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Design and analysis of a medium-temperature, concentrated solar thermal collector for air-conditioning applications

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HIGHLIGHTS

- A rooftop-based concentrating collector coupled with an absorption chiller was analyzed.
- A novel semi-passive tracking method was proposed for high annual optical efficiency.
- The optimal sizes of the solar assisted air-conditioning plants were obtained.
- Economic analysis indicated an achievable LCOC price of 0.60 $/kW-h.

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ABSTRACT

Solar thermal energy is considered as a promising source to drive air-conditioning applications due to the good correlation between supply and demand. The present work examines the feasibility of a novel, low-profile concentrated solar thermal collector to provide medium-temperature heat to commercial buildings for both heating and cooling purposes, aiming to reduce their non-renewable energy consumption levels. To the best of the authors' knowledge, the semi-passive tracking/concentrating platform employed in this collector represents a significant improvement for 'stationary' (internal tracking, the module itself remains fixed) solar concentrating technology. To investigate the real-world viability of this collector design for solar heating and cooling, a system-level techno-economic performance analysis is conducted using a validated TRNSYS model. The solar heating and cooling (SHC) system includes the proposed solar thermal collectors, an auxiliary heater, and a double-effect absorption chiller. In this study, the proposed solar collectors are employed to supply thermal energy to the chiller to offset the building cooling demand or the thermal energy can also be used directly to satisfy the building's heating demand. When sufficient solar energy is not available, the auxiliary heater provides the rest of the heating and cooling demand. The annual solar fraction and economic metrics (e.g. total levelized costs) were used as the selection criteria among design options. The simulation results demonstrate that a specific collector area of 2.4 m^2 per kW cooling and an optimal storage tank specific volume of 40 L/m^2 are sufficient to cover 50% of the load requirement of the building. The economic analysis indicates that a levelized cost of cooling energy (LCOC) of ~0.6 $/kW-h can be derived from this solar air-conditioning system.

1. Introduction

Due to growing environmental pressure and energy demand around the world, along with technological improvements, the use of solar energy is rapidly expanding. Solar thermal technologies still represent the largest aspect (~66%) of the global solar market, with an installed capacity of 667 GW_{th} in total as compared to ~227 GW_e in photovoltaics (PV), at the end of 2015 [1–3]. In the solar thermal market, low temperature (e.g. domestic hot water) collectors cover the lion's share – with more than 309.4 GW_{th} installed in China alone [1,2]. As such, it is clear that domestic hot water heating (requiring only temperatures below 100 °C) dominate today's solar industry – a fact which can be

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Nomenclature

A	area (m^2)
G	solar irradiation (W/m^2)
K	incidence angle modifier
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	power (W)
T	temperature (K)
C_p	specific heat capacity (J/kg K)
U_L	collector heat loss coefficient (W/m^2 K)

Greek letters

θ	incident angle (degree)
η	efficiency
ρ	reflectivity
τ	transmissivity
ε	emissivity

Subscripts

a	ambient
AC	absorber–condenser
ACH	absorption chiller
AH	auxiliary heater
abs	absorber
air	air
b	beam
C	cooling
CHW	chilled water
col	collector
CT	cooling tower
CW	cooling water
e	electricity
E	evaporator
f	fluid
G	generator
g	glass
H	heating
HW	hot water
in	inlet
L	load
loss	loss
len	lens
m	mean
n	refractive index
opt	optical
out	out
P	pump
r	receiver
t	total
th	thermal
w	water

Abbreviations

AC	annual cost [USD]
CC	capital cost [USD]
CFD	computational fluid dynamics
COP	coefficient of performance
CPC	compound parabolic concentrator
CPV	concentrating photovoltaics
CST	concentrated solar thermal
DNI	direct normal irradiance
EFP	evacuated flat plates
ETC	evacuated tube collector
FC	fuel cost
HTF	heat transfer fluid
IAM	incidence angle modifier
LCOC	levelized cost of cooling energy
LCOE	levelized cost of energy
LCOH	levelized cost of heating energy
HVAC	heating, ventilation and air conditioning
OMC	operating and maintenance costs
PTC	parabolic trough collector
PV	photovoltaics
SHC	solar heating and cooling

explained by their low levelized energy cost (~0.06 $/kW$_{th}$-h) [1,2]. In many locations, this is competitive (before subsidies) with conventional hot water systems (i.e. gas and electricity-based hot water range from 0.04 to 0.15 $/kW$_{th}$-h) [1,2].

However, in recent years, the average annual growth rate of solar water heating has been slowing, from ~12% in 2009–2014 to ~6% in 2015 [1,2]. The rapid growth of PV (~42% growth per year over the past five years) may soon result in a change of solar technology leadership, particularly with declining solar water heating markets in Europe and China. A major factor in the recent success of solar PV has been its continued march down the manufacturing learning curve and the associated $/W$_e$ (installed) price reductions [1,2].

To compete with solar PV, it is clear that solar thermal technologies must follow a similar trajectory of technical and economic improvement. In particular, solar thermal technology could benefit from moving into new applications – e.g. moving beyond domestic hot water [3]. At present, there is a growing interest to push towards higher temperatures (100–400 °C) for industrial process heating and for thermal-driven air-conditioning applications [4,5]. Medium temperature (100–300 °C) solar thermal collectors can, in principle, displace a significant fraction of fossil fuel inputs in these medium temperature applications, including: industrial process heating, building environmental control and other commercial applications [6–9]. Solar thermal collectors which match the needs of these applications are under-developed, but there is a clear and present need to investigate and develop this technology to make solar energy a viable option for these copiously energy consuming applications [10,11].

Since heat, particularly high-temperature heat, is hard to transport over long distances, rooftop heat production represents an inimitable opportunity for large buildings to exploit their unused real estate (large, flat rooftops) and a chance to convert volatile, external energy expenses into stable, internal capital investments [12]. Unfortunately, to date, only a few solar thermal collectors have been developed commercially which can meet the needs of these applications.

One barrier to concentrated solar systems is that they require tracking systems, which are relatively heavy, complex, and cumbersome to integrate with rooftops in comparison with PV racks [9]. Another challenge is that they need to compete with the relatively low cost of conventional systems (namely heat generated from burning gas). If these challenges can be overcome, though, solar thermal technology could tap into a huge (behind the meter) commercial and industrial market for high-quality heat [7,8].