Analysis of energy, economic and environmental performance of solar water heaters for domestic hot water supply in northern European climate

Anandhi Parthiban[a], Eoin Cotter[b], David McCloskey[c]

[a] *School of Physics, Trinity College Dublin, Dublin 2, Ireland, parthiba@tcd.ie, CA*
[b] *School of Physics, Trinity College Dublin, Dublin 2, Ireland, cottereo@tcd.ie*
[c] *School of Physics, Trinity College Dublin, Dublin 2, Ireland, mccloskd@tcd.ie*

Abstract:

A significant portion of energy expense of a residential household goes toward the provision of domestic hot water (DHW) ~19%. The use of solar thermal water heating provides a local way to offset this energy requirement with a renewable resource. Solar thermal water heating systems are commonly used in hot climates from Southern Europe to the Equator however in the past they were seen as not so economically viable in colder climates. The solar collector that is readily available on the market for DHW generation is the standard flat plate collector (SFPC), but they are not attractive for use in higher latitudes due to low operating temperature and high heat loss. Although convection suppression has been identified as a method to improve the performance of flat plate collector it has not yet achieved mainstream commercialisation. In this work we attempt to show that the conventional flat plate collector still has potential in higher latitude when modified to suppress convection heat loss. The modified FPC that is particularly of focus in this work is the one with honeycomb transparent insulation (MFPC). We compare the performance of SFPC and MFPC in colder climate considering different auxiliary heating options such as electricity, gas, and oil, at their recent energy prices. Using TRNSYS software, we modelled the annual energy generated by these collectors using a typical domestic load case and found that SFPC produced 1446.60 kWh/year while MFPC produced 1993.50 kWh/year. For a typical household with a daily hot water consumption of 200 L, SFPC requires 3858.69 kWh/year of auxiliary energy while MFPC requires 3458.24 kWh/year. The economic analysis shows that the MFPC with electrical heating is the highly viable option with a Net Present Value (NPV) of € 5078.95. The CO_2 emission reduction from the SFPC and MFPC with electrical auxiliary heating are 39.54 $kgCO_2$/year and 79.58 $kgCO_2$/year, respectively, compared to conventional electrical immersion heaters.

Keywords:

Solar water heater; Flat plate collector; Solar fraction; Evacuated tube collector; Economic analysis; Net Present Value.

1. Introduction

The global carbon dioxide emissions from space heating and water heating have hit a record high of 2500 Mt in 2021 [1]. Utilizing solar thermal technology for water heating offers a local solution to mitigate the CO_2 emissions linked to this process. Solar thermal water heating systems are commonly used to offset the energy requirement for domestic hot water (DHW) in hot climates from Southern Europe to the Equator, however in the past they were seen as not so economically viable in colder climates. The trend in northern Europe and UK is to promote heat pump technology for space heating and domestic hot water however this will add significant additional load to the electrical grid. Heat pumps are more suited to space heating than domestic hot water due to the higher tank temperature required and often an auxiliary heater such as an electrical immersion is required to meeting the DHW load requirements. As such and a local source of heat for Domestic Hot Water (DHW) would still be beneficial in colder climates to reduce electricity demand. Flat plate collectors (FPC) are well established and readily available Solar Water Heaters (SWH), but it suffers from poor performance in colder climates due to heat loss [2]. Numerous concepts have been employed in the past to mitigate heat loss from solar collectors, and one such concept is Evacuated Tube Collector (ETC), in which the gap between the absorber and the glass cover is evacuated to eliminate convection and conduction heat loss [3]. Although ETCs are more effective than traditional FPCs and attain significantly

https://doi.org/10.52202/069564-0222

higher collector temperatures, they tend to be costly to manufacture and install [4]. Solar thermal collectors incorporating transparent insulation offer a promising design to minimize heat loss while simultaneously reducing costs and weight. However, despite their potential benefits, these collectors have not yet achieved widespread commercialization due to challenges in manufacturing and the need to address issues related to stagnation temperature [5]. The inclusion of transparent insulation within the air gap between the absorber and the glass cover effectively reduces convection heat loss. This enhances the employability of FPCs, particularly in colder weather conditions.

Numerous works on the experimental and numerical analysis of SHW system can be found in literature and here we provide a review of selected works from the literature, highlighting their key findings and contributions. Ayompe and Duffy [6] conducted a year-round experimental analysis of a forced circulation SHW system installed in Dublin, Ireland which demonstrated that an FPC SHW system with a $4m^2$ collector area can yield a solar fraction of up to 32.2% for an annual global insolation of 15,680.4 MJ. Hazami et al. [7] investigated the year-round performance of FPC and ETC SHW systems that were commercialized in Tunisia. Their findings showed that the ETC system generated 9% more energy than the FPC system. Specifically, the ETC system, with a collector area of 3.4 m^2, achieved a solar fraction of 84.4%. Tiwari et al. [8] utilized numerical simulations to assess the efficacy of FPC systems in Indian climatic conditions. Their study revealed that an FPC system with a collector area of 5 m^2 can meet 70% of the residential hot water demand. Kalogirou et al. [9] proposed a novel TRNSYS model component to evaluate the effectiveness of thermosiphon solar hot water (SHW) systems, which they simulated in three different European climates: Freiburg (47.9990° N), Naples (40.8518° N), and Larnaca (34.9182° N). The model was validated by comparing its results with experimental data. The research findings demonstrate that as the latitude decreases from Freiburg to Larnaca, the simple payback period (SPB) of the SHW systems also decreases. Zainine et al. [10] employed TRNSYS simulation to optimize the flow rate for a solar domestic hot water (SDHW) system installed in Tunisia. They estimated that the optimal flow rate for the primary and secondary circuits, for maximum annual yield, were 10 kg/h m^2 and 15 kg/h m^2, respectively. Additionally, their economic analysis demonstrated that SHW systems with gas auxiliary heating are more economically feasible than replacing conventional electric heaters. Bernardo et al. [11] conducted a study on the benefits of retrofitting existing domestic hot water systems with SWH. Their findings indicated that incorporating a smaller tank with an immersion heater in series with the solar storage tank could lead to optimal performance, with a solar fraction of up to 50%. The study also demonstrated that the TRNSYS simulation software is a reliable tool for determining the thermal performance of SHW systems.

Vig et al. [12] studied a variable flow vacuum tube solar thermal collector system. Their research demonstrated that the variable flow SHW system collected more energy compared to the constant flow one. Their effect was particularly significant when the radiation was low or when the temperature of water in the storage tank was high. Hayek et al. [13] conducted experimental investigations on two types of ETC collectors in the Eastern Mediterranean climate. Their findings demonstrated that the heat pipe-based ETC collector was 15-20% more efficient than the water-in-glass ETC collector. However, due to their high initial cost, these ETC collectors are not an economically feasible option. Maraj et al. [14] reported the yearly energy performance of a heat pipe ETC collector under Mediterranean climatic conditions. Their findings indicated that the annual collector efficiency of the ETC system was 62%, while for an FPC system, it was 49.4%. This result demonstrates that the thermal performance of the ETC system was superior to the FPC system. Al-Madhhachi et al. [15] conducted a study on the potential of SHW systems in two cities in Iraq. Their findings indicated that the SHW system has the potential to supply almost 60% of the hot water demand in winter. Kalogirou and Papamarcou [16] conducted experiments and numerical simulations on a thermosyphon SHW system based on FPC. The results showed that a FPC system with a total collector area of 2.7 m^2 can meet all the hot water demand of a household during summer. The Economic analysis showed that the system has a simple payback period of 8 years and a net present value (NPV) of 161 $C£_{2000}$. Hobbi and Siddiqui [17] performed a simulation-based optimization study for a forced circulation solar water heating system in Canada. Their results showed that the proposed design could meet 83-97% and 30-62% of hot water demand in summer and winter, respectively. Gao et al. [18] compared the performance of water-in-glass and U-pipe evacuated-tube solar collectors and optimised their flow rate for maximum energy production. The literature review shows that the TRNSYS simulation is a reliable tool for the determination of the yearly performance of the SHW systems [19]. Zhou et al. [5] conducted a numerical study to investigate the impact of operating conditions on the performance of FPC integrated with Transparent Insulation Material (TIM). The results highlighted that FPC with TIM proves to be highly efficient, particularly in colder ambient temperatures. Specifically, the efficiency of FPC with TIM was found to be 6.2% higher compared to traditional FPC collectors. Kizildag et al. [20] conducted a comparative analysis between FPC and modified FPC incorporated with TIM. The results indicated a remarkable difference in energy production, with the modified FPC outperforming the standard collectors by 2.5 times during winter and 1.4 times during spring. Kessentini et al. [21] conducted a comprehensive study on FPC integrated with TIM and an overheating protection system. Their research demonstrated that the FPC with TIM can achieve performance levels comparable to commercially available solar collectors, all while maintaining a low-cost advantage. Despite

 https://doi.org/10.52202/069564-0222

the proven effectiveness of convection-suppressed flat plate technology utilizing transparent insulation in cold weather conditions, its widespread commercialization has not yet been realized. In this study, we aim to compare the performance of conventional flat plate technology with convection-suppressed flat plate technology in a European climate, considering current energy prices.

2. Modeling solar hot water heater system

2.1. System description

Flat plate collector refers to a particular geometry of solar collector employed for hot water generation. The FPC consists of an absorber plate that intercepts the incident light and generates thermal energy, which is transferred to water in the storage tank by the heat transfer fluid flowing through the cooling tubes attached to the absorber plate. To reduce the heat loss from the absorber, it is covered with a glass cover on top and thermal insulation at the sides and bottom. The glass cover on top reduces the convection heat loss and traps the long wave radiation emitted from the absorber plate thereby increasing the thermal energy available at the absorber. A solar selective coating is usually applied to the absorber plate which has strong absorption in the visible and near infra-red range and low emissivity in the infra-red range. The schematic of standard FPC and the modified FPC analysed in this work are given in Figure 1.

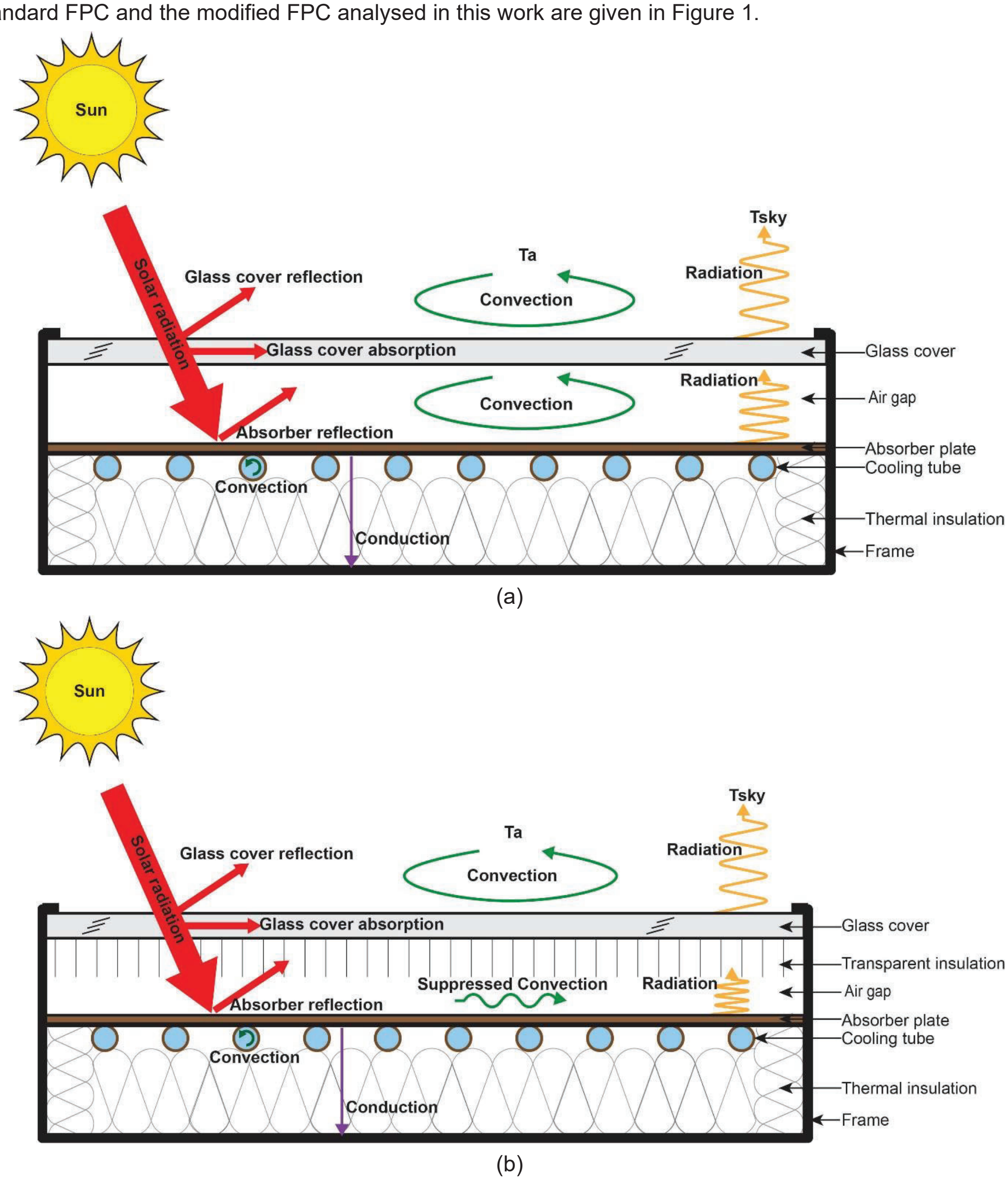


Figure. 1. Schematic of solar flat plate collector: a) SFPC, b) MFPC.

In the modified FPC design, a transparent insulation made of polycarbonate honeycomb is inserted in the airgap between the glass cover and the absorber plate with the aim to suppress the air circulation that is responsible for convection heat loss from the absorber plate. The performance of the solar thermal collector is described using a second order equation as a function of environmental and functional parameters and we use numerical simulation to determine the constants of the efficiency equation Eq. (1) [22].

$$\eta = a_0 - a_1 \frac{(T_m - T_a)}{G} - a_2 \frac{(T_m - T_a)^2}{G} \tag{1}$$

2.2. Numerical modeling for estimation of performance parameters

The steady state, two-dimensional thermal modeling of solar flat plate collector was done using the Multiphysics simulation software, COMSOL 6.1. For the numerical analysis, a portion of the FPC with one cooling tube was taken, this is supported by the assumption that the flow rate in each riser tube was the same. The specific collector being examined was the K420-EM2L, which was manufactured by KBB Kollektorbau GmbH and it has an aperture area of 1.97 m^2 [23]. Details of the computational domain and boundary conditions can be found in Figure 2. The thermophysical properties of the solid components that make up the FPC are constant and are listed in Table 1. It is assumed that the air flow between the absorber and the glass cover is laminar and incompressible. Therefore, the density of air is modeled as an incompressible ideal gas, using the Boussinesq approximation method [24]. The heat transfer and fluid flow problem were solved by solving the coupled continuity, momentum, and energy equations, with an additional transport equation for S2S radiation Eq. (2-4) [25].

Continuity equation, $\frac{\partial}{\partial x_j}(\rho u_j) = 0$ (2)

Momentum equation, $\frac{\partial}{\partial x_j}(\rho u_i u_j) = \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \rho g_i \beta (T - T_\infty)$ (3)

Energy equation, $\frac{\partial}{\partial x_j}(\rho u_j C_p T) = \frac{\partial}{\partial x_j}\left[\lambda \frac{\partial T}{\partial x_j}\right] + \dot{Q}$ (4)

2.3. Boundary conditions and methodology

The solar radiation input to the collector is modelled by considering a volumetric heat source at the absorber and the glass cover Eq. (5,6) [27]. The laminar forced convection from the inside of the cooling tube is modeled with a convective heat transfer coefficient h_f calculated from the Nusselt number for the case with constant heat flux boundary condition (Nu_f=4.36), at mean water temperature $\left(T_m = \frac{T_{out} + T_{in}}{2}\right)$ [28]. The top and bottom surfaces of the collector are subjected to external natural convection due to ambient air in contact with the collector surface. There are two instances of radiation heat loss in the collector: one occurs externally from the glass cover to the sky, while the other occurs internally between the absorber and the glass cover [29]. Once the computational domain is assigned with material properties and boundary conditions, the necessary physics to solve laminar natural convection, heat transfer, and S2S radiation are added and coupled. The governing equations are solved using the stationary solver-multifrontal massively parallel sparse direct solver (MUMPS) with a relative tolerance of 0.001. The purpose of this simulation is to obtain the efficiency curve of the solar collector (η vs $\frac{T_m - T_a}{G}$), and therefore, a parametric study was done by varying the mean water temperature (285 K≤T_m≤350 K) keeping the insolation constant (G=800 W/m^2).

Heat generation in absorber, $\dot{Q}_{abs} = \frac{G\,\tau_g \alpha_p}{t_{abs}}$ (5)

Heat generation in glass cover, $\dot{Q}_g = \frac{G\,\alpha_g}{t_g}$ (6)

Table 1. Thermophysical properties of FPC collector [26].

Component	λ, (W/m-K)	ρ, (kg/m^3)	C_p, (J/kg-K)
Glass cover	1.38	2200	770
Absorber and cooling tube (Aluminium-D_o:12 mm, D_{in}:11 mm)	238	2700	900
Insulation	0.022	30	1000
Transparent insulation (Polycarbonate)	0.2	1200	1200

https://doi.org/10.52202/069564-0222

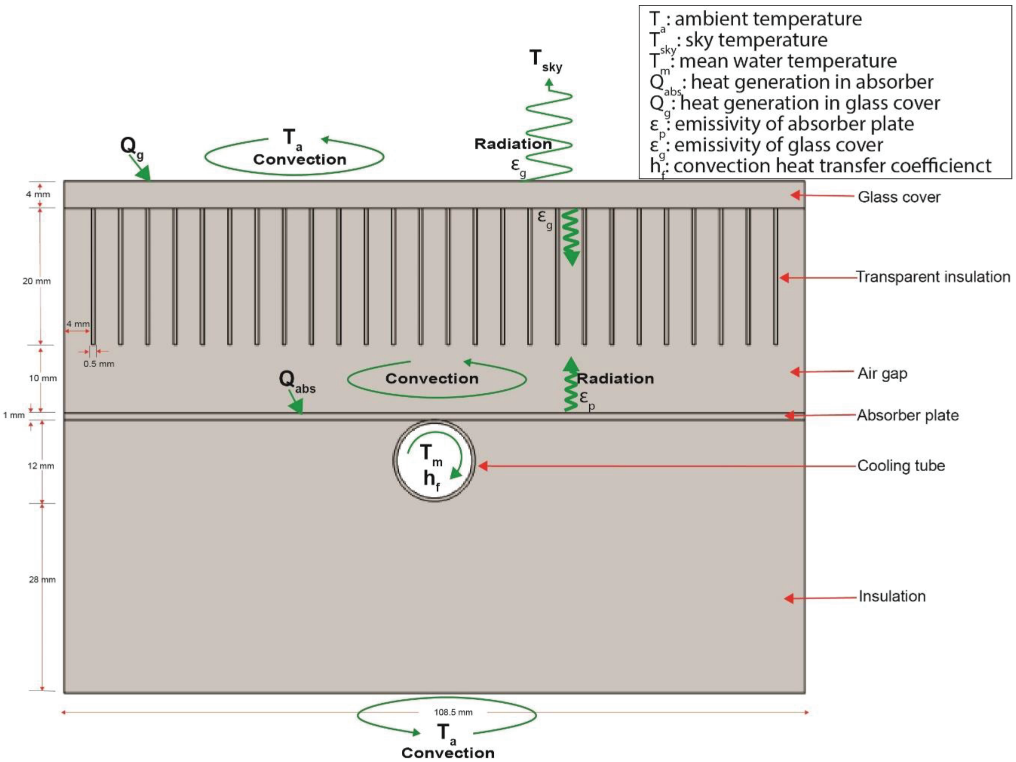


Figure. 2. Computational domain with boundary conditions.

2.4. Validation

The numerical model developed by Kim and Viskanta [30] for solving coupled laminar natural convection, surface radiation, and wall conduction in a differentially heated cavity is taken for validation. Figure 3 shows the plot of non-dimensional temperature $\left(\frac{T-T_c}{T_h-T_c}\right)$, obtained at the vertical wall; it can be seen that the proposed model agrees well with the existing model, with dimensionless temperature having a deviation between 0.25% and 7.61%.

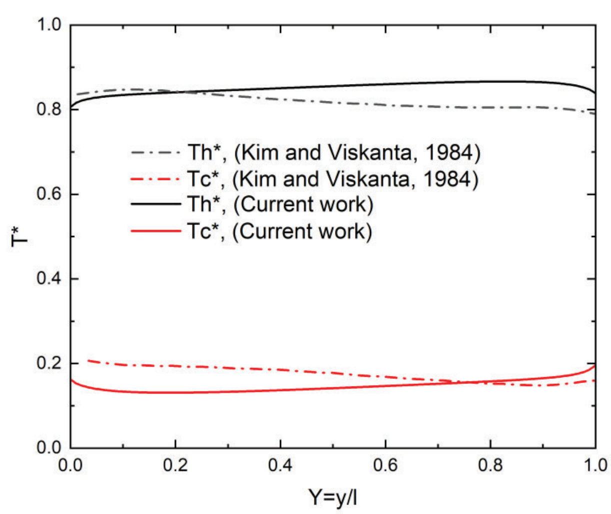


Figure. 3. Non-dimensional temperature obtained from the proposed model and the existing model.

2.5. TRNSYS simulation for the yearly energy produced

The useful thermal energy collected by the SFPC and MFPC over a year was obtained using the transient simulation software TRNSYS 18. In TRNSYS, models that represent the components of solar hot water system (Collector: Type 1b, Tank: Type 60d, Pump: Type 110) are connected similar to how they would be connected in real life. The forced circulation SHW system is implemented using a single tank model that has an internal heat exchanger coil connected to the solar collector. The hot water demand profile used is the EU reference tapping cycle 3 representing 200 L of hot water required in a day at 60 °C ($Q_{thermal}$ = 11.65 kWh/day) [31]. The storage tank has a built-in immersion heater (3kW) located at the middle of the tank and is turned ON in two batches, from 5 am to 7 am and 6 pm to 8 pm, whenever the tank top temperature falls below 55 °C. The overall heat loss coefficient of the tank is taken to be 1.6 W/m^2K [7]. The pump used is a constant flow rate pump and is controlled using an ON/OFF controller (Type: 2b). The controller sets the pump ON only when the difference in collector outlet water temperature and the tank bottom temperature exceeds 5°C, this is to ensure system operation at sufficient irradiance level. The FPC system modeling simulation diagram with interconnection of various components is given in Figure 4.

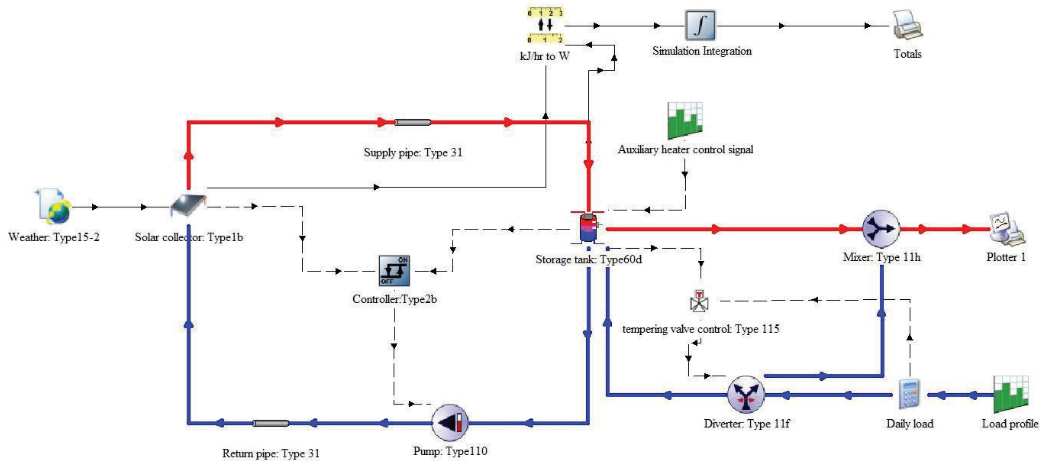


Figure. 4. TRNSYS simulation of SHW system modeling.

2.6. Economic and environment analysis

The economic evaluation parameters used in this study to show the benefit of installing a solar thermal hot water system are the net present value (NPV) and the simple payback period (SPB) Eq. (7,8) [29]. The NPV and SPB period are calculated for the two systems with different auxiliary fuels: electricity, oil, and gas at current energy price [32]. The economic analysis was done by assuming 8% annual discount rate and 20 years of useful life. The operation and maintenance cost were assumed to be 1% of the capital cost. The assumptions taken in the economic analysis of the solar hot water systems are listed in Table 2. The yearly CO_2 emission by the two solar hot water systems with different auxiliary fuel was calculated using Eq. (9). and are based on the country emission factor for CO_2 per unit of energy for particular fuel [33].

$$\mathrm{NPV} = \sum_{j=1}^{N} Q_u\, C_{aux}\, \eta_{aux}\, \frac{(1+i)^{j-1}}{(1+d)^{j}} - \sum_{j=1}^{N} C_{o\&m}\, \frac{(1+i)^{j-1}}{(1+d)^{j}} - C_{capital} \tag{7}$$

$$\mathrm{SPB} = \frac{C_{capital}}{Q_u\, C_{aux}\, \eta_{aux}} \tag{8}$$

$$Q_{CO2\ emission} = Q_{aux}\, S_{CO2} \tag{9}$$

Table 2. Economic analysis parameters [34,35].

Parameter	Value
Capital cost of FPC system	3500 €
Solar Water Heating Grant	1200 €
Inflation rate	3%
Cost of electricity	0.31 €/kWh
Cost of oil	0.14 €/kWh
Cost of gas	0.08 €/kWh
Efficiency of Electrical immersion heater	100%
Efficiency of oil boiler	65%
Efficiency of gas boiler	90%

 https://doi.org/10.52202/069564-0222

3. Results and Discussion

3.1. FPC characteristics curve

The heat transfer and the fluid flow model are solved to determine the constants of the characteristic equation that describe the performance of solar thermal collector. Numerical simulations are done for the input conditions, such as incident radiation of 800 W/m^2, ambient temperature of 283 K, and collector tilt of 45°.The obtained efficiency curves along with their characteristic equation are given in Figure 5. The area under the efficiency curve reflects the useful energy gained, and it is evident that the MFPC collects more energy compared to the SFPC. The MFPC exhibits a 20% optical loss, whereas the SFPC has a 22% optical loss. The MFPC system's first and second order heat loss coefficients have been determined to be 1.7618 W/m^{2}K and 3.058$\times 10^{-3}$ W/m^{2}K^2, respectively. Meanwhile, the SFPC system has first and second order heat loss coefficients of 3.0632 W/m^{2}K and 7.7136$\times 10^{-3}$ W/m^{2}K^2, respectively.

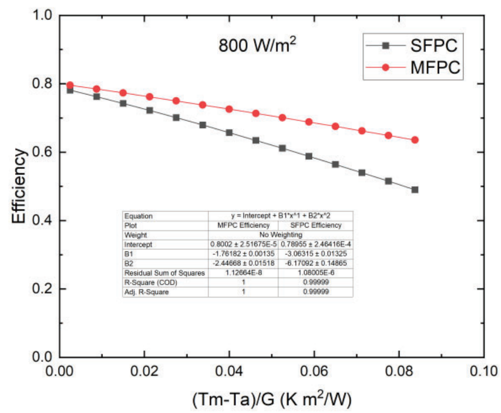
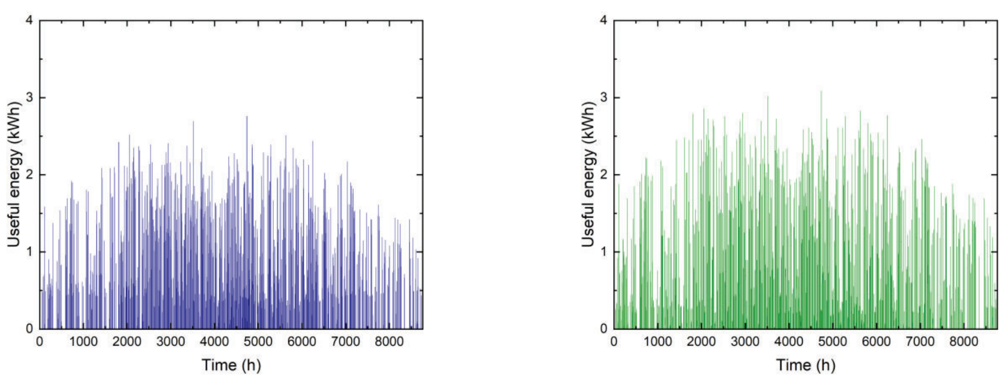


Figure. 5. TRNSYS simulation of SHW system modeling.

3.2. Yearly performance analysis

The yearly energy performance of the SFPC and MFPC SHW system was simulated in TRNSYS by using the performance parameters obtained from COMSOL simulations. The SHW system consisted of two FPC collectors connected in series each with absorber area 1.972 m^2. The collector tilt was taken to be 44°. The flow rate in the solar collector loop was maintained constant at 95 kg/h. The simulations were done for a year at 1 minute time step with meteorological data input relative to Dublin (53.3498° N, 6.2603° W). The SFPC and MFPC systems' yearly useful energy collected were 1446.60 kWh and 1993.50 kWh, respectively, as shown in Figure 6. The corresponding annual solar fractions of the SFPC and MFPC systems were 27.27% and 36.57%, respectively.



(a) SFPC (b) MFPC

Figure. 6. Useful energy generated by SFPC and MFPC for 4m^2 collector area installed in Dublin.

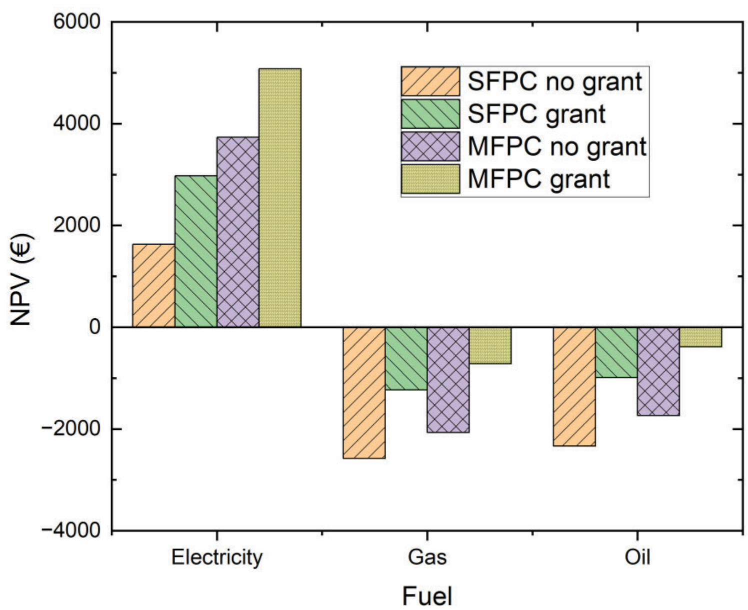
https://doi.org/10.52202/069564-0222

3.3. Economic feasibility and CO_2 emissions

The results of the NPV and SPB period calculations for both the SFPC and MFPC systems, using different types of fuel for auxiliary heating, are presented in Figures 7, respectively. The economic analysis reveals that FPC systems are financially viable only when electricity is used as the auxiliary fuel. After factoring in the solar grant, the NPV of the MFPC is notably high, amounting to € 5078.94. Additionally, the SFPC has a simple payback period of 5 years, whereas the MFPC has a comparatively shorter payback period of only 3.7 years when electricity is used as the auxiliary heating source. Table 3 shows the CO_2 emissions generated by the SFPC and MFPC systems when using different types of auxiliary fuel. It is evident that the CO_2 emissions are minimized when electricity is employed as the auxiliary heating source. The yearly CO_2 emissions from SFPC and MFPC SHW system with electricity as auxiliary heating is found to be 385.87 kg and 345.82 kg respectively. Using a conventional electrical immersion heater to generate hot water for a typical house result in an annual CO_2 emission of 425.22 $kgCO_2$. However, by implementing the proposed MFPC SHW system, this CO_2 emission could be significantly reduced to 345.82 $kgCO_2$/year.

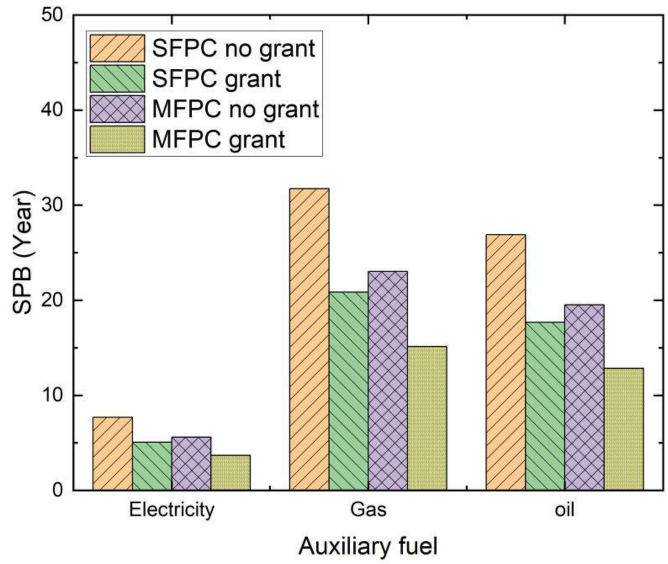
Table 3. CO2 emission from SHW system [36].

Auxiliary fuel	$kgCO_2$/kWh	$kgCO_2$ emissions/year	
		SFPC	MFPC
Electricity	0.10	374.29	335.62
Gas	0.20	782.93	702.03
Oil	0.26	991.68	889.22



(a)

https://doi.org/10.52202/069564-0222



(b)

Figure. 7. Economic analysis: a) NPV and, b) SPB for the SHW system with different auxiliary heating.

4. Conclusions

A study was conducted to investigate the feasibility of implementing a SHW system in a northern European climate, taking into account the current energy costs for auxiliary heating. The study focused on two different FPC systems, each with a total aperture area of $4m^2$. Numerical simulations were utilized to obtain the efficiency parameters of the systems based on a simplistic heat transfer and fluid flow model. These parameters were then utilized in TRNSYS simulations to determine the yearly thermal performance of each system. The energy collected by the two systems are found to be be 1446.60 kWh/year and 1993.50 kWh/year respectively. Results indicated that FPC systems are still a financially viable option for hot water generation, particularly when using electricity as the auxiliary heating source. The modified FPC system exhibited the best performance, with a high NPV of € 5078.94 and a short SPB period of 3.7 years. Moreover, by employing the MFPC system with electrical auxiliary heating, 79.58 $kgCO_2$ reduction in annual emissions is achievable when compared to conventional electrical immersion heaters. Future work is to optimize the collector size for different hot water consumption profile and also to explore the feasibility of using ETC collectors.

Acknowledgments

The financial support provided by Science Foundation Ireland under the project SOLARCOOL is acknowledged (grant no: 19/FIP/ZE/7484R). We would like to thank Cian Fogarty, a research assistant Nanothermal Research Group at Trinity College Dublin for the knowledge handed down on the modelling of collectors.

Nomenclature

a_0	intercept efficiency, %
a_1	efficiency slope, W/(m^2 K)
a_2	efficiency curvature, W/(m^2 K^2)
C	cost, €
C_p	specific heat, J/(kg K)
d	market discount rate, %
G	heat flux, W/m^2

g	gravitational acceleration, m/s^2
h_f	heat transfer coefficient, $W/(m^2\ K)$
i	inflation rate, %
N	useful life
$\overline{Nu}$	average Nusselt number
$\dot{Q}$	volumetric heat generation, W/m^3
Q_u	useful energy, Wh
S	CO_2 emission coefficient, $kgCO_2/(W\ h)$
T	temperature, K
t	thickness, m
u	velocity, m/s
x,y	cartesian coordinate

Greek symbols

α	absorptivity
β	thermal expansion coefficient, K^{-1}
ε	emissivity
η	efficiency, %
λ	thermal conductivity, W/(m K)
μ	viscosity, kg/(m s)
ρ	density, kg/m^3
τ	transmissivity

Subscripts

a	ambient
abs	absorber
aux	auxiliary fuel
c	capital
g	glass cover
in	inlet
m	average water
$o\&m$	operation and maintenance
out	outlet
th	thermal
u	useful

References

[1] Heating - Fuels & Technologies – IEA – Available at:<https://www.iea.org/fuels-and-technologies/heating> [accessed 1.3.2023].

[2] Pandey KM, Chaurasiya R. A review on analysis and development of solar flat plate collector. Renewable and Sustainable Energy Reviews. 2017 Jan 1;67:641-50.

[3] Sokhansefat T, Kasaeian A, Rahmani K, Heidari AH, Aghakhani F, Mahian O. Thermoeconomic and environmental analysis of solar flat plate and evacuated tube collectors in cold climatic conditions. Renewable Energy. 2018 Jan 1;115:501-8.

[4] Hazami M, Naili N, Attar I, Farhat A. Solar water heating systems feasibility for domestic requests in Tunisia: Thermal potential and economic analysis. Energy conversion and management. 2013 Dec 1;76:599-608.

[5] Zhou L, Wang Y, Huang Q. Parametric analysis on the performance of flat plate collector with transparent insulation material. Energy. 2019;174:534–42. doi:10.1016/j.energy.2019.02.168

[6] Ayompe LM, Duffy A. Analysis of the thermal performance of a solar water heating system with flat plate collectors in a temperate climate. Applied thermal engineering. 2013 Sep 1;58(1-2):447-54.

 https://doi.org/10.52202/069564-0222

[7] Hazami M, Kooli S, Naili N, Farhat A. Long-term performances prediction of an evacuated tube solar water heating system used for single-family households under typical Nord-African climate (Tunisia). Solar Energy. 2013 Aug 1;94:283-98.

[8] Tiwari AK, Gupta S, Joshi AK, Raval F, Sojitra M. TRNSYS simulation of flat plate solar collector based water heating system in Indian climatic condition. Materials Today: Proceedings. 2021 Jan 1;46:5360-5.

[9] Kalogirou SA, Agathokleous R, Barone G, Buonomano A, Forzano C, Palombo A. Development and validation of a new TRNSYS Type for thermosiphon flat-plate solar thermal collectors: energy and economic optimization for hot water production in different climates. Renewable energy. 2019 Jun 1;136:632-44.

[10] Zainine MA, Mezni T, Dakhlaoui MA, Guizani A. Energetic performance and economic analysis of a solar water heating system for different flow rates values: A case study. Solar Energy. 2017 May 1;147:164-80.

[11] Bernardo LR, Davidsson H, Karlsson B. Retrofitting domestic hot water heaters for solar water heating systems in single-family houses in a cold climate: A theoretical analysis. Energies. 2012 Oct 22;5(10):4110-31.

[12] Víg P, Seres I, Vladár P. Improving efficiency of domestic solar thermal systems by a flow control. Solar Energy. 2021 Dec 1;230:779-90.

[13] Hayek M, Assaf J, Lteif W. Experimental investigation of the performance of evacuated-tube solar collectors under eastern Mediterranean climatic conditions. Energy procedia. 2011 Jan 1;6:618-26.

[14] Maraj A, Londo A, Gebremedhin A, Firat C. Energy performance analysis of a forced circulation solar water heating system equipped with a heat pipe evacuated tube collector under the Mediterranean climate conditions. Renewable energy. 2019 Sep 1;140:874-83.

[15] Al-Madhhachi HS, Ajeena AM, Al-Bughaebi NA. Dynamic simulation and energy analysis of forced circulation solar thermal system in two various climate cities in Iraq. AIMS Energy. 2021 Jan 1;9(1):138-49.

[16] Kalogirou SA, Papamarcou C. Modelling of a thermosyphon solar water heating system and simple model validation. Renewable Energy. 2000 Nov 1;21(3-4):471-93.

[17] Hobbi A, Siddiqui K. Optimal design of a forced circulation solar water heating system for a residential unit in cold climate using TRNSYS. Solar energy. 2009 May 1;83(5):700-14.

[18] Gao Y, Zhang Q, Fan R, Lin X, Yu Y. Effects of thermal mass and flow rate on forced-circulation solar hot-water system: Comparison of water-in-glass and U-pipe evacuated-tube solar collectors. Solar Energy. 2013 Dec 1;98:290-301.

[19] Džiugaitė-Tumėnienė R, Streckienė G. Solar hot water heating system analysis using different software in single family house. InThe 9th International Conference “Environmental Engineering”, 22–23 May 2014, Vilnius, Lithuania 2014 May (p. 9).

[20] Kizildag D, Castro J, Kessentini H, Schillaci E, Rigola J. First Test field performance of highly efficient flat plate solar collectors with transparent insulation and low-cost overheating protection. Solar Energy. 2022;236:239–48. doi:10.1016/j.solener.2022.02.007

[21] Kessentini H, Castro J, Capdevila R, Oliva A. Development of flat plate collector with plastic transparent insulation and low-cost overheating protection system. Applied Energy. 2014;133:206–23. doi:10.1016/j.apenergy.2014.07.093

[22] Bouhal T, Agrouaz Y, Allouhi A, Kousksou T, Jamil A, El Rhafiki T, Zeraouli Y. Impact of load profile and collector technology on the fractional savings of solar domestic water heaters under various climatic conditions. International journal of hydrogen energy. 2017 May 4;42(18):13245-58.

[23] Biome solar industry- Available at:<http://www.biome-solar.com/medias/certification/performance%20test_K420-EM_english%20(2).pdf> [accessed 1.3.2023].

[24] Saravanan S, Sivaraj C. Combined thermal radiation and natural convection in a cavity containing a discrete heater: effects of nature of heating and heater aspect ratio. International Journal of Heat and Fluid Flow. 2017 Aug 1;66:70-82.

[25] Alvarado R, Xamán J, Hinojosa J, Álvarez G. Interaction between natural convection and surface thermal radiation in tilted slender cavities. International Journal of thermal sciences. 2008 Apr 1;47(4):355-68.

[26] Parthiban A, Mallick TK, Reddy KS. Integrated optical-thermal-electrical modeling of compound parabolic concentrator based photovoltaic-thermal system. Energy Conversion and Management. 2022 Jan 1;251:115009.

[27] Parthiban A, Reddy KS, Pesala B, Mallick TK. Effects of operational and environmental parameters on the performance of a solar photovoltaic-thermal collector. Energy Conversion and Management. 2020 Feb 1;205:112428.

[28] Incropera FP, DeWitt DP. Introduction to heat transfer. J. Wiley; 2002.

[29] Duffie JA, Beckman WA. Solar Energy Thermal Processes. New York etc.: Wiley; 1980.

[30] Kim DM, Viskanta R. Effect of wall conduction and radiation on natural convection in a rectangular cavity. Numerical Heat Transfer. 1984 Oct 1;7(4):449-70.

[31] European commission – Available at:<https://law.resource.org/pub/eu/mandates/m324.pdf> [accessed 1.3.2023].

[32] Fuel Cost Comparisons (seai.ie) – Available at:<https://www.seai.ie/publications/Domestic-Fuel-Cost-Comparison.pdf> [accessed 1.3.2023].

[33] Anoune K, Laknizi A, Bouya M, Astito A, Abdellah AB. Sizing a PV-Wind based hybrid system using deterministic approach. Energy conversion and management. 2018 Aug 1;169:137-48.

[34] How much do solar thermal panels cost in Ireland? (insulationcostsireland.com) – Available at:<https://insulationcostsireland.com/how-much-do-solar-thermal-panels-cost-in-ireland.html> [accessed 1.3.2023].

[35] Grant For Solar Water Heater | Home Energy Grants | SEAI Available at:<https://www.seai.ie/grants/home-energy-grants/solar-water-heating-grant/> [accessed 1.3.2023].

[36] Advice on installing solar water heating - Energy Saving Trust – Available at:< https://energysavingtrust.org.uk/advice/solar-water-heating/> [accessed 1.3.2023].

https://doi.org/10.52202/069564-0222