Renewable Energy 91 (2016) 361–373

Contents lists available at ScienceDirect

Renewable Energy

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

Experimental investigation of a novel solar thermal polygeneration plant in United Arab Emirates

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

[a] RAK Research and Innovation Center, 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

ARTICLE INFO

Article history:
Received 17 April 2015
Received in revised form
1 October 2015
Accepted 24 January 2016
Available online xxx

Keywords:
Absorption chiller
Air gap membrane distillation
Solar thermal
Poly-generation
Domestic hot water

ABSTRACT

The demands for space air conditioning and clean drinking water are relatively high in Middle East North African (MENA) countries. A sustainable and innovative approach to meet these demands along with the production of domestic hot water is experimentally investigated in this paper. A novel solar thermal poly-generation (STP) pilot plant is designed and developed for production of chilled water for air conditioning using absorption chiller, clean drinking water with membrane distillation units and domestic hot water by heat recovery. The STP system is developed with a flexibility to operate in four different modes: (i) solar cooling mode (ii) cogeneration of drinking water and domestic hot water (iii) cogeneration of cooling and desalination (iv) trigeneration. Operational flexibility allows consumers to utilize the available energy based on seasonal requirements. Performance of STP system is analyzed during summer months in RAKRIC research facility. Energy flows in STP pilot plant during peak load operations are analyzed for all four modes. STP system with trigeneration mode utilizes 23% more useful energy compared to solar cooling mode, which improves overall efficiency of the plant. Economic benefits of STP with trigeneration mode are evaluated with fuel cost inflation rate of 10%. STP plant has potential payback period of 9.08 years and net cumulative savings of $454,000 based on economic evaluation.

1. Introduction

In United Arab Emirates (UAE), around 30% of electricity requirement is accounted for building air conditioning and it increases to about 70% in peak summer months [1,2]. Another energy intensive process conducted in most of the MENA region is desalination due to non-availability of fresh water resources. Electricity demands in UAE are mostly met by fossil fuels which lead to global warming. These problems have been addressed by few researchers through integration of multiple thermal cycles as polygeneration system driven by renewable energy or waste heat. Calise et al. [3] dynamically simulated a solar (PV/T) tri-generation system for production of electricity, fresh water and cooling and analyzed both energetically and economically. Hussain [4] developed a novel trigeneration system for simultaneous production of cooling, clean water and electricity and analyzed with different technologies to provide cooling with vapor compression and vapor absorption systems and clean water with reverse osmosis and multi-effect distillation. Picinardi [5] analyzed the performance of cogeneration system integrating humidification-dehumidification (HD) desalination unit with absorption chiller. Desalination process is driven by heat rejected from condenser of the absorption chiller. The heat rejection at higher temperatures affects the performance of chiller but improves the efficiency of the cogeneration plant in terms of lower energy usage. Chiranjeevi and Srinivas [6] developed a cogeneration system integrating two stage HD desalination and absorption chiller, which is completely driven by solar thermal energy to achieve high energy utilization factor. Integrated performance of plant is studied for different humidifier efficiency. Optimized system produces 670 l/h of distillate and 75 kW of cooling. Choon et al. [7] investigated the performance of a large waste heat driven adsorption cycle for production of cooling and fresh water with the implementation of adsorption–desorption

* Corresponding author. RAK Research and Innovation Center, American University of Ras Al Khaimah, Formerly CSEM-UAE Innovation center, Ras Al Khaimah, United Arab Emirates.

E-mail addresses: gowtham@kth.se (G. Mohan), uday.kumar@aurak.ac.ae (N.T. Uday Kumar), Andrew.martin@energy.kth.se (A. Martin).

http://dx.doi.org/10.1016/j.renene.2016.01.072
0960-1481/

Nomenclature

A	Area (m^2)
C	Cost ($)
C_p	specific heat capacity (J/kg K)
F_r	heat removal factor
h	enthalpy (J/kg)
I_r	irradiance (W/m^2)
$\dot{m}$	mass flowrate (kg/s)
M	mass (kg)
Q	heat energy (kJ)
r	conversion factor (−)
T	temperature (K)
tp	Time period (h)
U	overall heat transfer coefficient (W/m^2K)
V	Volume (m^3)
X	molar fraction of water vapor (−)

Subscripts

amb	ambient
avg	average
B	benefits
c	cold
ch	chilled
col	solar collector
dis	distillate
DHW	domestic hot water
evp	evaporation
f	fuel
FW	fresh water
gen	generator
HST	hot storage tank
hyd	hydraulics
CST	cold storage tank
Ins	installation
in	inlet
MD	membrane distillation
n	node
h	hot
out	outlet
PHE	plate heat exchanger
sc	solar collector loop
T	thermal
VAC	absorption chiller
w	water

Greek notations

τ	transmittance
α	absorbance
η	efficiency (%)
Φ	porosity

phenomena. Silica gel-water is used as sorbent material in the analysis. It is reported that cycle produces 3.6 m^3 of freshwater and 77 kW of cooling. Nada et al. [8] experimentally investigated the performance of hybrid HD desalination and vapor compression air conditioning in Egypt. Enhanced production of fresh water and refrigeration capacity with minimal compressor work is achieved and demonstrated through the research experiments. Few researchers investigated the possibilities of energy savings by integrating SHC (solar heating and cooling) with other renewable energy resources as a hybrid polygeneration system [9–11].

Membrane distillation is a promising technology for production of clean water by utilizing low grade heat energy as the driving source. The temperature difference between the side of membrane acts as the driving force in the process [12]. Burrieza et al. [13] experimentally analyzed the performance of air gap membrane distillation (AGMD) modules for different temperatures and flow rates along the sides of membrane. The maximum specific distillate flux of 7 l/h m^2 is achieved with a flow rate of 1200 l/h on both hot and cold sides. With multi-stage configurations better heat recovery and thermal efficiencies are achieved.

Few researchers investigated the possibility of integrating membrane distillation unit with other thermal cycles to develop a polygeneration system. Kullab [14] numerically and experimentally investigated the possibility of utilizing air gap membrane distillation systems in cogeneration power plants. Further, the productivities of multi-effect configurations of two different integration layouts were analyzed for different feed and coolant water temperatures. Liu [15] numerically analyzed the possibilities of integrating membrane distillation units with gas engine to provide power and clean water to chip manufacturing unit. Mohan et al. [16] investigated the possibility of utilizing the waste heat rejected from the combined cycle power plant for producing chilled energy by absorption chiller and clean water by membrane distillation technology. The plant had an impressive payback period of 1.38 years and net cumulative saving of $66 Million. Uday kumar and Martin [17] developed a solar thermal cogeneration system for production of clean water using membrane distillation and domestic hot water for residential buildings in UAE. The system is developed to provide 20 l/day of fresh water and 250 l/day of domestic hot water and verified with detailed experimentations.

As shown in literature, several combinations for integration of solar cooling and different conventional desalination technologies like RO, MED and MSF were investigated by researchers. The potential of solar thermal driven MD technology and its possibilities of integration were demonstrated by few researchers. However, the possibility of solar thermal polygeneration system integrating absorption chillers and membrane distillation together is not been studied before according to our knowledge. In this paper, solar thermal driven polygeneration system for simultaneous production of cooling by absorption chiller, fresh water by membrane distillation and domestic hot water by heat recovery has been designed, developed and experimentally tested in weather conditions of United Arab Emirates.

2. Methodology

The system investigated in this project is a novel solar thermal polygeneration (STP) system integrating solar collectors, single stage absorption chiller and membrane distillation unit. The system is designed to operate during the sunshine hours without any auxiliary electrical heater in the weather conditions of United Arab Emirates. The schematic layout of the system considered for the investigation is shown in Fig. 1 which consists of seven different system loops.

- Solar collector circulation loop (SCW): Circulation of water between solar collector field and source side of hot water storage tank