Applied Energy 206 (2017) 382–392

Contents lists available at ScienceDirect

Applied Energy

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

Design optimization of a multi-temperature solar thermal heating system for an industrial process

A. Allouhi[a,*], Y. Agrouaz[a,b], Mohammed Benzakour Amine[c], S. Rehman[d], M.S. Buker[e], T. Kousksou[b], A. Jamil[a], A. Benbassou[a]

[a] *Ecole Supérieure de Technologie de Fès, U.S.M.B.A., Route d'Imouzzer, BP 242, Fez, Morocco*
[b] *Laboratoire des Sciences de l'Ingénieur Appliquées à la Mécanique et au Génie Electrique (SIAME), Université de Pau et des Pays de l'Adour – IFR – A. Jules Ferry, 64000 Pau, France*
[c] *Faculté des Sciences et Techniques de Fès, U.S.M.B.A, Route d'Imouzzer, BP 2202, Fez, Morocco*
[d] *Center for Engineering Research, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia*
[e] *Department of Aircraft Engineering, Necmettin Erbakan University, Konya, Turkey*

HIGHLIGHTS

- Integration of solar thermal energy into an industrial activity is presented.
- Hot water is required at four temperatures and load profiles.
- Design optimization based on the LCC method is introduced.
- Annual performance of centralized system is discussed.
- Sensitivity analysis based on economic variables is investigated.

ARTICLE INFO

Keywords:
Solar energy
Optimization
Life-cycle savings
Industrial process
CO_2 emissions

ABSTRACT

Presently, great challenges are being faced by the industrial sector in terms of energy management and environmental protection. Utilization of solar energy to meet a portion of heat demand in various industries constitutes tremendous economic opportunities for developing countries such as Morocco. Therefore, this paper introduces an optimization procedure and simulation of a centralized solar heating system providing hot water to four processes with different temperature levels and load profiles. As a case study, a Casablanca based Moroccan milk processing company is evaluated and the life cycle cost method is practiced to select the optimal size of the main design parameters for decision-making. It was found that 400 m^2 of evacuated tube collectors tilted at an angle of 30° and connected to a 2000 l storage tank can lead to a maximum life cycle saving cost of 179 kUSD for a total annual heat demand of 528.23 MWh. In this optimal configuration, the overall annual solar fraction is found to be 41% and the payback period of 12.27 years attained. The system has the potential to reduce around 77.23 tons of CO_2 equivalents of greenhouse gas emissions annually. The economic competitiveness of the solar thermal heating plant can be considerably improved with higher inflation rates and lower initial investments.

1. Introduction

The global energy map is changing, but further efforts must be scaled up to pilot the global energy system towards a more sustainable path. Currently, the major source of energy comes from fossil fuels and unfortunately oil, coal, and natural gas are being used mostly by industrialized and developing countries [1]. By 2035, the global energy demand is expected to rise by more than one-third and the conventional energy resources will remain under rising pressure [2]. Together with the environmental problems such as adverse climate changes and global warming, this trend will continually force the global community for serious energy reforms.

Industries are the most energy-intensive consumers in nearly all countries. The industrial sector accounts for approximately 50% of the world's energy consumption and causes 36% of energy related greenhouse gas (GHG) emissions [3]. According to the estimates given by the

* Corresponding author.
E-mail address: allouhiamine@gmail.com (A. Allouhi).

http://dx.doi.org/10.1016/j.apenergy.2017.08.196
Received 31 May 2017; Received in revised form 19 August 2017; Accepted 23 August 2017

Nomenclature

A_c	collector area [m^2]
ALCC	annual life cycle cost [USD]
ALCS	annual life cycle savings [USD]
c_p	specific heat at constant pressure [J/kg K]
d	market discount rate
f	solar fraction
FC	first year fuel cost [USD]
FCU	fuel cost utilization [USD]
F_R	collector heat removal factor
G_t	solar radiation [W/m^2]
i	inflation rate
IC	investment cost [USD]
MC	maintenance cost [USD]
$\dot{m}$	mass flow rate [kg/h]
n	number of years
PB	payback time [year]
PWF	present worth factor
Q	heat [J]
T	temperature [°C]
t	time [s]
U_L	heat loss coefficient [$W/m^2{\cdot}K$]
U	global heat transfer coefficient [$W/m^2{\cdot}K$]
V	volume [m^3]

Greek letters

η	collector efficiency
$\tau\alpha$	transmittance–absorbance product
η_b	boiler efficiency
ρ	density [kg/m^3]

Subscripts

a	ambient
H	hot water
L	load
i	number of segment
c	collector
o	outlet
fo	fuel only
in	inlet
sol	solar
aux	auxiliary
loss	losses

Abbreviations

GDP	gross domestic product
IAP	Industrial Acceleration Plan
STC	solar thermal collectors
USD	United State Dollar

US Energy Information Administration (EIA), energy consumption in the industrial sector is projected to rise by 56% between 2010 and 2040 [4]. Along with all these total figures, heat production is responsible for 37% of energy consumed mainly in developed countries, and 47% of the world's total energy consumption [5]. As a result, valuable efforts have been deployed to limit excessive energy usage in various industrial applications [6,7].

Among all the renewable energy sources, solar energy has gained considerable attention as the promising option for hot water production in industrial sectors [8,9]. Apparently, solar thermal technologies can fulfill a substantial amount of heat demand in these industrial sectors within any country, irrespective of its geographical location [10,11]. These solar thermal systems, for domestic and service applications, are continuously observing increasing market shares across Europe [12]. Nevertheless, solar heat for industrial processes is in an early stage of market development [13]. Hot water, steam, preheating, drying, dehydration processes, concentration, sterilization, cleaning, chemical processes, space heating, food processing, plastic, paper, and textile industries are the most important likely commercial and industrial uses and applications of solar thermal energy among others [14–17]. The amount of thermal energy required in most of the industrial production processes is below 250 °C which is a temperature level that could be easily provided by currently commercially available and marketed solar thermal technologies [18].

Morocco, with a considerably flourishing and growing industrial segment, has recently launched the new Industrial Acceleration Plan (IAP) that will extend to 2020. This plan aims to create half a million jobs in the industrial sector and substantially increase the share of industry in the Gross domestic product (GDP) from the current share of 14% to 23% in the upcoming years [19]. Currently, Morocco imports almost 96% of its energy requirements and experiences an average annual growth of 7% in energy demand [20,21]. From a solar energy perspective, Morocco has abundant solar resources with a potential of 2600 kWh/m^2/year and about 3000 h of sunshine per year [22].

The use of solar thermal energy in Morocco is principally limited to conventional hot water production in the building sector [23]. Despite the fast development of solar water-heating systems for domestic purposes, the application of solar heat to industrial processes is still scarce in Morocco and other developing countries as well. In this context, this work deals with the technical and economic viability of solar industrial process-heating systems for the Moroccan industry.

With regards to solar heating system utilization in the industrial sector, several research attempts has been reported in the literature. The recent studies published on the present topic has been reviewed and reported as following. Atkins et al. [24] studied the possibility of integrating an evacuated tube solar thermal system to generate a part of the process heat demand of a New Zealand milk powder production firm. The benefits of several integration strategies, including mass were analysed. They reported important savings in both hot and cold utilities when mass integration was applied together with solar thermal integration. Lauterbach et al. [25] conducted a study for the implementation of a solar process heat system in a German brewery based on measured data model simulation results. Possible faults that may occur in the solar thermal system were identified and their impact on its performance was evaluated. Walmsley et al. [26] introduced three general scenarios for the integration of industrial solar heating into a Heat Recovery Loop (HRL). A large multi-plant dairy was considered as a case study and the results indicated that arranging the solar collector in series could increase the time average solar heating target from 1.0 MW to 2.3 MW compared to the conventional parallel arrangement. Walmsley et al. [27] compared conventional HRL design method based on a CTS (constant temperature storage) and a new HRL design method using VTS (variable temperature storage) to estimate the possible gains of inter-plant heat integration and implementing solar heating. These methods were practiced for a dairy process. It was reported that, for the same minimum temperature, the VTS approach reached 37% more heat recovery compared to the CTS approach. Fernández-García et al. [28] numerically addressed the specific design of a small-sized industrial parabolic trough collector. The effect of including a flat glass aperture cover was checked to evaluate the thermal performance of the design option. Among three cases studied, it was highlighted that the collector design with a flat glass aperture cover has the highest thermal losses.