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Comparative Field Performance Study of Flat Plate and Heat Pipe Evacuated Tube Collectors (ETCs) for Domestic Water Heating Systems in a Temperate Climate

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Ayompe, L., Duffy, A., McCormack, S., McKeever, M., Conlon, M.: Comparative Field Performance Study of Flat Plate and Heat Pipe Evacuated Tube Collectors (ETCs) for Domestic Water Heating Systems in a Temperate Climate. Energy, Vol. 36, Issue 5, pp. 3370-3378. May, 2011. doi:10.1016/j.energy.2011.03.034

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Highlights

► Two domestic scale SWHs with evacuated tube and flat plate collectors (FPCs) were tested under the same conditions. ► The annual average collector efficiencies were 46.1% and 60.7% for the flat plate and evacuated tube collectors respectively. ► System efficiencies were 37.9% and 50.3% for the flat plate and ETCs respectively. ► Simple payback periods (SPPs) varied between 13 years and 48.5 years depending on the type of auxiliary heating system considered.

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doi:10.1016/j.energy.2011.03.034

Please cite this article in press as: Ayompe LM, et al., Comparative field performance study of flat plate and heat pipe evacuated tube collectors (ETCs) for domestic water heating systems in a temperate climate, Energy (2011), doi:10.1016/j.energy.2011.03.034

Energy xxx (2011) 1–9

Contents lists available at ScienceDirect

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Comparative field performance study of flat plate and heat pipe evacuated tube collectors (ETCs) for domestic water heating systems in a temperate climate

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A R T I C L E I N F O

Article history:
Received 14 July 2010
Received in revised form
8 March 2011
Accepted 11 March 2011
Available online xxx

Keywords:
Flat plat collector
Evacuated tube collector
Solar water heater
Solar fraction

A B S T R A C T

This paper presents a year round energy performance monitoring results of two solar water heaters with 4 m^2 flat plate and 3 m^2 heat pipe evacuated tube collectors (ETCs)operating under the same weather conditions in Dublin, Ireland. The energy performance of the two systems was compared on daily, monthly and yearly basis. Results obtained showed that for an annual total in-plane solar insolation of 1087 kWh m^{-2}, a total of 1984 kWh and 2056 kWh of heat energy were collected by the 4 m^2 FPC and 3 m^2 ETC systems respectively. Over the year, a unit area of the FPC and ETC each generated 496 kWh m^{-2} and 681 kWh m^{-2} of heat respectively. For 3149.7 kWh and 3053.6 kWh of auxiliary energy supplied to the FPC and ETC systems their annual solar fractions (SFs) were 38.6% and 40.2% respectively. The annual average collector efficiencies were 46.1% and 60.7% while the system efficiencies were 37.9% and 50.3% respectively for the FPC and ETC respectively. Economic analysis showed that both solar water heating (SWH) systems are not economically viable with NPVs ranging between −€4,264 and −€652 while simple payback periods (SPPs) varied between 13 years and 48.5 years.

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1. Introduction

Solar water heating (SWH) collectors are special kinds of heat exchangers that transform solar energy to the internal energy of a transport medium. They are the major components of a solar system. They absorb incoming solar radiation, convert it to heat and then transfer the heat to a solar fluid usually made up of a mixture of water and glycol that flows through the collector. In forced circulation water heating systems used in temperate climates, the solar fluid is circulated using a pump within a closed circuit. The collected energy is transferred to water in a storage tank via a solar coil installed at the bottom of the tank.

There are three common types of stationary collectors used in SWH systems. These are flat plate collectors (FPCs), evacuated tube collectors (ETCs) and compound parabolic collectors (CPCs). FPCs and ETCs are the most widely deployed collectors for small-scale water heating applications. Both collectors convert beam (direct) and diffuse (in-direct) solar radiation into heat.

Typical domestic installations for families of 4–6 persons in temperate climates consist of 4–6 m^2 FPCs and 3–4 m^2 ETCs connected to a 200–300 litres hot water tank [1]. Although ETCs are more efficient than their flat plate counterparts, they are however more expensive with 3 m^2 heat pipe ETCs costing approximately twice as much as 4 m^2 FPCs.

Different authors have investigated the performance of SWH systems with heat pipe ETCs [2–5] and FPCs [6–9]. Zambolin and Del Col [10] carried out a side by side testing of FPC and ETC in Padova, Italy. They performed steady-state and quasi-dynamic efficiency tests following the EN 12975–2 standard. Allen et al. [11] carried out an integrated appraisal of a solar hot water system in the UK residential sector to asses its overall energy, environmental and economic performance. Kologirou [12] studied the thermal performance, economic and environmental protection offered by thermosiphon SWH systems.

Roonprasang et al. [13] carried out experimental studies of a new solar water heater system using a solar water pump powered by steam produced from FPCs. Chien et al. [14] experimentally and theoretically investigated a two-phase thermosiphon solar water heater. Huang et al. [15] investigated the thermal performance of thermosiphon flat plate solar water heaters with a mantle heat exchanger in China while Al-Nimr and Akam [16] studied the thermal performance improvements of a conventional tubeless collector. Al-Nimr et al. [17] derived expressions for the optimum length of a flat solar collector that maximizes the life cycle savings

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doi:10.1016/j.energy.2011.03.034

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of the collector and optimal distribution of a finite amount of thermal insulation that minimizes energy loss. Most of these studies have investigated the collectors under operating conditions different from those which are typical of the service life of SWH systems.

This study, therefore, aims to compare the energy and economic performance of FPC and heat pipe ETC systems installed side by side subjected to similar operating conditions and weather conditions to those found in a temperate environment. Energy performance indices computed include: energy output from the collectors, energy delivered to the hot water tanks, collector and system efficiencies, heat loss in the pipes between the collectors and solar coils and SF.

1.1. Methodology

Two complete forced circulation SWH systems with 4 m^2 flat plate (FP) and 3 m^2 heat pipe evacuated tube (ET) collectors were installed side by side on a flat rooftop and subjected to similar weather and operating conditions in Dublin, Ireland. The two water heating systems each had a 300 l hot water tank equipped with an electrical auxiliary immersion heater which was used to top up the tank temperature to 60 °C in the morning and evening whenever the solar coil fell short of doing so. An automated hot water draw off system was developed which mimicked domestic hot water use; exactly the same hot water demand profile was applied to both SWH systems (shown in Fig. 1). System performance data were collected every minute.

2. System description

Typical SWH systems used in temperate climates consist of a hot water storage tank, control unit, pump station and either flat plate or ETCs. The collectors used in this study were installed on a flat roof of the Focas Institute building, Dublin Institute of Technology. They were south facing and inclined at 53° equal to the local latitude of the location. The hot water cylinders were installed nearby in the building's plant room. The solar circuits consisted of 12 mm diameter copper pipes insulated with 22 mm thick Class O Armaflex. All pipe fittings were also insulated to reduce heat losses. The solar circuit pipe length for the ETC supply and return were 14 m and 15.4 m respectively while they were 14 m and 15.6 m respectively for the FPC system.

The FPC and ETC used in this study are standard commercially available collectors that have been tested to EN 12975/6 standards and certified by the Solar Keymark. The zero-loss collector

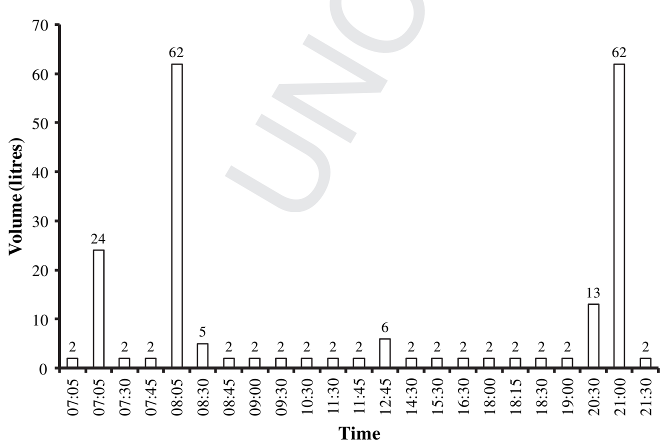

Fig. 1. Volume of hot water (60 °C) draw off at different times of the day.

efficiency, heat loss coefficient, and temperature dependence of the heat loss coefficient values are 0.778, 0.91 W m^{-2} K^{-1}, and 0.01 W m^{-2} K^{-1} for the ETC while for the FPC the respective values are 0.776, 3.95 W m^{-2} K^{-1}, and 0.017 W m^{-2} K^{-1}.

2.1. Evacuated tubes collector

The evacuated tubes collector was a Thermomax HP200 consisting of a heat pipe solar collector with a row of 30 ETs and an insulated water manifold. It has two separate circuits, one in each individual tube inside the heat pipe and one in the manifold through which the solar fluid circulates. The collector has an absorber surface of 3 m^2 and the tubes have a vacuum level of 10^{-5} mbar.

2.2. FPCs

The FPC system consisted of two K420-EM2L FPCs each with a gross area of 2.18 m^2 and aperture area of 2 m^2 connected in series giving a total area of 4 m^2. Each collector had maximum operating and stagnation temperatures of 120 °C and 191 °C respectively, a maximum operating pressure of 10 bar and a fluid content of 1.73 l.

2.3. Hot water tanks

The stainless steel hot water cylinders (model HM 300L D/coil **Q1** U44332). The tank height and diameter were 1680 mm and 580 mm respectively with an operating pressure of 3 bar. Each cylinder was equipped with two solar immersion heaters of 2.75/3.0 kW capacity located at the bottom and middle of the tank. The cylinders each had two heating coils with surface areas of 1.4 m^2 and a rating of 21 kW.

2.4. Hot water demand profile

The hot water demand profile employed was the EU reference tapping cycle number 3 equivalent to a daily energy output of 11.7 kWh representing 199.8 l of water at 60 °C. It is based on hot water use of the average European household described in the European Union mandate for the elaboration and adoption of measurement standards for household appliances EU M324EN [18]. Fig. 1 shows the volume of hot water extracted at different times of the day.

2.5. Auxiliary heating and hot water demand management system

A key innovation of the SWH systems field performance test was the introduction of an automated hot water dispensing unit which extracted water from the hot water tanks in such a way as to mimic real life operation where the users interact with the SWH systems. It consists of a programmable logic controller (PLC), contactors, relays, electrical fittings, solenoid valves, thermostats, impulse flow meters, etc. A software code was written to control the auxiliary heating system as well as opening and shutting of the solenoid valves. The operation was synchronised for the two SWH systems to ensure they operated identically.

The PLC turned on the immersion heaters between 5–8 am and 6–9 pm daily just before the two peak hot water draw offs. Analogue thermostats placed at the top of the hot water tanks were set to turn-off the electricities supply to the immersion heaters when the temperature of water at the top of the tank exceeded 60 °C. Hot water was dispensed using solenoid valves that were opened and closed using signals from the PLC. Pulse flow meters (1 pulse per litre) installed at the end of the solenoid valves were used to count the number of litres of water extracted from the hot water tanks. The solenoid valves were closed when the required

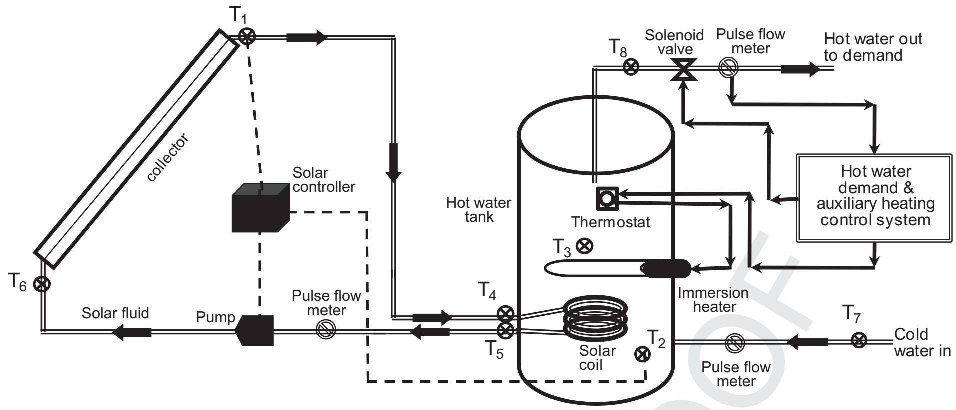

Fig. 2. Schematic diagram of the FPC and ETC systems.

volume of water was dispensed based on the water demand profile (Fig. 1).

Fig. 2 shows a schematic diagram of the experimental setup of the two SWH systems. It shows the location of the SWH system components as well as the position of the thermocouple sensors. Parameters measured include the following: solar fluid temperature at the collector outlet (T_1), water temperature at the bottom of the hot water tank (T_2), water temperature at the middle of the hot water tank (T_3), solar fluid temperature at inlet to the solar coil (T_4), solar fluid temperature at the outlet from the solar coil (T_5), solar fluid temperature at inlet to the collector (T_6), cold water inlet temperature (T_7), hot water supply temperature (T_8) and the volume flow rate of the solar fluid.

2.6. Data measurement and logging

Each SWH system was equipped with a RESOL DeltaSol M solar controller which had relay inputs to control the operation of the solar pump station. It also had temperature sensor inputs onto which PT1000 platinum resistance temperature sensors were connected to measure water and solar fluid temperatures (T_1–T_8) shown in Fig. 2. The volumetric flow rate of the solar fluid was measured using RESOL V40-06 impulse flow meters which react at 10 l per pulse. RESOL DL2 data loggers were used to store data every minute from the RESOL DeltaSol M solar controllers via RESOL VBus cables. The DL2 data loggers were equipped with a secure digital (SD) drive and a local area network (LAN) port for direct connection to a personal computer (PC). Data from the loggers was extracted using a Web browser or an SD card and then converted to text format using the RESOL Service Centre Software.

In-plane global solar radiation, ambient temperature and wind speed data were measured using a weather station consisting of an SMA Sunny Sensor Box equipped with an ambient temperature sensor and an anemometer. The solar radiation sensor had an accuracy of ±8% and a resolution of 1 W m^{-2}. The PT1000 platinum temperature sensors had an accuracy of ±0.5 °C while the ambient temperature sensor was a JUMO PT 100 U type with accuracy of ±0.5 °C. The anaemometer was a Thies small wind transmitter with accuracy of ±5%. Weather data was logged at 5 min intervals using a Sunny Box WebBox.

Table 1
Technical parameters.

Description	Units	Value
Electric heater efficiency	(%)	100
Oil boiler efficiency	(%)	65
Condensing natural gas boiler efficiency	(%)	90
Heat delivered by ETC	kWh y^{-1}	1699
Heat delivered by FPC	kWh y^{-1}	1639
FPC area for grant calculation	m^2	4.0
ETC area for grant calculation	m^2	3.2

3. Energy analysis

The energy performance indices evaluated in this study include: energy collected, energy delivered and supply pipe losses, SF, collector efficiency and system efficiency.

3.1. Energy collected

The useful energy collected by the solar energy collector is given as [19]:

$$Q_c = \dot{m}C_p(T_1 - T_6) \quad (1)$$

3.2. Energy delivered and supply pipe losses

The useful energy delivered by the solar coil to the hot water tank is given as

$$Q_d = \dot{m}C_p(T_4 - T_5) \quad (2)$$

Supply pipe losses were as a result of temperature drop as the solar fluid flowed between the collector outlet and the solar coil inlet to the hot water tank. These losses were calculated as:

$$Q_l = \dot{m}C_p(T_1 - T_4) \quad (3)$$

Table 2
Economic parameters.

Description	Units	Value
Electricity cost	€$_{2010}$/kWh	0.160
Gas cost	€$_{2010}$/kWh	0.055
Heating oil cost	€$_{2010}$/kWh	0.064
Gas price inflation rate	(%)	3
Electricity price inflation rate	(%)	3
Heating oil price inflation rate	(%)	3
Grant for FPC	(€/m^2)	250
Grant for ETC	(€/m^2)	300
Installed cost of FPC system	€$_{2010}$	4400
Installed cost of ETC system	€$_{2010}$	5000
System life	Years	20
Discount rate	%	8

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Table 3
Average daily solar insolation, energy collected, energy delivered and supply pipe losses for the FPC and ETC systems.

Month	In-plane Solar insolation (kWh m^{-2} d^{-1})	Total energy collected (KWh d^{-1})		Energy delivered (kWh d^{-1})		Supply pipe losses (kWh d^{-1})		Energy collected per unit area (kWh m^{-2} d^{-1})	
		FPC (4 m^2)	ETC (3 m^2)	FPC (4 m^2)	ETC (3 m^2)	FPC (4 m^2)	ETC (3 m^2)	FPC	ETC
Jan-10	1.5	3.0	2.4	2.5	2.0	0.5	0.4	0.8	0.8
Feb-10	1.9	4.1	3.0	3.4	2.4	0.7	0.5	1.0	1.0
Mar-10	3.3	6.7	6.2	5.4	5.4	1.0	0.9	1.7	2.1
Apr-10	4.5	9.2	8.5	7.5	7.4	1.4	1.3	2.3	2.8
May-10	4.2	7.7	9.0	6.4	7.4	1.3	1.6	1.9	3.0
Jun-09	4.6	8.2	9.5	7.1	7.7	1.1	1.8	2.1	3.2
Jul-09	3.6	5.5	6.7	4.5	5.3	1.0	1.4	1.4	2.2
Aug-09	3.7	5.9	7.1	5.0	5.7	1.0	1.5	1.5	2.4
Sep-09	3.3	5.8	6.5	4.9	5.2	0.9	1.2	1.4	2.2
Oct-09	2.2	3.9	4.1	3.2	3.4	0.7	0.7	1.0	1.4
Nov-09	1.8	3.3	3.0	2.6	2.5	0.7	0.5	0.8	1.0
Dec-09	1.2	2.0	1.7	1.6	1.5	0.4	0.2	0.5	0.6
Annual average	3.0	5.4	5.6	4.5	4.6	0.9	1.0	1.4	1.9
Annual total	1,087	1,984	2,056	1,639	1,699	326	366	496	681

3.3. Solar fraction

The solar fraction (SF) is the ratio of solar heat yield to the total energy requirement for water heating and is given as [20]:

$$SF = \frac{Q_s}{Q_s + Q_{aux}} \tag{4}$$

3.4. Collector efficiency

The efficiency of the plat plate (FP) and ET collectors are calculated as [21,22]:

$$\eta = \frac{\dot{m}C_p(T_1 - T_6)}{A_c G_t} \tag{5}$$

3.5. System efficiency

The efficiency of the FPC and ETC systems is calculated as [21,22]:

$$\eta = \frac{\dot{m}C_p(T_4 - T_5)}{A_c G_t} \tag{6}$$

4. Economic analysis

In order to compare the economic viability of the two SWH systems, simple payback period (SPP) and net present value (NPV) were used. Calculations were based on potential savings compared to using an electric immersion water heater, a condensing gas boiler and an oil fired boiler. Tables 1 and 2 show the technical and economic parameters used in the economic analysis of the SWH systems. The quantities of heat delivered by the FPC and ETC systems were obtained from field performance data. The cost of electricity, gas and heating oil used are 2010 market prices in Ireland.

The annual operation and maintenance cost was estimated to be 1% of the initial capital cost and it was assumed that it increased at a rate of 1% per year as used by Kalogirou [12]. The system life was assumed to be 20 years which is in line with the duration quoted by most manufacturers/suppliers of SWH collectors.

The SPP is one of the most common ways to evaluate the economic value of a project. It is the minimum amount of time in years required for the positive cash flows to surpass the initial investment, without regard to the time value of money. The main drawbacks of this method are that the timing of cash flows is ignored and cash flows beyond the payback period are not accounted for [23]. However, it has the advantage of being the easiest for the public to understand of all economic measures. The payback period is the ratio of the extra first cost, ΔC_0 (or capital cost) to the annual savings, S and is given as [24]:

$$SPP = \frac{\Delta C_0}{S} \tag{7}$$

The extra first cost is the incremental cost of the SWH system and does not involve costs that would arise in any other case for the corresponding building component. Annual revenues are the averaged energy cost avoided annually, which consists of the annual energy savings multiplied by the cost per energy unit.

The quantity of conventional energy displaced annually (E_c) is computed as:

$$E_c = Q_u/\eta_h \tag{8}$$

where η_h is the auxiliary heater efficiency and Q_u is the useful energy collected by the solar collector.

Table 4
Energy extracted from the hot water tanks and auxiliary energy supplied to the FPC and ETC systems.

Month	Energy extracted (kWhd^{-1})		Auxiliary energy (kWhd^{-1})		Solar fraction (%)	
	FPC (4 m^2)	ETC (3 m^2)	FPC (4 m^2)	ETC (3 m^2)	FPC (4 m^2)	ETC (3 m^2)
Jan-10	13.2	12.9	11.6	11.4	20.7	17.2
Feb-10	13.4	13.1	11.1	11.1	26.8	21.0
Mar-10	12.0	11.8	8.3	8.0	44.5	43.7
Apr-10	14.3	14.2	6.6	6.9	58.2	56.2
May-10	14.9	14.3	7.4	7.2	51.0	55.4
Jun-09	14.8	14.2	5.4	4.9	60.4	66.1
Jul-09	14.9	14.3	7.3	6.7	42.9	49.8
Aug-09	14.7	14.3	6.9	6.4	46.4	52.7
Sep-09	14.3	14.0	7.6	7.3	43.2	47.1
Oct-09	14.0	13.7	9.2	9.0	29.7	31.2
Nov-09	13.9	13.4	10.5	10.3	23.8	22.2
Dec-09	13.4	13.1	11.8	11.6	14.6	12.7
Annual average	14.0	13.6	8.6	8.4	38.6	40.2
Annual total (kWh)	4,591.2	4,455.6	3,149.7	3,053.6		

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Table 5
FP and ET collector and system efficiencies.

Month	Collector efficiency (%)		System efficiency (%)	
	FPC	ETC	FPC	ETC
Jan-10	51.5	53.5	42.2	44.1
Feb-10	54.5	52.6	45.6	43.2
Mar-10	50.0	62.3	40.3	54.4
Apr-10	51.6	63.2	41.7	55.0
May-10	45.7	71.4	37.8	58.8
Jun-09	44.5	68.7	38.4	55.8
Jul-09	38.5	62.5	31.6	49.3
Aug-09	39.6	63.4	33.2	50.5
Sep-09	43.8	65.6	36.9	53.0
Oct-09	44.3	62.2	36.2	51.3
Nov-09	45.5	54.6	36.4	45.5
Dec-09	43.7	48.3	34.9	42.8
Annual average	46.1	60.7	37.9	50.3

The total life cycle cost of the SWH systems (C) is the sum of the capital cost (C_0) and the operation and maintenance cost ($C_{O\&M}$) given as:

$$C = C_0 + C_{O\&M} \tag{9}$$

$$C_{O\&M} = \sum_{n=1}^{n=N} \frac{c_{O\&M}(1+e)^n}{(1+d)^n} \tag{10}$$

where, $c_{O\&M}$ is the annual operation and maintenance cost, e is the fuel annual escalation rate, N is the service life and d the discount rate.

The total revenue (R_t) accrued over the service life of the SWH system is given as:

$$R_t = \frac{Q_u}{\eta_h} \sum_{n=1}^{n=N} \frac{(1+e)^n}{(1+d)^n} \tag{11}$$

The NPV for the SWH systems is given as:

$$NPV = R_t - C \tag{12}$$

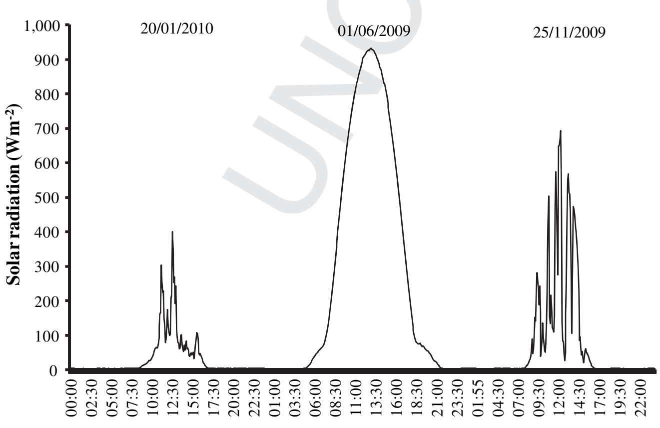

Fig. 3. In-plane global solar radiation for three characteristic days.

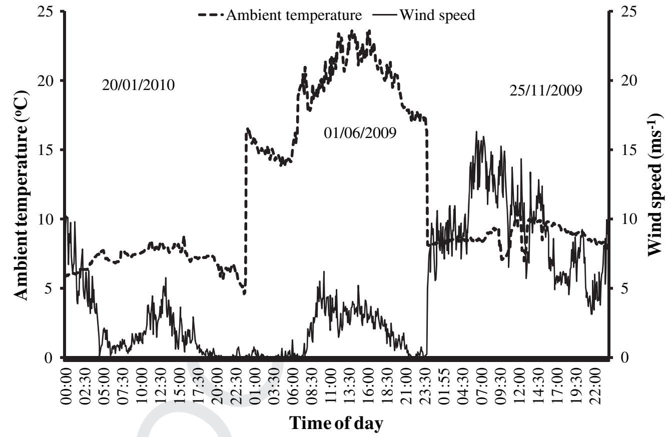

Fig. 4. Ambient air temperature and wind speed for three characteristic days.

5. Results and discussions

5.1. Energy collected

Table 3 shows average daily solar insolation, energy collected, energy delivered and supply pipe losses from the FPC and ETC systems. The average daily energy collected by the FPC ranged between 2.0 kWh d^{-1} and 9.2 kWh d^{-1} in December and April respectively, while it ranged between 1.7 kWh d^{-1} and 9.5 kWh d^{-1} in December and June respectively. The annual total energy collected by the 4 m^2 FPC and 3 m^2 ETC was 1984 kWh y^{-1} and 2056 kWh y^{-1} respectively. The 3 m^2 ETC system therefore generated 3.5% more energy than the 4 m^2 FPC system. The results also show that over the year a unit area of FPC and ETC generated 496 kWh m^{-2} y^{-1} and 681 kWh m^{-2} y^{-1} of heat energy respectively.

5.2. Energy delivered and supply pipe losses

It is seen in Table 3 that the FPC system delivered a daily average of 1.6 kWh d^{-1} and 7.5 kWh d^{-1} of heat energy in December and April respectively while the ETC system delivered a daily average of 1.5 kWh d^{-1} and 7.7 kWh d^{-1} of heat energy in December and June respectively.

Heat losses occur along the supply side of the solar circuit especially at high collector outlet temperatures. The FPC and ETC systems had annual supply pipe heat losses of 326 kWh y^{-1} and 366 kWh y^{-1} respectively corresponding to 16.4% and 17.8% of energy collected.

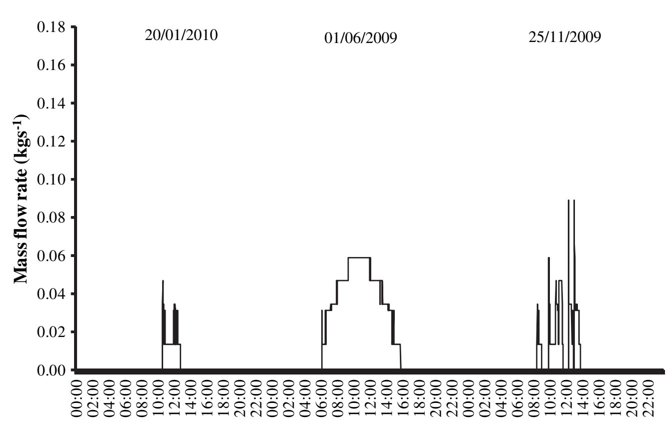

Fig. 5. Solar fluid mass flow rate for the FPC system.

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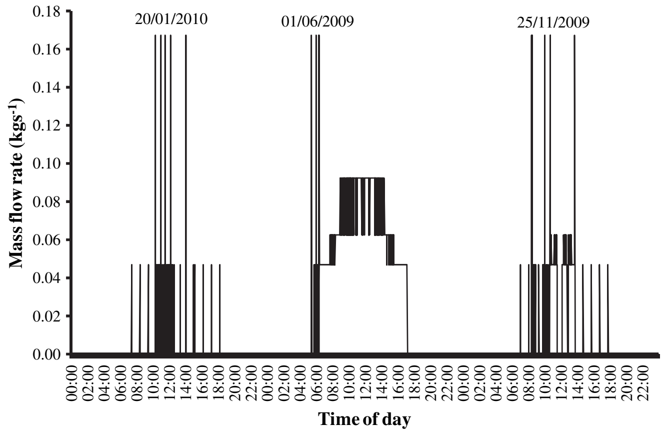

Fig. 6. Solar fluid mass flow rate for the ETC system.

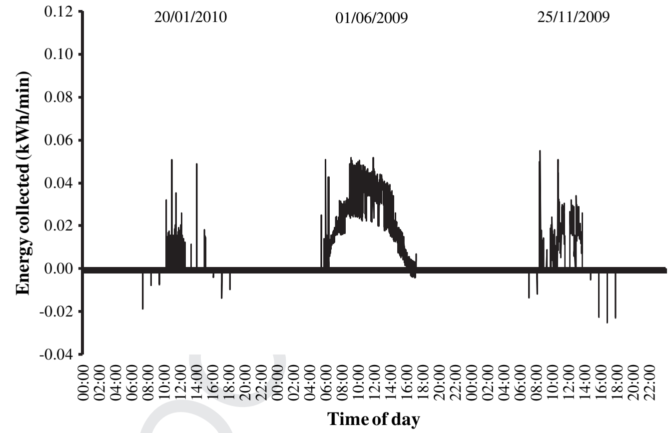

Fig. 8. Energy collected by the ETC system.

These losses are quite significant representing 65.7% and 53.7% of the energy generated by a unit area of FPC and ETC respectively annually. The supply pipe length should therefore be kept as short as possible and all joints insulated to reduce heat losses.

5.3. Energy extracted and auxiliary energy

Table 4 shows monthly average daily, annual average and annual total energy extracted from the hot water tanks and auxiliary energy supplied to the FPC and ETC systems. During the monitoring period a total of 4591.2 kWh and 4455.6 kWh of heat energy were extracted from the hot water tanks of the FPC and ETC systems respectively. The results also show that the monthly average quantity of auxiliary energy added varied between 5.4 kWh d^{-1} and 4.9 kWh d^{-1} in June and 11.8 kWh and 11.6 kWh in December for the FPC and ETC systems respectively.

5.4. Solar fraction

Table 4 shows the monthly and annual SF for the FPC and ETC systems. The SF of the FPC system range between 14.6% and 60.4% in December and June respectively while the SF for the ETC ranged between 12.7% and 66.1% in December and June respectively. It is seen that the FPC system had higher SF between January and April as well as November and December while the ETC system had higher SF between May and October. The FPC and ETC systems had annual average SFs of 38.6% and 40.2% respectively. It is seen that the quantity of energy required for auxiliary heating decreases with increase in SF.

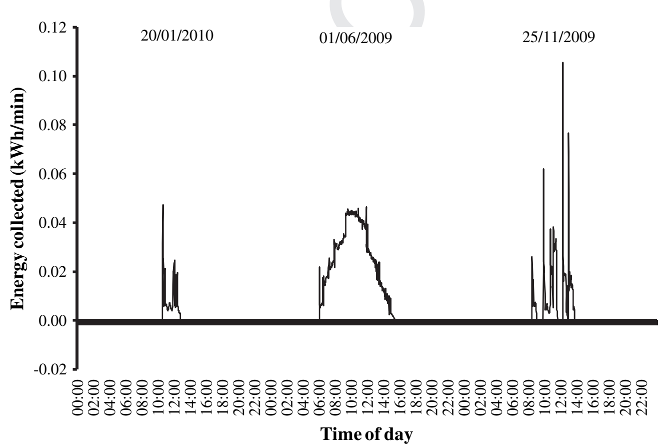

Fig. 7. Energy collected by the FPC system.

5.5. Collector and system efficiency

Table 5 shows results of collector and system efficiencies for the FPC and ETC systems. The respective minimum and maximum efficiencies of the FPCs was 38.5% in July and 54.5% in February while those of the ETCs were 48.3% in December and 71.4% in May. Similarly, the range of efficiencies of the overall FPC system varied from 31.6% in July to 45.6% in February and from 42.8% in December to 58.8% in May for the ETC system.

5.6. Daily performance

5.6.1. Solar radiation

Fig. 3 shows plots of in-plane global solar radiation for three 'typical' days characterised by heavily overcast sky (20/01/2010), clear sky (1/06/2009) and intermittent cloud covered sky (25/11/09) measured at 5 min intervals. The maximum solar radiation was 398.8 W m^{-2}, 932.1 W m^{-2} and 692.5 W m^{-2} on the heavily overcast, clear and intermittent cloud covered sky days respectively.

5.6.2. Ambient temperature and wind speed

Fig. 4 shows plots of ambient air temperature and wind speed for the three days measured at 5 min intervals. The maximum ambient air temperatures were 8.8 °C, 23.6 °C and 10.3 °C while the maximum wind speeds were 10.2 m s^{-1}, 6.2 m s^{-1} and 16.3 m s^{-1}

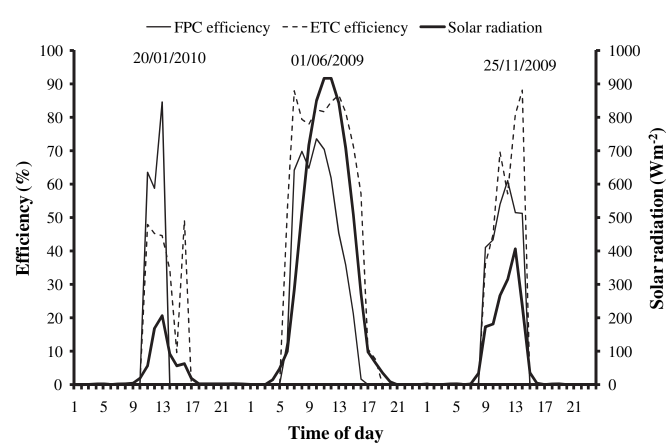

Fig. 9. Hourly global in-plane solar radiation, FPC and ETC efficiencies.

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Table 6
Seasonal values of solar insolation, energy collected, energy delivered, supply pipe losses and energy collected per unit area for the FPC and ETC systems.

Season	Solar insolation ($kWh\,m^{-2}\,d^{-1}$)	Energy collected ($KWh\,d^{-1}$)		Energy delivered ($kWh\,d^{-1}$)		Supply pipe losses ($kWh\,d^{-1}$)		Energy collected per unit area ($kWh\,m^{-2}\,d^{-1}$)	
		FPC (4 m^2)	ETC (3 m^2)	FPC (4 m^2)	ETC (3 m^2)	FPC (4 m^2)	ETC (3 m^2)	FPC	ETC
Winter	1.5	3.0	2.3	2.5	2.0	0.5	0.4	0.8	0.8
Spring	4.0	7.9	7.9	6.4	6.7	1.2	1.3	2.0	2.6
Summer	4.0	6.5	7.8	5.5	6.2	1.0	1.5	1.6	2.6
Autumn	2.4	4.3	4.5	3.6	3.7	0.8	0.8	1.1	1.5

on the heavily overcast, clear and intermittent cloud covered sky days respectively.

5.6.3. Solar fluid mass flow rate

The two systems both had variable speed pumps controlled by the Resol DeltaSol M controller. Fig. 5 shows plots of the solar fluid mass flow rate for the FPC system. During the heavily overcast day the mass flow rate was largely below 0.02 $kg\,s^{-1}$ and only occasionally reached 0.04 $kg\,s^{-1}$. During the clear sky day the mass flow rate showed a more regular pattern at sunrise and sunset peaking at 0.068 $kg\,s^{-1}$. During the day with intermittent cloud cover, the mass flow rate peaked at 0.088 $kg\,s^{-1}$ and was occasionally zero.

Fig. 6 shows plots of the solar fluid mass flow rate for the ETC system. During the heavily overcast day the pump cycled on and off regularly to peaks of 0.045 $kg\,s^{-1}$. During the clear sky day the pump operated largely continuously between 0.045 $kg\,s^{-1}$ and 0.098 $kg\,s^{-1}$, peaking intermittently at 0.168 $kg\,s^{-1}$ during early morning. During the day with intermittent cloud cover the mass flow rate occasional peaked at 0.17 $kg\,s^{-1}$ but was typically 0.056 $kg\,s^{-1}$.

5.6.4. Energy collected

Fig. 7 shows plots of the energy collected by the FPC system at 1 min intervals. It can be seen that the total energy collected during the days with heavily overcast and intermittent cloud cover was very low with intermittent spikes as a result of the pump turning on and off as the intensity of solar radiation varied. The energy collected during the clear sky day peaked at around solar noon.

Fig. 8 shows plots of the energy collected by the ETC system. Unlike the FPC system, the ETC system tends to operated during low levels of solar insolation at sunrise and sunset. This has an impact on the quantity of energy collected since short intermittent flows of the solar fluid tends to carry heat away from the hot water tank and dump it into the collector leading to energy losses as seen on the 20/01/2010 and 25/11/2009. This results in a reduction in the energy collected and, in some periods during the cold winter months to net negative energy balances. This shows that there is scope for improvement in the operation of ETC systems equipped with heat pipe collectors.

5.6.5. Collector efficiency

Fig. 9 shows plots of hourly global in-plane solar radiation, FPC and ETC efficiencies on the 20/01/2010, 01/06/2009 and 25/11/2009. It is seen that during the heavily overcast day in winter (20/01/2010) with a maximum hourly solar radiation of 207 $W\,m^{-2}$, the FPC and ETC had maximum hourly efficiencies of 84.7% and 48.0% respectively. During the clear sky day in summer (01/06/2009) with a maximum hourly solar radiation of 918 $W\,m^{-2}$, the ETC was more efficient than the FPC with maximum hourly efficiency of 88.1% compared to 73.7% for the FPC. During the intermittently cloud covered day in Autumn (25/11/2009) with a maximum hourly solar radiation of 407 $W\,m^{-2}$, the ETC was again more efficient than the FPC with maximum hourly efficiency of 88.2% compared to 61.1% for the FPC. The results show that the FPC was more efficient than the ETC during days with low levels of solar radiation while the ETC was more efficient during days with high levels of solar radiation and intermittent cloud cover.

5.8. Seasonal performance

Table 6 shows seasonal daily average values of solar insolation, energy collected, energy delivered and supply pipe losses. It is seen that the 4 m^2 FPC system collected and delivered more heat energy than the 3 m^2 ETC system in winter. Both systems collected 7.9 $kWh\,d^{-1}$ of heat energy in Spring while the ETC system collected and delivered more heat energy than the FPC system in Summer and Autumn. The supply pipe losses for the FPC and ETC systems were highest in Spring and Summer respectively.

Table 7 shows seasonal average daily collector and system efficiencies, energy extracted and auxiliary energy for the FPC and ETC systems. The collector and system efficiencies for the FPC ranged from 40.9% in summer to 49.9% in winter while those for the ETC ranged from 51.5% in winter to 65.6% in spring. These results show that the FPC system was most efficient in winter while the ETC was most efficient in Spring. 6.5 $kWh\,d^{-1}$ and 6.0 $kWh\,d^{-1}$ of auxiliary energy was added to the FPC and ETC system hot water tanks respectively using the electric immersion heaters in summer, while 11.5 $kWh\,d^{-1}$ and 11.3 $kWh\,d^{-1}$ was added in winter.

5.9. Simple payback period

Fig. 10 shows plots of SPPs for SWH systems fitted with different types of auxiliary heaters. It is seen that systems fitted with electric immersion heaters had the lowest SPPs while the systems using condensing boiler auxiliary heaters had the highest payback periods. The SPPs vary between 13.0 years and 48.5 years for FPC systems with grant aid fitted with electric immersion heaters and

Table 7
Seasonal average daily collector and system efficiencies, energy extracted and auxiliary energy for the FPC and ETC systems.

Season	Collector efficiency (%)		System efficiency (%)		Energy extracted ($kWhd^{-1}$)		Auxiliary energy ($kWhd^{-1}$)	
	FPC (4 m^2)	ETC (3 m^2)	FPC (4 m^2)	ETC (3 m^2)	FPC (4 m^2)	ETC (3 m^2)	FPC	ETC
Winter	49.9	51.5	40.9	43.4	13.3	13.0	11.5	11.3
Spring	49.1	65.6	39.9	56.1	13.7	13.4	7.4	7.4
Summer	40.9	64.9	34.4	51.9	14.8	14.3	6.5	6.0
Autumn	44.6	60.8	36.5	49.9	14.1	13.7	9.1	8.9

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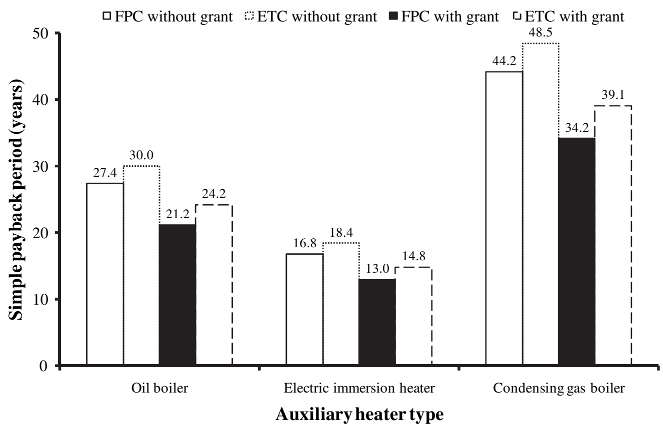

Fig. 10. Simple payback period for different types of auxiliary heaters.

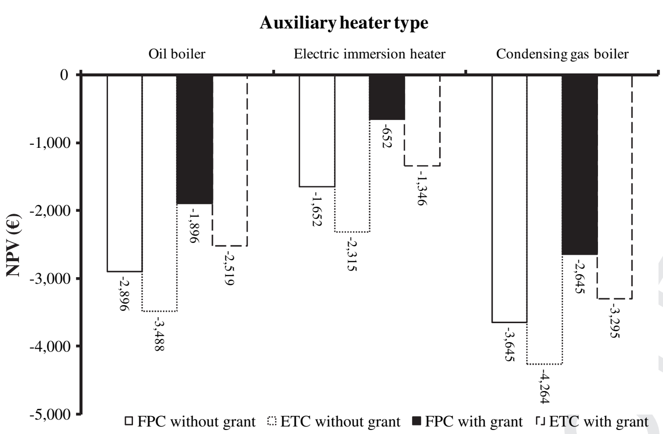

Fig. 11. Net present value for different auxiliary heater types.

ETC systems without grant aid fitted with condensing gas boilers respectively.

5.10. Net present value

Fig. 11 shows plots of the NPV for SWH systems fitted with different types of auxiliary heaters. It can be seen that over the anticipated service life of 20 years, none of the SWH systems was economically viable. The FPC SWH system with grant aid fitted with an immersion heater had the best NPV of −€652 while the ETC system without grant aid fitted with a condensing gas boiler had the worst NPV of −€4264. The results showed that under prevailing system costs (2010), existing grant aid structure and the assumed discount rate, SWH systems are not yet economically viable in Ireland.

6. Conclusions

The year round energy performance analysis of two commonly installed forced circulation SWH systems in temperate climates has been carried out using trial installations in Dublin, Ireland. The SWH systems were designed and operated to mimic real life operation of taking into consideration interaction between the collectors, storage tank and users. An immersion heater was used to supply auxiliary energy when the solar coil was unable to raise the tank water temperature to the required temperature.

Results obtained show that for an annual total in-plane solar insolation of 1087 kWh m^{-2}, a total of 1984 kWh and 2056 kWh of heat energy were collected by the 4 m^2 FPC and 3 m^2 ETC systems respectively. Over the year, a unit area of the FPC and ETC each generated 496 kWh m^{-2} and 681 kWh m^{-2} of heat respectively. For 3149.7 kWh and 3053.6 kWh of auxiliary energy supplied to the FPC and ETC systems their annual SFs were 38.6% and 40.2% respectively. The annual average collector efficiencies were 46.1% and 60.7% while the system efficiencies were 37.9% and 50.3% respectively for the FPC and ETC respectively. Economic analysis showed that both SWH systems are not economically viable with NPVs ranging between −€4264 and −€652 while SPPs varied between 13 years and 48.5 years.

The results of the energy performance analysis show that the 4 m^2 FPC system compares quite favourably with the 3 m^2 ETC system when connected to a 300 l hot water tank. These results are useful as they would provide valuable information to households, policy makers and installers.

Nomenclature

A_c: collector area (m^2)
C_p: specific heat capacity of solar fluid (J kg^{-1} K^{-1})
C_0: capital cost (€)
$C_{O\&M}$: operation and maintenance cost (€)
ΔC_0: extra first cost (€)
d: discount rate (%)
e: fuel annual escalation rate (%)
E_c: conventional energy displaced (kWh)
ET: evacuated tube
ETC: evacuated tube collector
FP: flat plate
FPC: flat place collector
G_t: total in-plane solar radiation (W m^{-2})
$\dot{m}$: solar fluid mass flow rate (kg s^{-1})
N: service life (years)
NPV: net present value (€)
Q_{aux}: auxiliary heating requirement (kWh)
Q_c: useful heat collected (W)
Q_d: useful heat delivered (W)
Q_l: supply pipe heat loss (W)
Q_s: solar yield (kWh)
Q_u: useful energy collected by the solar collector (kWh)
R_t: total revenue (€)
S: annual savings (€)
SF: solar fraction (%)
SPP: simple payback period (years)
SWH: solar water heater
T_a: ambient temperature (°C)

Greek symbols
η_c: collector efficiency (%)
η_h: auxiliary heater efficiency (%)

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