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A comprehensive, multi-objective optimization of solar-powered absorption chiller systems for air-conditioning applications

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ABSTRACT

Solar heating and cooling (SHC) systems are currently under rapid development and deployment due to their potential to reduce the use of fossil fuel resources and to alleviate greenhouse gas emissions in the building sector – a sector which is responsible for ~40% of the world energy use. Absorption chiller technology (traditionally powered by natural gas in large buildings), can easily be retrofitted to run on solar energy. However, numerous non-intuitive design choices must be analyzed to achieve the best techno-economic performance of these systems. To date, there has been little research into the optimal configurations among the long list of potential solar-driven absorption chiller systems. To address this lack of knowledge, this paper presents a systematic simulation-based, multi-objective optimization of three common, commercially available lithium bromide-water absorption chillers – single-effect, double-effect and triple-effect – powered by evacuated tube collectors (ETCs), evacuated flat plate collectors (EFPCs), and concentrating parabolic trough collectors (PTCs), respectively. To the best of authors' knowledge, this is the first study of its kind that compares the optimized designs of the most promising configurations of solar-assisted absorption chillers against a common set of energy, economic, and environmental metrics from a holistic perspective. A simulation model of these three configurations is developed using TRNSYS 17. A combined energy, economic, and environmental analysis of the modeled systems is conducted to calculate the primary energy use as well as the levelized total annual cost of each plant, which are considered as two conflicting objective functions. By coupling TRNSYS and MATLAB, a multi-objective optimization model is formulated using a genetic algorithm to simultaneously minimize these objectives, thereby determining a set of optimal Pareto solutions corresponding to each SHC configuration. The performance of the proposed systems at their optimal designs is then compared to that of a reference conventional system. A sensitivity analysis is also performed to assess the influence of fuel cost, capital cost of innovative components, and the annual interest rate on the Pareto front of optimal solutions. Overall, the optimization results reveal that of the proposed configurations, the SHC double-effect chiller has the best trade-off between the energetic, economic and environmental performance of the system, having a total cost of ~0.7–0.9 M$ per year and reducing the annual primary energy use and CO_2 emissions by 44.5–53.8% and 49.1–58.2% respectively (relative to the reference conventional system). With the high capital cost associated with these systems, government subsidies and incentives are still required in order for them to achieve satisfactory payback times and become cost-competitive with conventional HVAC systems.

1. Introduction

1.1. Background

The primary energy consumed in buildings is dominated by space cooling, heating and ventilation in many regions in the world [1–3]. About 40% of greenhouse gas emissions in the building sector is due to the use of conventional air-conditioning systems, most of which are based on electrically-driven mechanical vapor compression chillers [4–7]. Conventional systems have dominated the market over the last few decades, due mainly to their relatively low capital cost. Nonetheless, with the looming trifecta of: (i) rising demand for indoor comfort, (ii) increasing concerns about climate change, and (iii) depletion of fossil fuel resources, finding an environmentally and energy efficient alternatives to conventional

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Nomenclature

a	characteristic coefficient (–)
A_a	aperture area (m^2)
AUD	Australian dollar
c_1	first-order heat loss coefficient (W m^{-2} K^{-1})
c_2	second-order heat loss coefficient (W m^{-2} K^{-2})
c_3	wind speed dependence of heat losses (J m^{-3} K^{-1})
c_4	long-wave irradiance dependence of heat losses (–)
c_5	the collector effective thermal capacitance (J m^{-2} K^{-1})
c_6	wind dependence of the zero loss efficiency (s m^{-1})
c_{CO_2}	CO_2 emissions penalty cost (AUD tonne $CO_{2\text{-}e}^{-1}$)
CDE	carbon dioxide emission (tonne)
CDEC	carbon dioxide emission cost (AUD)
CDERC	carbon dioxide emission reduction cost (AUD)
c_E	unit cost of electricity (AUD kWh^{-1})
CES	cost of energy saving (AUD)
CI	capital investment cost (AUD)
C_{INSTL}	installation, integration, and piping costs (AUD)
c_{NG}	unit cost of natural gas (AUD GJ^{-1})
COP	coefficient of performance (–)
c_p	specific heat at constant pressure (kJ kg^{-1} K^{-1})
CR	concentration ratio (–)
CRF	capital recovery factor (–)
C_{tot}	total cost (AUD year^{-1})
E	annual energy consumption (kWh)
e	characteristic coefficient (–)
EF	emission factor (kg CO_2 kWh^{-1})
EFPC	evacuated flat plate collector
E_L	long-wave irradiance (W m^{-2})
ETC	evacuated tube collector
F'	collector efficiency factor (–)
FC	fuel cost (AUD)
$F'(\tau\alpha)_n$	collector zero loss efficiency at normal incidence (–)
GA	genetic algorithm
G_b	solar beam irradiance (W m^{-2})
G_t	global irradiance on the tilted collector (W m^{-2})
i	the average annual interest (discount) rate (%)
IRR	internal rate of return (%)
$K(\theta)$	incidence angle modifier (–)
LINMAP	Linear Programming Technique for Multidimensional Analysis of Preference
m	characteristic coefficient (kW °C^{-2})
$\dot{m}$	mass flow rate (kg s^{-1})
n	system economic lifetime (year)
NCF	net cash flow (AUD)
NPV	net present value (AUD)
NTU	number of transfer units
OMC	operating and maintenance cost (AUD)
OMRC	operating and maintenance reduction cost (AUD)
PBP	payback period (year)
PEC	primary energy consumption (kWh, GWh)
PEF	primary energy factor (–)
PES	primary energy saving (kWh, GWh)
PTC	parabolic trough collector
$\dot{Q}$	heat transfer rate (kW)
r	characteristic coefficient (kW)
R^2	coefficient of determination
r_i	average inflation rate (%)
r_n	nominal annual escalation rate (%)
r_r	real annual escalation rate (%)
s	characteristic coefficient (kW °C^{-1})
SF	solar fraction
T	temperature (°C)
t	time (s)
u	wind velocity (m/s)
U_L	collector overall heat loss coefficient (W m^{-2} K^{-1})
V	volume (L m^{-2}, m^3)
$\dot{W}$	power consumption (kW)
Z	purchased equipment cost (AUD)
$\Delta\Delta T'$	characteristic temperature difference (°C)

Greek symbols

η	thermal efficiency (–)
θ	solar incidence angle on the collector (°)
σ	Stefan–Boltzmann constant (W m^{-2} K^{-4})

Subscripts

a	air, ambient
AC	absorber-condenser
ACH	absorption chiller
AH	auxiliary heater
avg	average
b	beam
C	cooling
CHW	chilled water
CT	cooling tower
CTRL	controller
CW	cooling water
d	diffuse
DV	diverting valve
E	electricity, evaporator
G	generator
H	heating
HP	high pressure
HW	hot water
j	jth year of the system operation (year)
L	levelized, load
l	linear
LP	low pressure
MV	mixing valve
NG	natural gas
P	pump
PRV	pressure relief valve
q	quadratic
ref	reference conventional HVAC system
SC	solar collector
SCW	solar collector water
SHC	solar heating and cooling
SP	set-point
ST	storage tank
u	useful
VFD	variable frequency drive
w	water
WCH	water-cooled mechanical chiller
1-e	single-effect
2-e	double-effect
3-e	triple-effect
0	the beginning of the first year of system operation

HVAC systems has become a global priority [8]. Of the potential renewable energy solutions, solar energy represents an ideal candidate for air-conditioning applications given the high correlation between buildings cooling demand and solar resources [9]. Solar-driven absorption chillers are a promising near-term alternative to conventional air-conditioning systems, since much of the tech-