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A novel solar thermal polygeneration system for sustainable production of cooling, clean water and domestic hot water in United Arab Emirates: Dynamic simulation and economic evaluation

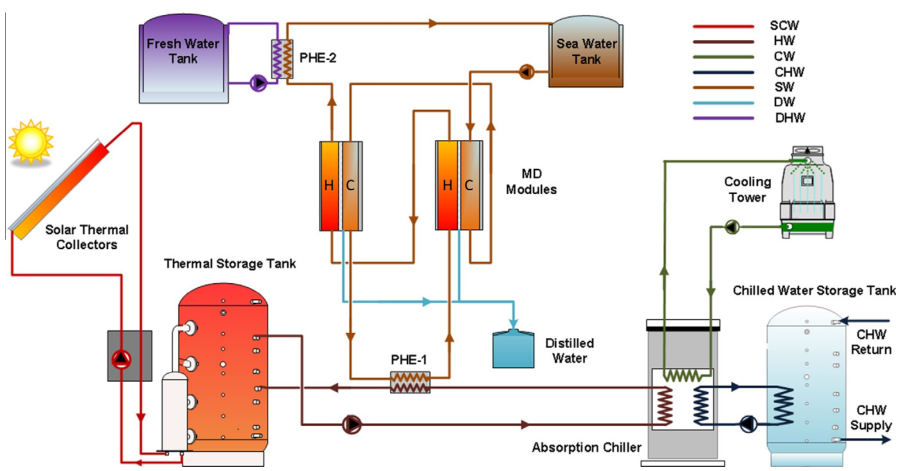
Gowtham Mohan [a,b,*], Uday Kumar [a,b], Manoj Kumar Pokhrel [a], Andrew Martin [b]

[a] RAK Research and Innovation Center (RAKRIC), American University of Ras Al Khaimah, Formerly CSEM-UAE Innovation Center, Ras Al Khaimah, United Arab Emirates
[b] Department of Energy Technology, KTH Royal Institute of Technology, Stockholm 10044, Sweden

HIGHLIGHTS

- A new polygeneration system is proposed to simultaneously produce cooling, clean water and domestic hot water.
- Membrane distillation systems and absorption chillers are integrated to develop a novel solar thermal polygeneration system.
- The polygeneration system is optimized to maximize the system efficiency and minimize investment costs.
- Complete energy, economic and environmental benefits of the polygeneration system is investigated.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, a novel solar thermal polygeneration (STP) system for production of cooling, clean water and domestic hot water is modeled and analyzed for the weather conditions of United Arab Emirates (UAE). The system comprises of solar collectors for production of thermal energy, single stage LiBr–H_2O absorption chiller (VAC) for providing air conditioning to office cabins and membrane distillation (MD) modules for clean water production along with domestic hot water generation as by-product. The performance of STP is analyzed with three different solar collectors – flat plate collectors (FPC), evacuated tube collector (ETC) and compound parabolic collector (CPC). The system is modeled and dynamically simulated using TRNSYS software for optimization of various design parameters like slope of the collectors, mass flow rate through the collector loop, storage capacity and area of collectors. Combined and system efficiency of the STP system has been determined for optimum conditions. Economic benefits are analyzed for different collectors and fuel costs savings. A lowest payback period of 6.75 years is achieved by STP with evacuated tube collector field having gross area of 216 m^2. STP system has cumulative savings of $520,000 over the life time of the project through roof top solar collector installation. In terms of environmental benefits, 109 metric tons/year of CO_2 emissions would be avoided and hence the overall payback period would be reduced by 8% based on cost saving through carbon credits. Economic

* Corresponding author at: RAK Research and Innovation Center (RAKRIC), American University of Ras Al Khaimah, Formerly CSEM-UAE Innovation Center, Ras Al Khaimah, United Arab Emirates. Tel.: +971 7 244 6929; fax: +971 7 244 6951.
E-mail addresses: gowtham@kth.se (G. Mohan), uday.kumar@aurak.ac.ae (U. Kumar), manojpokrel@gmail.com (M.K. Pokhrel), Andrew.martin@energy.kth.se (A. Martin).

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Nomenclature

A	area (m^2)
ACH	air changes per hour
b	thickness of membrane (mm)
C	cost ($)
C_p	specific heat capacity (J/kg K)
CP	thermal capacitance (J/K)
E	energy flux (kJ)
F_r	heat removal factor
H	height (m)
h	enthalpy (J/kg)
I_r	irradiance (W/m^2)
k	thermal conductivity
L	length (m)
l	air gap distance (mm)
$\dot{m}$	mass flowrate (kg/s)
M	mass (kg)
MC	molar concentration (M/L)
N	molar flux
p	partial pressure
P	pressure (bar)
Q	heat energy (kJ)
r	conversion factor (–)
T	temperature (K)
ΔT_{LMTD}	logarithmic mean temperature difference (K)
U	overall heat transfer coefficient (W/K)
V	volume (m^3)
X	molar fraction of water vapor (–)

Subscripts

amb	ambient
AG	air gap
avg	average
c	cold
col	collector
dis	distillate
f	fuel
gen	generator
HS	heat storage tank
HST	hot storage tank
hyd	hydraulics
CST	cold storage tank
Ins	insulation
in	inlet
L	latent heat
M	membrane
MD	membrane distillation
n	node
h	hot
out	outlet
PHE	plate heat exchanger
sc	solar collector loop
T	thermal
w	water

Greek notations

τ	transmittance
α	absorbance
η	efficiency (%)
Φ	porosity
λ	latent heat of condensation
μ	conductivity (W/mK)
δ	thickness of insulation layer (mm)

and environmental benefits were aided by steady system performances of absorption chiller (35 kW), membrane distiller (80 l/day) and heat recovery system (1.2 m^3/h) throughout the year. The complete simulation results of the STP system is utilized for the development, installation and testing of a polygeneration system at RAKRIC.

1. Introduction

Electricity demand in UAE has increased fivefold in past two decades due to rapid industrialization and population growth [1]. The electricity demand is mostly met by fossil fuels leading to emission of greenhouse gases thus causing global warming. Around 30% of electricity consumption is attributed to building air conditioning [2] with significant peaks in summer months between June and August [3]. In addition UAE and adjacent countries in MENA region do not have adequate natural fresh water resources, hence most of the fresh water demand is met by energy-intensive fossil fuel driven sea water desalination technologies. On the other hand, UAE has abundant solar resources with an average global irradiation potential of 600 W/m^2 [4], and technologies exist for utilizing this energy in meeting cooling and freshwater demands. Solar thermal technologies are widely accepted for space heating, cooling, desalination and power generation processes, while photovoltaic systems are popularly used for electricity production. Thus solar thermal technology is more promising in simultaneously providing air conditioning and potable water, especially in small and medium sized applications.

Focusing on solar thermally-driven cooling in UAE, Ssembatya et al. [5,6] analyzed the performance of single stage absorption chiller plant designed to provide summer cooling to office cabins installed in Ras al Khaimah. In another study, Al-Alili et al. [7,8] dynamically simulated a 10 kW solar driven absorption chiller for the weather conditions of Abu Dhabi; here the performance of the absorption chiller is analyzed energetically and economically for several design parameters. Ghaith and Abusitta [9] conducted numerical analyses to investigate thermal performance and potential energy savings of integrated Solar Heating Cooling systems. Various commercial projects have also been reported on the Internet, for example solar-cooled office buildings in Dubai [10] and Abu Dhabi [11]. Results from these and other studies (see Mokri et al. [12] for additional references) show that it is feasible to utilize solar driven absorption chiller systems in UAE.

Solar driven desalination processes are quite popular among various research initiatives in recent years in UAE. Thermal desalination processes include Multi-stage flash and Multi-effect desalination, although these technologies are most appropriate for large-scale systems. Solar still is the oldest and simplest small scale thermal desalination technique and widely researched;

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