Journal of Cleaner Production 204 (2018) 511–524

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Residential use of solar water heating in Turkey: A novel thermo-economic optimization for energy savings, cost benefit and ecology

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ARTICLE INFO

Article history:
Received 22 May 2018
Received in revised form
6 September 2018
Accepted 7 September 2018
Available online 8 September 2018

Keywords:
Solar water heating
Water-in-glass collector
Optimization
Transient modeling
Energy savings
Greenhouse emission

ABSTRACT

Recent trends in residential solar water heating and its efficient usage in Turkey were presented in this study. A novel methodology for determining the optimum orientation and sizing of water-in-glass evacuated tube solar water heating systems has been outlined. Transient modeling was conducted for the prediction of a full year's system performance via the System Advisor Model. In this model, the typical meteorological year data of certain climate zones in Turkey were considered, daily hot water consumption was estimated using the Rand hot water profile, and the monthly averaged mains water temperatures measured by the municipalities were analyzed. In addition, a typical performance rating of a water-in-glass evacuated tube collector produced by the collector manufacturer in Turkey was taken into consideration, and the effects of collector area, storage tank volume, daily average delivery temperature and daily hot water consumption data on the annual solar fraction were analyzed. The verification of the simulation results were compared with the literature and good agreement was obtained. Subsequently, a thermo-economic optimization was employed by using P_1–P_2 methodology. The methodology presented guarantees to obtain reliable results with a minimal run-time. The diminution in the initial system cost and payback period are shown to be possibly achieved at the level of 7.5% in a 1.5 year period, respectively, while the energy savings are approximately 12% higher annually when implementing optimum results. The results indicate that Turkey would save 300 MW_{th} annually if evacuated tube solar water heaters in Turkey's cities are configured based on optimal sizing. An evacuated solar water heater in a typical residential building in Turkey has the potential to mitigate 5–22 g CO_2-equivalent/kWh of greenhouse gas emissions per annum if properly installed.

1. Introduction

Domestic water heating is one of the major concerns in the energy consumption of residential buildings when its share is considered compared to the total consumption (Ibrahim et al., 2014; Lenz et al., 2017). Energy demand for water heating can be met in a variety of ways such as using electricity or fossil fuels; however, it is costly to heat water using these resources. Not only do solar based water heaters have the ability to reduce this cost but they also possess the distinguished advantages of clean and sustainable energy production (Koroneos and Nanaki, 2012; Yılmaz and Söylemez, 2012; Zambrana-Vasquez et al., 2015), a lower carbon footprint, and the technology is applicable to rural areas. These systems are proven technologies, and are widely used around the world even if the local solar potential is not superfluous. Recent developments make these systems technologically more efficient and attractive based on their increasing impacts day by day (Iranmanesh et al., 2017; Mwesigye et al., 2018; Sharafeldin and Gróf, 2018).

As one of the countries located in the *sunny belt* of the earth, Turkey has an advantage in terms of capturing solar radiation. The greatest share of this captured potential has been particularly used in solar water heating for residential applications (Benli, 2016). The country currently retains its third ranking around the world due to the high number of installed water collectors (Sadiq, 2018; Weiss et al., 2017). In Turkey, flat plate collectors (FPCs) are widely used, and are about four times more popular than evacuated tube collectors (ETCs) (Yılmaz, 2018). However, the trend has strongly shifted towards the ETC technology in recent years due to its lower capital costs. Fig. 1 demonstrates the variation in the cumulative installed collector area by year for water collector systems. Supply-and-demand for these systems has increased gradually due to both guaranteed performance and short payback periods. Although the

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https://doi.org/10.1016/j.jclepro.2018.09.060

Nomenclature

A_c	collector area, m^2
A_{WST}	surface area of WST, m^2
C_A	total area-dependent cost, \$/m^2
C_E	total cost of equipment independent of collector area and WST volume, \$
C_F	the first period's unit energy cost delivered from fuel, \$/kWh
c_p	specific heat of water, J/kg·°C
C_V	total volume-dependent cost, \$/m^3
d	market discount rate in fraction
f	solar fraction
F_R	collector heat removal factor
i	energy price rate in fraction
I_T	incident radiation on tilted collector surface, W/m^2
K_θ	incidence angle modifier
L	thermal load, kWh/yr
LCS	life cycle savings, \$
$\dot{m}_{draw}$	mass flow rate of drawn fluid, kg/s
N_p	payback period, yr
P_1	ratio of life cycle energy cost savings to first year energy cost savings
P_2	ratio of life cycle expenditures incurred because of additional capital investment to initial investment
$\dot{Q}$	net rate of heat transfer, W
$\dot{Q}_{aux}$	auxiliary heating, W
$\dot{Q}_l$	heat loss from the WST, W
$\dot{Q}_u$	useful heat gain delivered, W
t	time, s
T_a	ambient temperature, °C
$T_{delivered}$	delivery temperature, °C
T_{in}	fluid temperature inside tubes, °C
T_{mains}	mains water temperature, °C
T_{set}	mean value of delivery set temperature, °C
T_{WST}	mean tank temperature, °C
U_L	overall collector heat loss coefficient, W/m^2·°C
U_{WST}	heat loss coefficient of WST, W/m^2·°C
V_{WST}	volume of the WST, m^3

Greeks

β	tilt angle, °
θ	incidence angle, °
ρ	density of collector fluid, kg/m^3
$(\tau\alpha)_n$	transmittance-absorbance product at normal incidence

Abbreviations

FPC	flat plate collector
ETC	evacuated tube collector
SAM	System Advisor Model
SWH	solar water heater
TMY	Typical Meteorological Year
WST	water storage tank

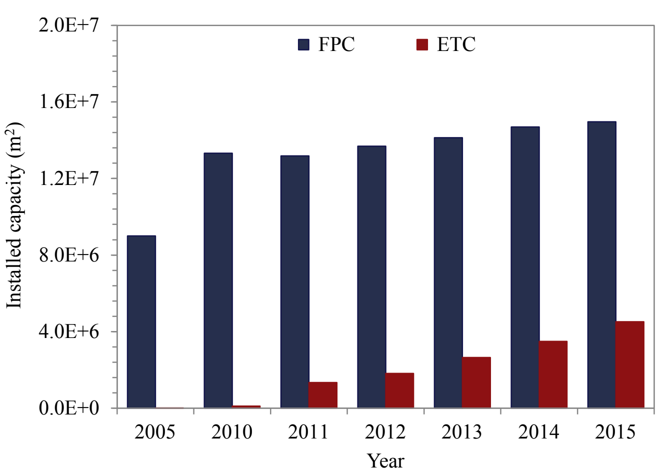

Fig. 1. Total collector area in operation by year (Benli, 2016; IEA-SHC, 2017).

economic viability of these systems is becoming increasingly acceptable, optimum capacity selection and installation are needed to assure increased solar collection over a long-term period. It is not only important to make them attractive for the market but also to specify the proper size, which is an important issue. In Turkey, there are a great number of manufacturers producing collectors of varying types and performance. Most of the system installations are made by trial and error, i.e., without prior optimum system sizing. For this reason, obtaining maximum yield from these systems is usually not achieved.

The optimal design of a solar water heater (SWH) depends on many system parameters (Akinoğlu et al., 1999) including weather data, hot water consumption rate/profile, tilt angle, collector specifications (area, working fluid, flow rate, storage tank volume, etc.). Reduction in the initial capital cost of a SWH is usually expected when lowering the overall system size. Selecting optimum values for the system components promote efficient harnessing of solar energy with a minimal capital cost.

The design and selection of SWH systems have made use of derived correlations or simulation tools in the literature. Various correlations were proposed including the ϕ method, the generalized ϕ method, the $\overline{\varphi}$ method, the f-chart method, and the $\overline{\varphi}$, f-chart method. These correlations were widely used for design purposes. In addition, a number of simulation software products such as F-chart, TRNSYS, T*SOL, Polysun, RETScreen, TermoDim, Helios-Chart, Solterm, and SolarEnergy are commercially available in the market (Nogueira et al., 2016). A new open source software program was developed by the National Renewable Energy Laboratory, named the System Advisor Model (SAM, 2018), which enables the simulation of the transient behavior of SWH systems, yielding very fast runtimes and good agreement for a time-based analysis. On the other hand, several researchers have recently studied on the optimization of SWH systems by applying either their own methods/simulation programs (Coetzee et al., 2017; Hasan, 2001; Kontopoulos et al., 2016; Kulkarni et al., 2007; Wang et al., 2017) or the software products mentioned above (Kalogirou, 2004; Li et al., 2015; Shariah and Löf, 1996; Shariah and Shalabi, 1997; Yan et al., 2015).

ETCs involve three configurations: heat pipe, all-glass passive and all-glass active circulations (Milani and Abbas, 2016). The former two are the common types; however, all-glass passive circulation, also known as flooded or water-in-glass ETCs, are widely used for residential applications in Turkey. They feature a relatively lower cost with respect to the heat pipe type; hence, customers usually prefer the flooded type. Given the literature review below,