar hot water system in a domestic house throughout a year in a northern maritime climate (Dublin). Sol. Energy 137, 261–272. doi:10.1016/j.solener.2016.07.052

Hazami, M., Kooli, S., Lazâar, M., Farhat, A., Belghith, A., 2010. Energetic and exergetic performances of an economical and available integrated solar storage collector based

on concrete matrix. Energy Convers. Manag. 51, 1210–1218. doi:10.1016/j.enconman.2009.12.032
Hazami, M., Kooli, S., Lazaar, M., Farhat, A., Belghith, A., 2005. Performance of a solar storage collector. Desalination 183, 167–172. doi:10.1016/j.desal.2005.03.033
Keste, A.A., Patil, S.R., 2012. Investigation of Concrete Solar Collector: A review. IOSR J. Mech. Civ. Eng. 6, 26–29.
Krishnavel, V., Karthick, A., Murugavel, K.K., 2014. Experimental analysis of concrete absorber solar water heating systems. Energy Build. 84, 501–505. doi:10.1016/j.enbuild.2014.08.025
O'Hegarty, R., Kinnane, O., McCormack, S., 2016a. Parametric Analysis of Concrete Solar Collectors. Energy Procedia, Proceedings of the 4th International Conference on Solar Heating and Cooling for Buildings and Industry (SHC 2015) 91, 954–962. doi:10.1016/j.egypro.2016.06.262
O'Hegarty, R., Kinnane, O., McCormack, S.J., 2016b. Review and analysis of solar thermal facades. Sol. Energy 135, 408–422. doi:10.1016/j.solener.2016.06.006
Sarachitti, R., Chotetanorm, C., Lertsatitthanakorn, C., Rungsiyopas, M., 2011. Thermal performance analysis and economic evaluation of roof-integrated solar concrete collector. Energy Build. 43, 1403–1408. doi:10.1016/j.enbuild.2011.01.020
SEAI, 2016. Domestic Fuel Cost Comparison October 2016. Sustain. Energy Auth. Irel.