Solar Energy 162 (2018) 165–177

Contents lists available at ScienceDirect

Solar Energy

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

New design approach and implementation of solar water heaters: A case study in Michigan

Sina Jahangiri Mamouri*, André Bénard

Department of Mechanical Engineering, Michigan State University, East Lansing, MI 48824 USA

ARTICLE INFO

Keywords:
Evacuated tube
Cold region
System advisor model
Parametric study

ABSTRACT

The potential of evacuated tube solar water heaters is evaluated for the state of Michigan, which has regions with low solar resources, for year-round usage. Simple empirical equations for the initial sizing design stage are provided for the entire state for a given system. The analysis includes experimental results obtained for a setup at Michigan State University and model-based results for 26 locations dispersed throughout the state. These are obtained using the System Advisor Model (SAM) software package from National Renewable Energy Laboratory. The results show that evacuated tube collector solar water heaters are appropriate for typical household water usage for Michigan's climate with payback periods as low as 8 years (variations are due to local weather conditions). In addition, a study on the optimum collector area for various hot water demands is performed; this led to identification of empirical equations useful for estimating the optimal area of a given system as a function of the hot water demand for locations throughout Michigan. A parametric study is carried out and it is found that the overall heat gain coefficient of an evacuated tube collector affects significantly its performance and it should be considered in order to select an appropriate system. The impact of additional parameters such as heat gain and heat loss coefficients on the performance of the system is also discussed.

1. Introduction

In 2010, the buildings sector constituted 41.1% of the United States primary energy usage. Residential buildings accounted for 54.7% of energy used in the buildings sector while commercial buildings accounted for 45.3%. Only 9% of the energy used in buildings sector came from renewable systems, while 77% came from fossil fuels. Water heating is the second largest energy demand and accounts for 12% of the energy used in buildings. Fig. 1 illustrates the buildings sector energy consumption by demand (Kelso, 2011). Among different forms of renewable energy systems, solar energy plays an increasing role (Kalogirou, 2013). Although remarkable progress has been achieved, obstacles such as high costs still impede broader implementation of solar water heating. In this regard, Mills (2004) investigated the market prospects of the existing solar thermal technologies in Europe, Australia, and the United States. He described existing funding systems and made suggestions for more effective programs of support.

Interest in solar water heating for residential buildings is increasing today due to concerns with CO_2 emissions (Zhai et al., 2007). The market associated with solar power is increasing and in 2015, solar energy jobs in United States grew by 22% compared to the past year. The United States formed the 5th largest market for solar thermal collectors (Sawin et al., 2016).

A Solar Water Heater (SWH) can be used to preheat water before it enters a conventional water heater system and remarkably reduce the fossil fuel usage and concomitant pollutant emissions. Solar water heating typically provides an important fraction of the energy demand and a backup auxiliary system is typically required to meet the entire energy demand (Maguire et al., 2013). There are two main types of solar water heaters (Weiss et al., 2009; Mamouri et al., 2014; Mosleh et al., 2015): Flat Plate Collector Solar Water Heaters (FPC-SWHs), and Evacuated Tube Collector Solar Water Heaters (ETC-SWHs). Evacuated Tube Collectors (ETCs) are increasingly more popular because of their remarkable efficiency (Sabiha et al., 2015), and their declining costs (Tang et al., 2011). A common ETC is made of concentric glass pipes with the air in the gap between the pipes being evacuated to minimize heat losses; a heat pipe is located at the center. Available ETCs can be categorized into two types: single-glazed ETCs, and double-glazed ETCs. Double-glazed ETCs (the common type) have inner and outer tubes. The inner tube is coated to improve the absorbance of the collector. ETCs are used for solar water heating (Tang et al., 2011; Mangal et al., 2010; Morrison et al., 2004, 2005; Gao et al., 2013; Xue, 2016; Sakhrieh and Al-Ghandoor, 2013), air conditioning (Mehta and Rane, 2013; Nkwetta et al., 2012; Li et al., 2012), and even solar cookers

* Corresponding author.
E-mail address: mamouri@msu.edu (S. Jahangiri Mamouri).

https://doi.org/10.1016/j.solener.2018.01.028
Received 2 November 2017; Received in revised form 8 January 2018; Accepted 10 January 2018
0038-092X/

Nomenclature

A_c	area of the collector (m^2)
b_0	incident angle modifier coefficient
C_0	initial invested amount ($)
C_n	annual cost in year n ($)
C_p	specific heat (J/(kg·K))
d	nominal discount rate
E_n	generated solar energy in year n (kWh)
F_R	collector heat removal factor
G	incident radiation (W/m^2)
I_b	beam radiation (W/m^2)
I_d	diffuse radiation (W/m^2)
I_g	ground-reflected radiation (W/m^2)
i	inflation rate
K	incident angle modifier
q	real discount rate
T_a	ambient temperature (°C)
T_i	inlet temperature (°C)
T_o	outlet temperature (°C)
Q_u	utilized solar energy gain rate (W)
U_L	collector's overall heat loss coefficient (W/(m^2·K))
V	daily hot water demand (m^3)

Greek symbols

α	absorptance factor
β	collector slope angle
η	thermal efficiency
τ	transmittance factor
θ	angle of incidence

Abbreviations

DNI	direct normal irradiance
EC	energy cost
ETC	evacuated collector solar
FPC	flat plate collector
SAM	system Advisor Model

(Sharma et al., 2005; Gupta et al., 2015). They have also industrial applications (Sabiha et al., 2015) such as in heat engines (Madduri et al., 2012), solar drying (Sharma et al., 2009; Lamnatou et al., 2012; Fudholi et al., 2010), and steam generation (Vendan et al., 2012).

A typical FPC-SWH includes a transparent glass cover (glazed or unglazed), headers, heat transfer medium, insulations, and a blackened absorber. A common FPS-SWH is very sensitive to ambient air conditions and there is a high probability of freezing in frigid weather when using water as a working fluid (Ogueke et al., 2009; Esen and Esen, 2005). A well-designed FPC-SWH can perform with a high efficiency of 40–60%, reaching temperatures between 50 °C and 75 °C for a typical water demand (Hang et al., 2012). A typical ETC-SWH consists of an anti-freezing heat transfer medium, manifold, headers, and evacuated tube collectors with heat pipes embedded in the tubes. A heat pipe is a two-phase heat transfer device that can provide a high heat transfer rate with a small temperature difference between its heat source and heat sink (Mamouri et al., 2014; Mosleh et al., 2015). A well designed ETC-SWH can perform with an efficiency of 40–50%, reaching temperatures up to 120 °C, but usually costs almost twice as much as a FPC-SWH (Hang et al., 2012). ETC-SWHs however are less dependent on solar angle than FPC-SWH because of the cylindrical shape of tubes and reduced heat losses to the environment. These features make ETC-SWH a good year-round candidate for locations with cold ambient temperatures by mitigating heat losses.

Several analyses have been carried out at national (Maguire et al., 2013; Cassard et al., 2011; Denholm, 2007; Sanders and Webber, 2015; Jacobson et al., 2015) and local levels (Rylatt et al., 2001; Gadsden et al., 2003; Karteris et al., 2013; Benli, 2016; Grubert and Webber, 2015) to evaluate the potential of the solar water heaters. In addition, the efficiency of evacuated tube collectors for solar water heating has been investigated in different studies (Ayompe et al., 2011; Budihardjo and Morrison, 2009; Mazarrón et al., 2016). However, there is a lack of literature on the use of evacuated tube collectors for solar water heating in cold climates with comparably low annual available solar resources. Those are locations where the potential of conventional flat plate collector solar water heaters is limited to seasonal (summer) or short-term usages. Specifically, there is no study evaluating the potential of ETC-SWHs for the state of Michigan, where water heating constitutes a large portion of energy consumption in buildings.

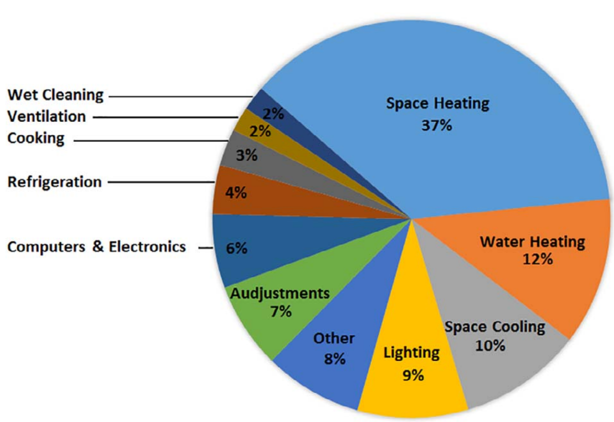

Fig. 1. Buildings sector energy consumptions in 2010 by demand (Kelso, 2011).

The performance of an evacuated tube collector solar water heater is evaluated for an environment with low solar irradiance using a system installed on the campus of Michigan State University (MSU). Data obtained from the system is compared with results from a software package named SAM. The efficiency of evacuated tube collector solar water heaters is then evaluated by performing simulations for locations throughout the state of Michigan. A formula to determine the design collector size for different hot water demands is also presented. The impact of some parameters such as heat gain and heat loss coefficients on the performance of the system is studied.

2. Michigan's climate

Michigan has a continental climate with hot summers and cold winters in the Lower Peninsula, and warm and short summers and cold winters in the northern regions of Michigan (northern Lower Peninsula and the Upper Peninsula). The annual average temperature for the entire state is 6.9 °C. Therefore heating contributes a great portion of energy use in Michigan compared to the U.S. average (Outlook, 2010). Fig. 2 is map provided to contrast the annual average temperature of the US continental states including Michigan.

Since the state of Michigan is surrounded by the Great Lakes, Michigan has numerous cloudy days. Fig. 3 illustrates the annual average of solar resource of all the continental states including Michigan which has a low solar resource of only 3.75 kWh/m^2/day.

A detailed average monthly Direct Normal Irradiance (DNI) of Michigan is tabulated in Fig. 4. The data is obtained from National Renewable Energy Laboratory (NREL), and provides monthly average over surface areas or cells of 0.1°in both latitude and longitude (about 10 km in distance, or 100 km^2 in area). The results are obtained using