COST EFFECTIVE DOMESTIC SOLAR THERMAL ENERGY CONVERSION SYSTEMS FOR NORTHERN MARITIME CLIMATES

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Abstract

The current cost of installed solar water heating systems in the United Kingdom using accredited installers results in payback periods which can be substantially longer than the projected lifespan (25 years). This paper investigates integration of non-imaging Compound Parabolic Concentrators (CPCs) and lower cost thermal energy storage units fabricated from thermoplastics as a method for reducing the current high cost of solar water heating in the UK. Experimental results from outdoor testing of a non-evacuated flat plate solar collector incorporating a non-imaging CPCs is presented and compared to current proprietary systems. The heat removal factor (F_R) and heat loss coefficient (F_RU_L) of a direct flow CPC solar thermal collector under an irradiance of 800W m^{-2} was measured as 0.52 and 1.72 W m^{-2} K^{-1} respectively. A hot water storage tank fabricated from a thermoplastic and incorporated with a solar water heater was evaluated under extended outdoor testing and its heat loss coefficient measured as 1.3W K^{-1} , 7.4 times lower than an installed domestic solar hot water storage unit.

1. Introduction

The issue of energy is one which is of concern to everybody's daily life throughout the EU and the globe through its economic effects (rising energy costs), environmental implications (anthropogenic climate change and other forms of pollution) and security of supply (unequal distribution of energy resources). Currently 80% of primary European energy supplies are derived from the combustion of non-renewable fossil fuels. Past economic growth and prosperity in Europe has been built on the extensive use of these leaving the EU vulnerable to energy supply disruptions from other external sovereign regimes exporting energy to the EU, fluctuating energy costs and to severe environmental change via anthropogenic climate change. By 2020 the EU is aiming for an 80 % reduction in carbon emissions compared to 1990 levels through the introduction of new renewable energy technologies. As a member of the EU, the UK government is obligated to meet these commitments, thus there are specific environmental, political and economic drivers to harness alternative energy sources [1].

Currently (2010) 1% of thermal energy requirements in the UK are met using renewable energy sources. To meet the EU carbon emission reduction targets, 12% of thermal energy must be derived from renewable sources by 2020 [2]. One proven method of simultaneously reducing the use of fossil fuel supplies and carbon dioxide emissions is the use of domestic solar water heaters which can supply almost 100% of hot water loads in summer and annually around 40 to 80% of service hot water demands. In 2009 the estimated European production of heat using solar thermal collectors was $16TW_{th}$ preventing the emission of 7 million tones of CO_2 [3].

The annual efficiency of well designed Flat Plate Solar Water heaters, (FPSWHs) and Evacuated Tube Solar Water Heaters, (ETSWHs) has been reported as 35-40% and 45-50% respectively. Thus under an irradiance of 1000kWh yr^{-1} FPSWHs can supply 350-400kWh/m^2, whereas the figure for ETSWHs is 450-500kWh/m^2, [4]. The annual carbon dioxide savings of a typical 3.5m^2 solar collector subjected to the UK's northern maritime climate ranges from 260kg to 530kg, depending on which fuel is substituted [5]. Bioenergy sources could be utilized as another renewable source of heat but the impact on land use is substantial, for example in terms of land area the electrical conversion efficiency of PV is 50 times higher than biomass [6]. As solar energy conversion devices can be mounted on the rooftops of existing south facing buildings their impact on land is minimal in comparison to other forms of renewable energy. Additionally the annual system efficiency of solar thermal systems ranges from 35 to 50% [4] whereas that of solar PV is 10.1% [7]. Presently in the UK solar thermal collectors are used mainly for providing domestic hot water not space heating.

The current reported cost of installed solar water heating systems in the United Kingdom ranges from £3000-£5000, (costing based on a 3.5m^2 solar thermal collector) using these figures the cost of solar water heaters ranges from £860 to £1430 m^{-2} of installed collector area [5]. Depending on which types of fuel solar energy systems are substituting for (coal, oil, gas, electricity), the annual cost saving has been reported as £50 to £85 resulting in a Simple Payback Period (SPP) ranging from 36 to 100 years. As the projected life span of solar thermal collectors is reckoned to be approximately 25 years clearly the cost of solar energy systems must be substantially reduced if the use of such systems in northern maritime climates such as the UK is to be cost effective, uptake increased and international policy obligations to be met. This paper examines two methods that if adopted could potentially reduce the cost of solar thermal energy conversion systems. Firstly the use of more thermally efficient hot water storage tank materials and secondly the integration of Compound Parabolic Concentrators (CPCs). Using a hot water storage tank material with a lower thermal conductivity slows thermocline degradation by reducing thermal losses to the external environment and heat transfer to lower fluid layers via wall conduction improving thermal stratification and hence the performance of the solar thermal collector. The integration of reflective concentrators increases the amount of solar radiation collected per unit area of absorber and reduces radiative heat losses as the area of radiating surface is reduced relative to total collector area.

The cost of hot water storage tanks could be reduced and thermal performance increased if plastics were used as the material from which tanks are fabricated. Hot water storage tanks fabricated from copper or stainless steel have a thermal conductivity of 401 W/m.K and 13.4 W/m.K respectively, [8] in contrast High Density Polyethylene (HDPE) has a thermal conductivity of 0.45 W/m.K. High Density Polyethylene (HDPE) can withstand temperatures of up to 120°C which is more than sufficient for domestic hot water or space heating requirements. Heat-pipe solar thermal collector systems would be ideal for integration with plastic hot water storage tanks as their maximum working temperature can be predetermined through careful selection of the working fluid preventing the tank from mechanical failure when thermal demands are low and solar irradiance is high. The current cost (2010) per tonne of copper, stainless steel (316 grade) and HDPE is £4370, £3376 and £881 [9]. Clearly HDPE has both a thermal and cost advantage (57% to 80% lower cost) than the materials currently used for fabricating hot water storage tanks. CPCs can be integrated with flat plate solar collectors to improve the thermal performance and cost effectiveness as the area of absorber used is reduced [10]. A previous study using an asymmetrical CPC designed for Northerly latitudes reported that a tested design could provide 75% of the energy typically expected from a flat plate collector [11].

2. Methodologies

2.1 Fabrication and testing of CPC

A direct flow truncated CPC solar collector with a half acceptance angle of 30° and a concentration ratio of 1.82X was fabricated in house at the University of Ulster. This was tested under a northern maritime climate to investigate how effective these would be under typical operating conditions. Incident solar radiation was measured to an accuracy of ±1%, temperature measurements were made at the collector inlet, collector outlet and the ambient using platinum resistance thermometers (accuracy±0.06°C). Temperatures inside the Hot Water Storage Tank were measured using a vertical array of thermocouples located along the central axis of the tank (accuracy ±0.1°C). The hot water storage tank had a volumetric capacity of 50 liters and constructed from High Density Polyethylene (HDPE). Measurements were sampled every 10 seconds, averaged over a five minute period and then recorded using a multi-channel logger. The CPC was orientated along its east-west axis and the hot water storage tank used as a calorimeter and the energy stored by the system determined from the diurnal change in MBTT (after standing losses). The amount of absorbed incident radiation removed by water was calculated using equation 1 where Q_u was the rate of useful heat removal (W), m was the mass flow rate of the water circulating through the collector (kg s^{-1}), T_o was the collector outlet temperature (°C) and T_i was the collector inlet temperature (°C). The instantaneous thermal efficiency of the solar collector (η_i) was determined using equation 2 were A_c (m^2) was the aperture area of the collector and G_T (W m^{-2}) was the solar radiation incident on the collector aperture [10].

$$Q_u = mC_p(T_o - T_i) \tag{1}$$

$$\eta_i = \frac{Q_u}{A_c G_T} \tag{2}$$

Equation 3 was used to calculate the useful energy collected for each diurnal period, equation 4 to determine the total incident solar irradiance and equation 5 the diurnal efficiency of the CPC system exposed to a northern maritime climate [12].

$$Q_{useful} = mC_p\ (MBTT_f - MBTT_i) \tag{3}$$

$$G_T = \sum_{i=1}^{n} dt \tag{4}$$

$$\eta = \frac{Q_{useful}}{G_T A_c} \tag{5}$$

2.2 Thermal retention and stratification performance of hot water storage tanks

An HDPE hot water storage tank of volume 245 litres was fabricated and incorporated within a heat-pipe ETSWH system which was then subjected to the northern maritime climate at the University of Ulster's outdoor solar test facility. Simultaneously the monitoring of a solar water heating system using a direct flow ETSWH and a storage tank comprised of copper installed in a domestic dwelling to current industry best practice standards was undertaken over a monitoring period of 6 months so that the performance of a proprietary domestic solar water heater could be compared to the prototype systems under test at the University. To quantify thermal losses from the storage units, the heat loss coefficient (U) of both the HDPE and copper hot water storage tanks was calculated using 6, [13] where ρ was the density of water over the temperature range in question, C_p was the specific heat of water, V was the volume of the hot water storage tank in m^3 and t was the time period in seconds. Thermal losses were measured from the decrease in the mean hot water storage tank temperature nocturnally when there were neither thermal loads nor incident solar radiation.

$$U = \frac{\rho C_p V}{t} In\left[\frac{T_i - T_a}{T_f - T_a}\right] \quad (6)$$

2.2 Thermal energy generated using fossil fuels, cost calculations

The current annual cost of generating domestic hot water using fossil fuel based systems was calculated using published boiler seasonal efficiency figures reported [14] these are reproduced in table 1. The cost of electrical resistance heating was assumed as 100% efficient with a current cost of 15.3p/kWh [15]. The quantity of thermal energy required for production of service hot water was reported to be 50 litres per person per day delivered at a temperature of 45°C [4].

Table 1 thermal energy production using fossil fuel based central heating boilers

Boiler type	Seasonal efficiency (%)	Cost of hot water using oil (p/kWh)	Cost of hot water using gas (p/kWh)
Old boiler heavy weight	55	7.67	7.6
Old boiler light weight	65	6.49	6.5
Modern boiler non-condensing	78	5.41	5.4
Modern boiler condensing	88	4.77	4.8

3. Results

3.1. CPCs

Figure 3 shows the measured instantaneous efficiency of the direct flow CPC at solar noon under northern maritime climatic conditions.

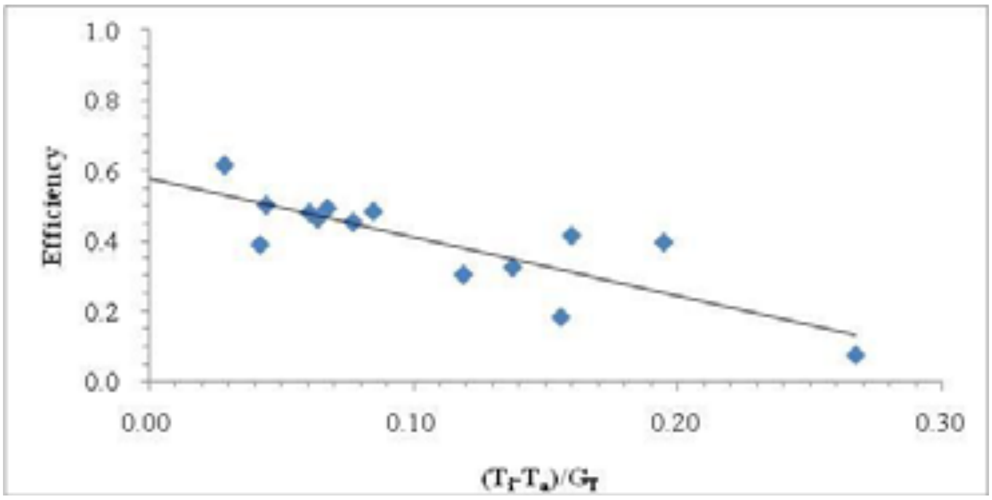

Fig.3. Outdoor test results for thermal performance of direct flow CPC under northern maritime climate

Under northern maritime climatic conditions F_R and F_RU_L was calculated as 0.52 and 1.72 W m-2 K^{-1} respectively and the mean diurnal efficiency of the system measured as 28.1% using equations 3 to 5. In comparison to the performance a standard flat plate solar water heater this system had a diurnal efficiency that was 70 to 80% lower.

3.2. Hot water storage units

The overall heat loss coefficient of the HDPE and Copper hot water storage tanks was calculated using equation 6 over 50 days as 1.3 W/K and 9.6 W/K respectively.

3.3. Economics

From table 1, the generation of thermal energy from fossil fuels using the boiler efficiency parameters reported by the SEDBUK database ranged from 4.8p to 7.7p/kWh assuming that the only paid input is fuel. Using the range of capital costs provided reported by the energy saving trust of [5] £3000 to £5000, assuming that the installed collector area is 3.5m^2 the generic performance data reported by [4] & the experimental data reported here, an assumed solar energy system life span of 25 years and discount rates of 2%, 5%, 8%, 10% with the capital repaid over the useful life of the collector. All costs and saving where calculated in terms of Present Worth (PW) using equation 7 [10] for the parameters above, where A was the annuity payment, *d* the discount rate, *i* the interest rate and N the time period (years).

$$PW = \frac{A(1+i)^{N-1}}{(1+d)^N} \quad [7]$$

When the economic benefits outweigh the costs then in financial terms an investment would result in a gain for the individual investor. The expected costs and savings in terms of PW from generating thermal energy using current proprietary solar water heaters over the expected service life were quantified and the benefit to cost ratio calculated.

The average cost of generating thermal energy using currently available proprietary solar thermal collectors was found to be 0.08p/kWh (FPSWH costing with initial cost (£3000) to 0.31p/kWh (worst case scenario ETSWH with initial cost of £5000). The cost benefit analysis showed that solar water heating using current technology is economic but only when the cost of fuel increases by 10% per annum. This shows that depiction of annual savings on official websites might benefit from showing estimated costs under different scenarios and also per kWh to allow consumers to make a more informed decision which is easily compared to other fuels. Thus if fuel costs rise at this rate then installation of a solar water heater would be economic.

4. Discussion

4.1. Current situation

Clearly generation of hot water using solar energy conversion systems in the UK is not economic under current conditions with the cost of solar thermal energy calculated as 59.3 to 89.3% higher than fossil fuel based systems. From this the cost of energy delivered by solar thermal systems must be decreased by more than a factor of 2. The cost of such devices is reduced by either increasing the efficiency (whilst maintaining the cost) or by reducing the cost (whilst maintaining the efficiency) This study has considered both approaches through the improved storage efficiency of the HDPE hot water storage tanks and the reduced costs of the collector through integration of reflective concentrators.

Two means of achieving this have considered by this study and it has been shown that CPCs integrated with non-evacuated flat plate solar energy systems can operate with an average system similar efficiency slightly lower than well designed FPSWHs but using nearly 50% less copper. The HDPE tank investigated had a heat loss coefficient 7.4 times lower than that measured in a hot water storage tank installed by an accredited installer using so called “best practice”. Clearly if solar thermal systems are to assist the UK in meeting its international obligations then the cost must be reduced drastically and technological interventions such as these proposed by this study are required.

4.2 Future directions

Obviously further technical innovations supported using appropriate policy measures are required if solar energy conversion devices are to economically contribute towards generation of thermal energy in the UK. The technical innovation required, is the design of a system costing 50% of current systems but with similar performance. This initial study has shown that a CPC solar collector can operate in a northern maritime climate but at a reduced efficiency compared to FPSWHs. Under current conditions the installed cost of a solar water heating system in the UK needs to be reduced to around £1000 to stimulate the market. Installing a system costing from £3000 to £5000 with annual fuel savings of £50 to £85 does not appeal to consumers as the simple payback period vastly exceeds the expected lifetime of the system.

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