HEFAT2008
6th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
30 June to 2 July 2008
Pretoria, South Africa
Paper number: GV1

SUSTAINABLE DESALINATION: A CASE FOR RENEWABLE ENERGY

V. Gude[1] and N. Nirmalakhandan[2]*
[1] Research Engineer, Cascade Eco Solutions Inc., Bothell, WA 98021, USA
[2] Professor, New Mexico State University, Las Cruces, NM 88003, USA
*Corresponding author: email: nkhandan@nmsu.edu; phone: 1 (505) 646 5378

ABSTRACT

A new energy-efficient and sustainable desalination system has been developed in this research. This system operates under near-vacuum conditions created by exploiting natural means of gravity and barometric pressure head. The system can be driven by low grade heat sources such as solar energy or waste heat streams. Theoretical and experimental studies were conducted to evaluate and demonstrate the feasibility of the proposed process. Theoretical studies included thermodynamic analysis and process modelling to evaluate the performance of the process driven by the following alternate energy sources: solar thermal energy, solar photovoltaic/thermal energy, geothermal energy, and process waste heat emissions. Experimental studies included prototype scale demonstration of the process using direct solar and a combination of solar photovoltaic/thermal sources. In the tests using direct solar energy, freshwater production of 5 L/d was achieved using direct solar energy alone, at efficiencies ranging from 65 to 75%. In the tests using solar photovoltaic/thermal energy, freshwater production of 10 L/d was achieved, at efficiencies ranging from 65 to 90%. Specific energy required for this process to produce 1 kg of freshwater was 2926 kJ, all of which was derived from solar energy.

INTRODUCTION

Thermal desalination technologies require large quantities of energy. Traditionally, fossil fuels have been used to provide the energy requirements for desalination of seawater or brackish waters. In an effort to conserving natural fossil fuel resources, desalination industry has been adopting several energy-saving measures in recent years. Examples include recovery and recycling of energy as in the case of staging, low temperature desalination, and utilization of waste heat or renewable energy.

In this research, a new low temperature desalination process has been developed which can utilize low grade heat sources such as waste heat releases, or solar, photovoltaic, photovoltaic/thermal, or geothermal energy. Since the process operates at lower temperatures, energy losses and hence the energy requirements for desalination are reduced. As this process utilizes waste heat releases and renewable energy, it does not directly contribute to any greenhouse gas emissions, and can be considered a sustainable process.

NOMENCLATURE

A	[m^2]	area
C	[%]	concentration
c	[kJ/kg-K]	specific heat
h_L	[kJ/kg]	latent heat
I	[kJ/hr-m^2]	insolation
m	[kg]	mass
Q	[kJ/hr]	energy or useful energy
p	[Pa]	pressure
U	[kJ/hr-m^2-K]	heat transfer coefficient
$\dot{V}$	[m^3/hr]	volumetric flow rate
V	[m^3]	volume of the saline water or storage tank
q	[kJ/hr]	evaporation energy
t	[hr,s]	time
T	[K]	temperature

Special characters

α_m	[kg-K$^{0.5}$/m^2-Pa-s]	experimental coefficient
f	[-]	concentration factor
ρ	[m]	density
η	[%]	efficiency

Subscripts

i, in	inlet, supply
w	withdrawal
e	evaporation, electrical
G	geothermal, glass
l, L	losses
p	plate
r, R	recycle
s	saline water, supply, surface, solar
C	cooling layer

eff	volumetric effective expression

DESCRIPTION OF THE DESALINATION SYSTEM

The proposed system is shown schematically in Figure 1. The components of the desalination unit include an evaporation chamber (EC), a condenser (CO), two heat exchangers (HE1 & HE2), and three 10-m tall columns. These three columns serve as the saline water column; the brine withdrawal column; and the desalinated water column, each with its own holding tank, SWT, BT, and DWT, respectively. The heat input to EC is provided by the low grade waste/renewable energy source.

The EC is installed atop the three columns at a height of about 10 m above ground level to create vacuum naturally in the headspaces of the feed, withdrawal, and desalinated water columns. This configuration drives the desalination process without any mechanical pumping (Al-kharabsheh, 2003). The saline water enters the evaporation unit through a tube-in-tube heat exchanger (1, 2). The temperature of the head space of the feed water column is maintained slightly higher than that of the desalinated water column. Since the head spaces are at near-vacuum level pressures, a temperature differential of 10ºC is adequate to evaporate water from the feed water side and condense in the distilled water side (3, 4, and 5). In this manner, saline water can be desalinated at about 40-50ºC, which is in contrast to the 60-100ºC range in traditional solar stills and other distillation processes. This configuration enables brine to be withdrawn continuously from the EC through HE1 preheating the saline water feed entering the EC (6,7). Further, by maintaining constant levels of inflow and outflow rates in SWT, BT and DWT, the system can function without any energy input for fluid transfer. Dissolved gases in the feed water may be released during evaporation which in turn can increase the operating pressure of the evaporation chamber. A vacuum pump has to be employed to remove the accumulated gases as the pressure builds up.

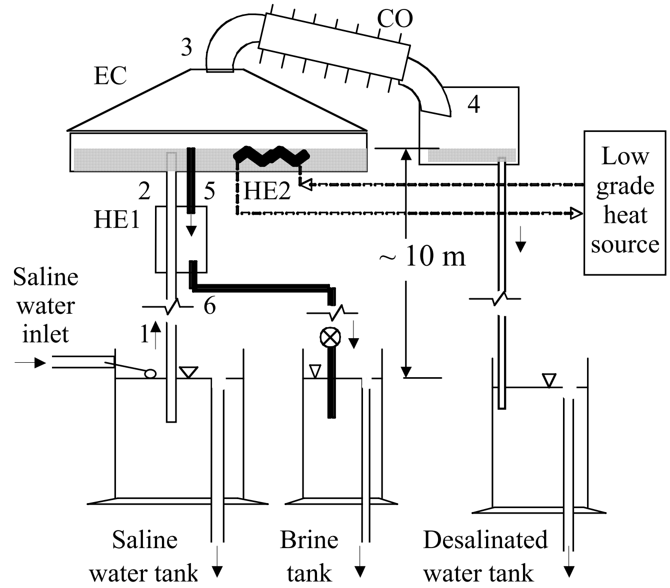

Figure 1. Low temperature desalination system

MODELING OF THE DESALINATION SYSTEM

The evaporation unit is same for all the cases while the heat source is different for each case (Figure 1). Theoretical analysis for different energy sources and the results from the modelling studies are presented in this section. The expressions for energy sources can be substituted in the overall heat balance equation to generate simulations. The following mass and heat balance equations apply to the evaporation unit:

Mass balance on water in the EC:

$$\frac{d}{dt}(\rho V) = \rho_i \dot{V}_i - \rho_w \dot{V}_w - \rho_e \dot{V}_e \tag{1}$$

Mass balance on solute in the EC:

$$\frac{d}{dt}(\rho C V)_s = \rho_i C_i \dot{V}_i - \rho_w C_w \dot{V}_w \tag{2}$$

Heat balance for the EC:

$$\frac{d}{dt}(\rho c_p V T)_s = Q_{in} + (\rho c_p T)_i \dot{V}_i - (\rho c_p T)_w \dot{V}_w - Q_e - Q_L \tag{3}$$

Evaporation rate is expressed as Jobson, 1973(3):

$$q_e = \frac{A\alpha_m}{\rho}[f(C_s)\frac{p(T_s)}{(T_s+273)^{1/2}} - \frac{p(T_f)}{(T_f+273)^{1/2}}] \tag{4}$$

where, $p(T) = e^{(63.042 - 7139.6/(T+273) - 6.2558\ln(T+273))} \times 10^2\, Pa$

Evaporation energy is given as:

$$Q_e = \rho\, h_L(T_S)\, q_e \tag{5}$$

Latent heat of evaporation is given as:

$$h_L(T) = [(3146 - 2.36(T + 273\,^0K)] \tag{6}$$

Desalination efficiency, η_d, is defined as:

$$\eta_d = \frac{m_e h_L}{\sum Q_{in}\Delta t} \tag{7}$$

Heat losses and latent heat dissipation through the condenser and the design procedure are presented elsewhere [Gude, 2007].

Feed water characteristics and other model parameters considered in modelling are presented in Tables I and II.

Table I. Feed water Characteristics

Parameter	Value	Parameter	Value
Feed water temperature	25^0C	Feed water density	1020 kg/m^3
Feed water concentration	3.5 %	Ambient temperature	10-40 ^{0}C

Table II. Model Parameters

Parameter	Value	Parameter	Value
Solar evaporation chamber (SEC) area	1-5 m^2	Solar Insolation	400-1100 kJ/hr-m^2
Height of SEC	0.25-0.5 m	Heat source temperature	50-70 ^{0}C
Water depth in SEC	0.05-0.1 m	Condenser area	1-5 m^2

Solar collectors

Solar collectors supplying low grade heat (50-70ºC) can be used to run the proposed system during sunlight hours. The sensible heat stored in the bulk water in the evaporation chamber would result in evaporation of fresh water during non sunlight hours. Solar collector area of 1 m^2 and an evaporation rate of 1 m^2 were considered for the analysis. Water level in the evaporation chamber was fixed at 0.05 m. The reference temperature was set at 25ºC. Heat balance across the solar panel and thermal energy storage tank:

$$\frac{d(m_S c_s T_{S1})}{dt} = F_R A_C\left[(\tau\alpha) I_S - U_L (T_{S1} - T_a)\right] - U_S A_S (T_{S1} - T_a) - m_R c_r (T_{S1} - T_e) \qquad (8)$$

Photovoltaic thermal (PV/T) collectors

Photovoltaic thermal (PV/T) collectors can produce both electrical and thermal energy from solar energy. The overall efficiency of the PV/thermal panels is higher than the sum of the efficiencies of separate photovoltaic modules and solar thermal collectors (Helden et al, 2004). Thermal energy produced from photovoltaic/thermal collectors is suitable for low temperature desalination by the proposed process. Theoretical analysis for the desalination system utilizing photovoltaic thermal energy is as follows. Overall steady state energy balance on the PV/T collector can be written as follows:

$$Q = Q_S - q_{losses} - P_E = mC_{pf}(T_f - T_{in}) \qquad (9)$$

$$Q_S = I_S \tau_G \alpha_P \qquad (10)$$

$$q_{losses} = \varepsilon_r \varepsilon_g \sigma \{T_P{}^4 - T_G{}^4\} + h_{pg}(T_P - T_G) \qquad (11)$$

$$P_E = I_S \tau_G F_C \eta_{std} \{1 - 0.005\,(T_P - 298.15)\} \qquad (12)$$

Overall temperature of the absorber (PV laminate) can be calculated as follows:

$$MC\frac{dT_{PVT}}{dt} = Q_S - q_{losses} - P_E - m\overset{\circ}{C}_{pf}(T_f - T_{in}) \qquad (13)$$

$$T_f = (T_{PVT} - T_{in})\{1 - \exp(-4 * \frac{(x/d)Nu}{\mathrm{Re}\,.\,\mathrm{Pr}})\} + T_{in} \qquad (14)$$

Efficiencies are given as [Garg et al. 1995]:
Thermal efficiency of collector:

$$\eta_{PVT} = \frac{\overset{\circ}{m}\, C_{pf}(T_f - T_{in})}{IA_C} \qquad (15)$$

Total PV/T efficiency =

$$\eta_{PVT} = \frac{\overset{\circ}{m}\, C_{pf}(T_{out} - T_{in}) + \sum P_e}{IA_C} \qquad (16)$$

Geothermal energy

Low grade geothermal source with temperature of about 60ºC can be used directly to heat the saline water or to maintain a thermal energy storage tank which can then provide the energy to the evaporation chamber. The amount of thermal energy supplied by the geothermal flow can be quantified as:

$$Q_{in} = \dot{m}_g\, C_{pg}(T_g - T_w) \qquad (17)$$

Theoretical analysis of low temperature desalination using waste heat rejected from absorption refrigeration system (ARS) system has been studied previously [Gude and Nirmalakhandan, 2008].

SUMMARY OF THEORETICAL MODELING RESULTS

Results from the modelling studies presented in this section show that the proposed process has the potential to be driven solely by renewable energy sources or waste heat releases, and can be operated on a continuous basis with moderate yields. Details of the theoretical modelling results have been presented elsewhere [Gude, 2007]

Solar Collectors

The study showed that the propsoed desalination system coupled with 1 m^2 solar collector area can produce up to 7.5 L/d of freshwater which is more than two times the productivity of a flat basin solar still. Desalination efficiencies of 70-80% can be achieved by this configuration.

Photovoltaic/ Thermal Collectors (PV/T)

Model simulations showed that 200 L/d of freshwater can be produced with a PV/T area of 25 m^2 while supplying the energy demand of 21 kW-h/d for a baseline house. The cost for PV/T collectors is lower than the cost for solar collectors and PV modules purchased separately for this purpose. PV/T modules have higher electricity generation capacities due to the cooling provided by the circulating water.

Geothermal energy

Geothermal water sources have the potential for large scale application of the proposed desalination system. Geothermal water flow rate of 100 kg/hr has been considered for numerical simulations. Theoretical simulations showed that this system can produce up to 60 L/d of desalinated water with an average evaporation rate of 2.5 L/hr. Geothermal waters provide continuous source of water and qualify as a new source of water as the feed itself can be the geothermal water or depending on the availability of brackish water/seawater sources.

Waste heat sources

The feasibility of driving the proposed system with the heat rejected by an absorption refrigeration air-conditioning system has been evaluated previously (Gude and Nirmalakhandan, 2008). Modelling studies showed that the heat rejected by a domestic air-conditioning unit rated at 3.25 kW is adequate to produce 108 L/d of desalinated water. Based on World Health Organization requirements of 20 L/d for basic hygiene needs for a person, this configuration can provide for a family of 6.

Specific Energy Requirements

Specific energy required to produce 1 kg of freshwater using the above four energy sources are summarized in Table III. Specific energy requirements include the heat energy used for evaporation and mechanical energy for pumping the heat source. These results suggest that the above configurations have the potential to produce freshwater in either batch or continuous modes of operation. The specific energy requirement is also dependent on the mode of operation. The ARS configuration is most suitable for domestic application since free energy is available from the ARS condenser and the specific energy requirements are smaller than the other configurations considered.

Table III. Specific energy requirements for low temperature desalination process using different sources of energy

Energy source	Mode of operation	Energy requirement [kJ/kg freshwater]		
		Thermal	Mechanical	Total
Solar collector	Batch	3,118	4	3122
PV/T collector	Batch	3,118	4	3122
Geothermal	Continuous	2,934	144	3078
Waste heat (ARS)	Continuous	194	14	208

SUMMARY OF EXPERIMENTAL RESULTS

Experimental studies have been conducted using direct solar energy and photovoltaic energy. A solar evaporator area of 1 m^2 and photovoltaic area of 6 m^2 is used. Solar energy is directly utilized during sunlight hours and photovoltaic energy stored in batteries is used during non-sunlight hours. Figure 2 shows the est system.

Figure 2. Photo of the experimental setup with photovoltaic modules

Direct solar energy

The experimental studies were conducted in summer at the engineering research facility in Las Cruces, USA. Solar insolation varied between 600 W/m^2 to 1150 W/m^2 during 8 hours of the test day. Maximum saline water temperature recorded was 52.75 ^{0}C while the maximum ambient temperature for the day was 36 ^{0}C. Maximum saline water temperature predicted by the model was 52 ^{0}C (Figure 3).

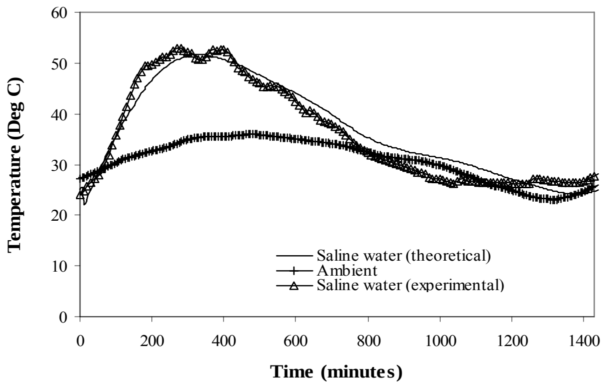

Figure 3 Temperature profiles for theoretical and experimental studies using direct solar energy

Theoretical daily distillate yield for the simple solar evaporation unit was 5.25 L/d while the experimental daily distillate was 4.95 L/d (Figure 4). The difference in the yield of 5.5% is due to the fact that in theoretical simulations, it was assumed that all the vapour produced has condensed on the freshwater side; while, during the experiments, some of the water vapour returned to the pool of saline water without flowing into the condenser. Theoretical efficiency varied between 60 to 80 % most of the day with an average efficiency of 64 %, while the experimental efficiency varied between 50 to 85 % most of the day with an average efficiency of 61 % as shown in Figure 5.

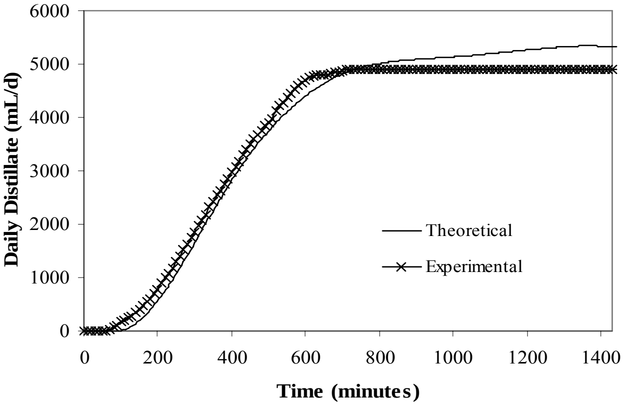

Figure 4. Theoretical and experimental yields for the configuration utilizing direct solar energy

Solar/photovoltaic energy

In this configuration, the evaporator top is exposed to sun to receive solar energy and heaters are arranged to supply electrical energy during non-sunlight hours. This test was performed to study the effectiveness of utilizing the photovoltaic energy during non-sunlight hours. The solar insolation and energy profiles are presented in Figure 6 for a typical day in the month of July.

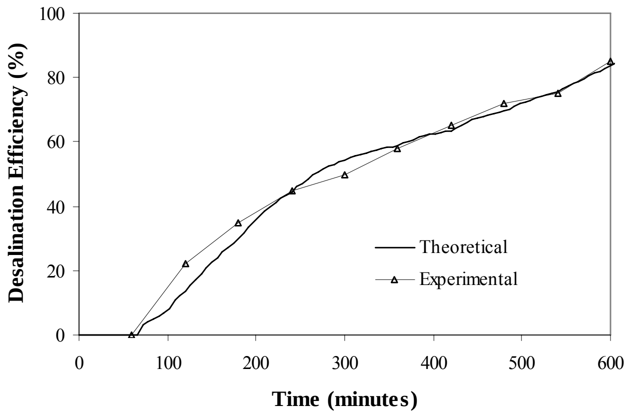

Figure 5. Theoretical versus experimental efficiencies

Energy produced by the PV modules during sunlight hours is stored in the batteries and is supplied to the evaporator during non-sunlight hours. Energy storage and supply trends can be seen in Figure 6. When the energy is being supplied to the evaporation chamber during non-sunlight hours, negative quantity of energy indicates that the energy is released from batteries. During sunlight hours, photovoltaic energy is not required for evaporation, so the energy is stored in the batteries. The energy produced by photovoltaic modules is proportional to the solar insolation in the day as can be seen from Figure 6.

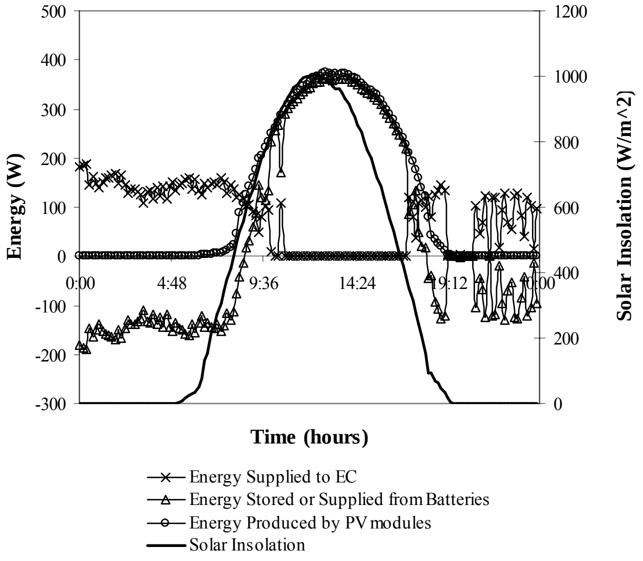

Figure 6. Solar insolation and energy profiles

Temperature profiles for the desalination system over 24 hour period are shown in Figure 7. As can be seen in Figure 7, the evaporation temperature remained at 50 ^{0}C during night time and reached 54-56 ^{0}C during the day time. During the night times the evaporator top was covered with insulation material to prevent heat losses.

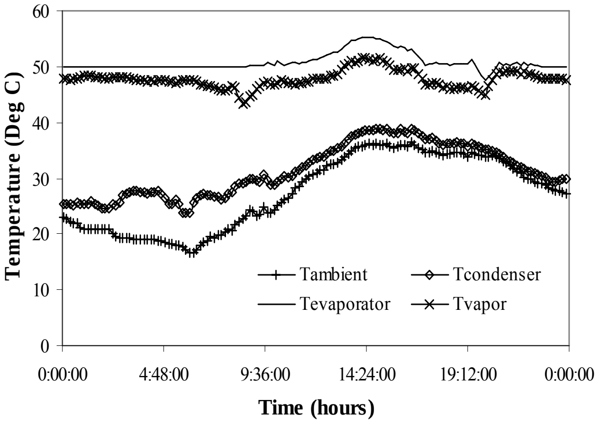

Figure 7. Temperature profiles over 24 hour period for a set evaporation temperature of 50 ^{0}C.

Photovoltaic energy generated during the day is sufficient to produce freshwater of 4-5 L/d during the night time. The efficiency of the PV modules is 14 %. Specific energy required for this process to produce 1 kg of freshwater was 2926 kJ. Freshwater production rates up to 10 L/d are obtained from this configuration.

Greenhouse gas emissions

Energy requirements for the proposed process are compared with the following commonly used desalination processes in Table 2 (Kalogirou, 2005): multi-stage flash distillation (MSF); multi-effect distillation (MED); mechanical vapour compression (MVC); reverse osmosis (RO); and electrodialysis (ED). The process developed in this study eliminates green house gas emissions by using renewable energy while the other processes consume non-renewable sources for thermal and mechanical energy requirements and with green house gas emissions contributing to global warming. In this comparison, 30% production efficiency for the production of electricity from fossil fuels is considered. The carbon dioxide emissions in Table IV are estimated based on the assumption that 1 kW-hr electricity production results in 0.96 kg of CO_2 emissions (DOE, 2000).

Table IV. Green house gas emissions by different desalination processes and this process

Process	Energy requirement [kJ/kg freshwater]		CO_2 emission
	Thermal	Mechanical	[kg/kg freshwater]
MSF	980	44	0.38
MED	410	26	0.16
MVC	0	192	0.07
RO	0	120	0.05
ED	0	144	0.05
Solar still	0	4	0.001
This process- Solar/PV	0	0	0

CONCLUSION

Numerical and experimental results are presented to show that the proposed low temperature desalination system has potential for both small and large scale applications. This system could be most suitable for remote areas without electrical grid. However, the benefit of utilizing natural vacuum principle to save mechanical energy needs has to be evaluated at a large scale to validate the process feasibility.

The proposed process has lower specific energy requirements compared to other single stage evaporation units. The performance of this system can be further improved by adding multi-effect configuration. Ability of this process to utilize renewable energy sources can minimize greenhouse emissions that contribute to global warming, making this a sustainable process. Recovering waste heat from other processes such as air-conditioning systems and power plants to drive this process can significantly improve the overall economies of the combined processes.

ACKNOWLEDGEMENTS

The research reported here was supported, in part, by a grant from the New Mexico Water Resources Research Institute (WRRI).

REFERENCES

[1] Al-Kharabsheh, S. & Goswami, D.Y., "Analysis of an innovative water desalination system using low-grade solar heat" , *Desalination.,* 156, 323-332, 2003

[2] Gude V., Desalination using low grade heat sources, PhD Dissertation, New Mexico State University, Las Cruces, NM, USA, 2007

[3] Wim, G.J. Helden., Ronald J.Ch.Z., and Herbert A.Z., "PV thermal Systems: PV Panels Supplying Renewable Electricity and Heat", *Progress in Photovoltaics: Research and Applications*, 12, 415-426, 2004

[4] Garg, H.P., and Agarwal, R.K., "Some aspects of a PV/T collector Forced Circulation Flat Plate Solar Water Heater with Solar Cells", *Energy Conversion Management*, 36, 87-99, 1995.

[5] Gude V., and Nirmalakhandan N., Desalination using low grade heat sources, to appear in *ASCE Journal of Energy Engineering, 2008*.

[6] Kaligirou, S. A. "Seawater desalination using renewable energy sources", *Prog. In Energy and Combustion ScI.*, 31, 242-281, 2005.

[7]http://www.eia.doe.gov/cneaf/electricity/page/co2_report/co2report.html#electric