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Water desalination with concentrating photovoltaic/thermal (CPVT) systems

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Abstract

A coupled system is proposed, comprised of a concentrating photovoltaic/thermal collector field and a multi-effect evaporation desalination plant. The combined system produces solar electricity and simultaneously exploits the waste heat of the photovoltaic cells to desalinate water. A detailed simulation was performed to compute the annual production of electricity and water. The cost of desalinated water was estimated and compared to that of alternative conventional and solar desalination plants. Several economic scenarios were analyzed. The results indicate that the proposed coupled plant can have a significant advantage relative to other solar desalination approaches. In some cases, CPVT desalination is even more cost-effective than conventional desalination.

Keywords: Cogeneration; Polygeneration; Concentrating photovoltaics; CPV; Desalination; Multi-effect evaporation

1. Introduction

Desalination with solar energy is a natural combination: regions with abundant solar radiation are often also short in potable water supply. Three processes are commercially available for large-scale desalination plants: Reverse Osmosis (RO), Multi-Stage Flash distillation (MSF), and Multiple Effect Evaporation (MEE). RO requires electricity, a high-grade form of energy; however, MEE and MSF consume thermal energy, and can readily operate with alternative low-grade heat sources such as solar energy. Solar desalination has been proposed in the past, based on several approaches: thermal desalination processes with solar thermal collectors (El-Nashar and Samad, 1998; García-Rodríguez and Gómez-Camacho, 1999, 2001; John et al., 2001; Alarcón et al., 2005); RO with electricity from solar photovoltaic (PV) systems (Ahmad and Schmid, 2002; Kershman et al., 2002; Tezen et al., 2004); and thermal desalination with waste heat from a solar thermal power plant (cogeneration) (Sagie et al., 2005). A recent review of solar desalination options can be found in (Mittelman et al., 2007b).

RO driven by solar electricity is not really an integrated application, since the solar electricity can be fed into the grid, while the electricity for the RO plant can be drawn from the grid, and can be either solar or conventional in origin. The issues of generation and desalination are therefore decoupled except for very small stand-alone plants where no grid exists. Obviously, RO driven by solar electricity would make sense economically only if the solar electricity is competitive against conventional grid power, on its own without relation to the desalination application.

For the solar thermal desalination processes there is no equivalent ‘grid' for the heat. Therefore, the solar component and the desalination component have to be evaluated together as an integrated application. Based on past analyses, the projected cost of water desalinated with the thermal processes driven by solar heat is still significantly higher

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Nomenclature

A	area [m^2]
B	brine stream [kg/s]
BPE	boiling point elevation [°C]
C	concentration ratio
C_p	specific heat [kJ/kgK]
C_{des}	desalination system investment cost [$]
C_e	annualized energy cost [$/yr]
C_{solar}	solar system investment cost [$]
C_y	total annualized cost [$/yr]
CF	capacity factor
CRF	capital recovery factor [1/yr]
D	distillate stream [kg/s]
$\mathbf{D}$	tank diameter [m]
d	heater stream [kg/s]
$\bar{d}$	vapor stream from flash box [kg/s]
G	radiation flux [W/m^2]
H	layer thickness [m]
LMTD	log mean temperature difference [°C]
M	mass flow rate [kg/s]
M^*	maintenance cost [$/yr]
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
NEA	non equilibrium allowance [°C]
PWF	present worth factor
Q	power [W]
r	interest rate
R	replacement cost [$]
sA	specific area [m^2/(kg/s)]
SCF	solar capacity factor
T	temperature [°C]
TBT	top brine temperature [°C]
t	feed temperature [°C]
$\mathbf{t}$	system lifetime [yr]
U	heat transfer coefficient [W/m^{2}K]
X	salinity

Greek

Δ	difference
λ	latent heat [kJ/kg]
η	efficiency

Subscripts

b	beam
bd	blowdown
C	PV cell
c	condenser
coll	collector
cw	cooling water
d	distilled
e	evaporator
EL	electric
f	feed
h	heater
INC	incident
INV	inverter
j	effect number
k	year number
L	load
n	total number of effects
OPT	optical
PAR	parasitic
pre	preheater
PV	PV module
REC	receiver
sw	seawater
TH	thermal
s	storage
v	vapor

than that of conventional desalination processes, due to the required investment in the solar thermal collectors (Milow and Zarza, 1996; El-Nashar and Samad, 1998; García-Rodríguez and Gómez-Camacho, 1999; Szacsvay et al., 1999).

Many small solar desalination systems (<1000 m^3/d) have been investigated in recent years (García-Rodríguez, 2002). These small systems are usually considered where conventional alternatives are absent or impractical. The current work addresses larger plants (10,000–100,000 m^3/d) that benefit from economy of scale. Entry into this large-scale market is critical for the adoption in practice of solar desalination. Furthermore, the implementation of large plants obviously has a greater environmental benefit and may be eligible for environmental incentives.

The approached investigated here is solar cogeneration of electricity and heat, using a Concentrating Photovoltaic and Thermal (CPVT) system. The heat generated in PV cells is usually rejected to the environment and wasted. Collecting and using this thermal energy, in addition to the electricity production, seems an attractive approach to obtain solar thermal energy. The solar heat is available at very low cost, because the investment of the solar collector is borne by the electricity production. This approach has been investigated for cogeneration of solar cooling (Mittelman et al., 2007a) and of water heating (Kribus et al., 2006), demonstrating high cost-effectiveness under a suitable range of economic conditions.

Some PV-Thermal (PV/T) systems are based on flat collectors without concentration. This area has seen much activity recently, with different collector designs