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Integrated PV-thermal system for desalination and power production

Veera Gnaneswar Gude[a*], Nagamany Nirmalakhandan[a], Shuguang Deng[b]

[a]*Civil Engineering Department, New Mexico State University, Las Cruces, NM 88003, USA*
Tel.: +15307516061; Fax: +15418851654; email: gudevg@gmail.com
[b]*Chemical Engineering Department, New Mexico State University, Las Cruces, NM 88003, USA*

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ABSTRACT

A new process configuration for efficient utilization of solar energy for simultaneous production of potable water and electricity is presented. The proposed configuration incorporates photovoltaic/thermal (PVT) collectors to produce electricity and to collect thermal energy, which is used to drive a low temperature phase-change desalination process to produce potable water. This configuration takes advantage of the fact that PVT collectors operating at lower temperatures are more efficient than the traditional PV panels; and low temperature phase-change desalination processes are more efficient than the traditional ones. Results from the theoretical analysis and mathematical modeling of the integrated system show that the PVT area of 30 m^2 with a cooling mass flow rate of 40–50 kg/h m^2 is adequate to supply the electricity (16–18 kWh) and freshwater needs (120 L) of a household of four. A case study was conducted to study the annual performance of the integrated system to provide the needs of the freshwater and electricity. Based on the economic analysis, additional costs incurred to modify an existing PV system will result in freshwater costs of 12.9$/$m^3$ which is acceptable for small scale desalination systems.

Keywords: Desalination; Solar energy; Photovoltaic thermal collectors; Electricity; Renewable energy

1. Introduction

Incident solar energy, an abundant source of renewable energy, is said to be sufficient to support the energy needs of the world. For example, it has been reported that the annual solar radiation reaching the earth is 7,500 times the global annual electricity demand, which is about 450 EJ [1]. Collecting and converting solar energy to electricity can be a cleaner and sustainable approach as the conversion process does not emit environmental pollutants or greenhouse gases and the source is a renewable one. Photovoltaic (PV) cells with an input-to-output energy ratio of 1:7 are currently being used as solar energy harvesting factories in many domestic and industrial applications [2]. 70–80% of incident solar radiation on the PV panels is absorbed by absorber plate and rejected to the environment in the form of heat. As a result, it is very common that the PV laminate temperatures can reach as high as 35°C above ambient temperatures [3]. However, the performance of PV panels decreases as the panel temperature increases and the relationship between electrical power production by PV panels and panel temperature can be described by the following equation [4]:

$$P_e = \eta_{std}\{1 - 0.005(T_{pv} - 298.15)\} \quad (1)$$

where P_e is the electrical energy, η_{std} is the efficiency at the standard conditions and T_{pv} is the photovoltaic

*Corresponding author. Present address: Oregon Institute of Technology, Civil Engineering Department, 3201 Campus Drive, Klamath Falls, OR 97601, USA

panel operating temperature. Based on this equation, it can be seen that the power output can decrease by 22% when the temperature increases from 25 to 70°C. The energy absorbed by the panels is eventually dissipated to the environment.

In PVT collectors, thermal energy absorbed by the PV modules is harvested by a circulating cooling fluid, whereby the temperature of the panel is kept low maintaining a higher electrical efficiency compared to the panels without cooling fluid circulation. The outlet temperature of the circulating fluid can be as high as 60°C, which has the potential to serve as a low-grade heat source for many domestic and industrial applications [5–8]. The combined energy efficiency of PVT systems can be higher than PV and solar thermal collectors (SC) operated individually. It has been reported that 1 m^2 of the ST collector and 1 m^2 of PV would together yield 520 kWh thermal and 72 kWh electrical energy annually; whereas 2 m^2 of PVT collector would alone yield 700 kWh thermal and 132 kWh electrical energy [3]. Cost of the PVT system is equal to or 25% lower than the combined cost of solar collectors and PV panels [9]. The economic payback time is much shorter for PVT systems compared to PV modules [3,10]. The life cycle greenhouse gas emission of PV modules is only 30–45 gCO_2 equivalent/kWh compared to 960 gCO_2/kWh for coal-fired power plants [11–13]. In addition to the above advantages, other benefits of PVT systems include: (1) lower capital costs; (2) smaller footprint; (3) reliable source of thermal and electrical energy; (4) clean and environment-friendliness; (5) aesthetically pleasing without any noise pollution; and (6) low maintenance.

The performance of the photovoltaic thermal collector system depends on various factors such as collector type and design, packing factor, cooling fluid circulation rate and climatic conditions and therefore is site specific [14–17]. Thermal and electrical energy production efficiencies at different operating temperatures for different solar devices are presented in Fig. 1 [18,19]. From this comparison, it can be seen that the energy production is higher at lower operating temperatures regardless of the harvesting device whether PVT collectors, or ST collectors, or PV modules. To further improve the solar energy utilization, appropriate technologies have to be integrated to utilize the low-grade heat harvested by the circulating fluid. This means the energy harvested by the PVT sources will be best utilized if they are coupled with an energy-efficient process.

We have developed a low-temperature, low-pressure phase-change desalination process that can be driven by low-grade heat sources at temperatures as low as 50°C [20,21]. These studies have shown that

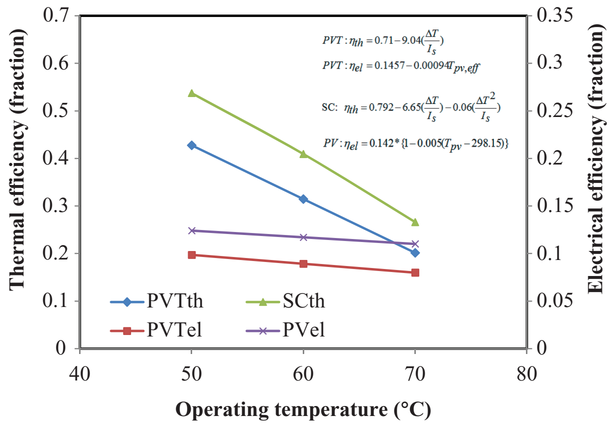

Fig. 1. Effect of operating temperature on the efficiency of PVT, PV and SC collectors.

this desalination system could produce freshwater at a rate of 4.5 kg/h by utilizing the waste heat released by a domestic absorption refrigeration system of cooling capacity of 0.975 tons. The auxiliary energy requirement for this process was 208 kJ/kg which is only 60% of that required by multistage flash distillation system (338 kJ/kg). Prototype performance evaluation of the process was also studied through experimental studies using grid energy, direct solar/PV energy and low grade heat sources [22–26].

In many applications, thermal energy extracted was used for hot water supply and heating and cooling applications. A multi-effect desalination configuration with the use of concentrating CPVT collectors was proposed by Mittelman [27]. However, this process may not be suitable for domestic and small scale applications due to higher initial capital costs. In this study, we are proposing a more beneficial and valuable application where thermal energy extracted by the PVT collectors through the circulating fluid is utilized to drive an energy-efficient low temperature desalination process. This combined process can provide the water and energy needs of a household in rural areas where the grid power is not available. Theoretical analysis of the proposed configuration, simulation results, and estimated energy costs for freshwater production indicate that the proposed approach has the potential to provide electricity needs as well as potable water needs in a cost-effective and sustainable manner, particularly for smaller communities in remote and rural areas.

1.1. Description of the integrated PV/T-Desalination system

The schematic of the integrated PVT Desalination system is shown in Fig. 2. The design of this integrated system is based on the electricity needs of a typical household with a regular demand of 14–16 kWh for

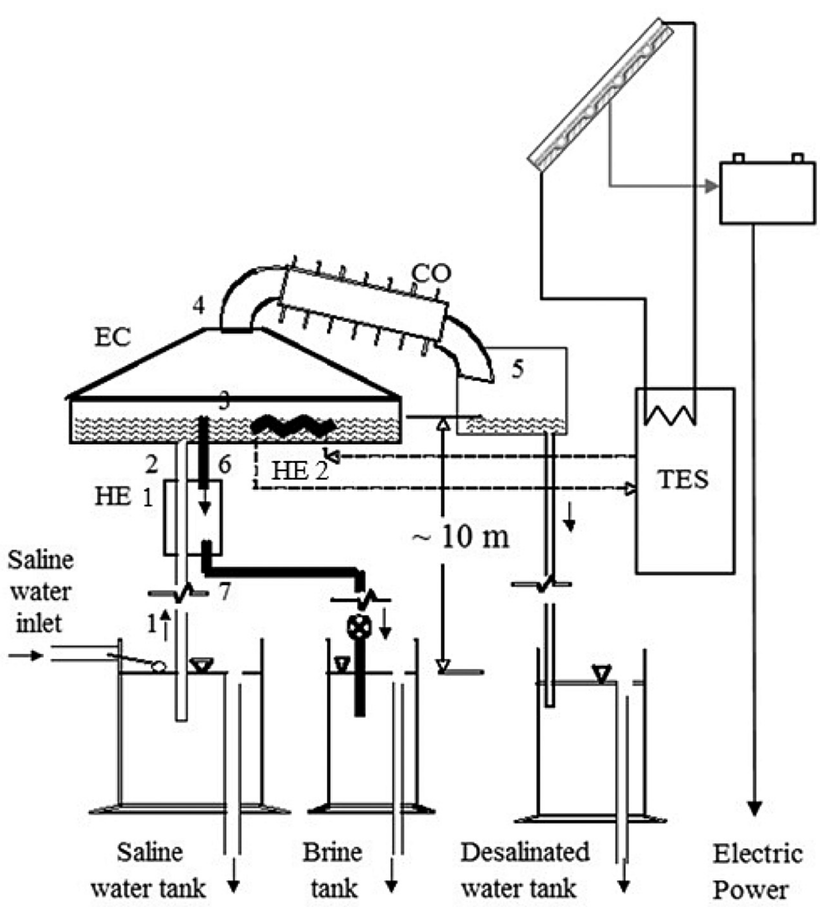

Fig. 2. Schematic of the integrated PV-Thermal-Low temperature desalination system.

domestic purposes. Details of the electricity needs and duration of the energy demand are provided elsewhere [28]. A glazed type PVT collector design was considered in the modeling studies. Thermal energy harvested by the circulating fluid in the PVT collectors will feed the thermal energy storage (TES) tank which in turn serves as the heat source to the low temperature desalination process described below.

1.2. Description of the low temperature desalination system

The schematic of the proposed low temperature desalination system is shown in Fig. 2. The major 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 circulating fluid from the PVT module provides the heat input to thermal energy storage tank and the TES tank supplies to the EC through the heat exchanger 2 (HE2).

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 within the desalination unit except for the start-up [29]. However, mechanical energy is necessary to circulate the heat transfer medium between the PVT collectors and the TES tank and the TES tank to the desalination unit. 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 10°C 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 40–50°C, which is in contrast to the 60–100°C 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.

2. Theoretical analysis

2.1. PVT collector system

Solar energy incident on the PVT collectors results in generation of both thermal and electrical energy. Part of the incident solar energy is lost to the environment by radiation and heat losses from the PVT collector materials. The energy balance on the PVT collector and the absorber plate can be written as follows [30]:

$$M_p C_p \frac{dT_{pvt}}{dt} = Q_s - Q_{ls} - P_e - Q_u, \tag{2}$$

where M_p and C_p are the mass and specific heat capacity of the absorber plate, Q_s is the incident solar energy, Q_{ls} are the losses from the PVT collector, P_e is the electrical energy derived from the module and Q_u is the useful energy (thermal) extracted by the collector fluid.

Solar energy absorbed by the PVT panel material is given as:

$$Q_s = I_s \tau_g \alpha_p. \tag{3}$$

Heat losses through radiation and convection from the PVT absorber plate to the glass cover can be written as [30]:

$$Q_{ls} = \varepsilon_a \varepsilon_g \sigma \left\{ T_p^4 - T_g^4 \right\} + h_{pg}\left(T_p - T_g\right). \tag{4}$$

Electrical energy generated by PVT collector system is given as [31]:

$$P_e = I_s \tau_g F_c \eta_{std} \left\{ 1 - 0.005\left(T_{pv} - 298.15\right) \right\}. \tag{5}$$

Useful thermal energy derived from PVT collectors can be expressed as:

$$Q_u = mC_{pf}(T_f - T_i), \tag{6}$$

where T_f is the collector fluid exit temperature and T_i is the collector fluid inlet temperature. m and C_{pf} are the mass flow rate and specific heat capacity of the collector fluid which is water in this case.

The circulating fluid exit temperature, T_f, can be calculated as follows [30]:

$$T_f = (T_{PVT} - T_i)\left\{ 1 - \exp\left(-4 * \frac{(x/d)Nu}{\text{Re. Pr}} \right) \right\} + T_i, \tag{7}$$

where T_{PVT} is the absorber plate temperature, x and d are the length and diameter of the circulating fluid tube, respectively.

Thermal and electrical efficiencies of the PVT collector at a given time are as follows [32]:

$$\text{Thermal efficiency of the PVT collector} = \eta_{PVT,thermal} = \frac{mC_{pf}(T_f - T_i)}{IA_c}, \tag{8}$$

$$\text{Total PV/Thermal Collector efficiency} = \eta_{PVT} = \frac{mC_{pf}(T_f - T_i) + P_e}{IA_c}, \tag{9}$$

where A_c is the collector area.

2.2. Prime energy saving efficiency

Thermal and electrical energies produced by PVT system differ from each other in that one is high-grade form of energy since it is converted from thermal energy. To account for the energy saving efficiency of the PVT system, the following expression known as *prime energy saving efficiency* can be used [33]:

$$\eta_{pes} = \frac{\eta_{el}}{\eta_{Tpower}} + \eta_{th}, \tag{10}$$

where η_{pes} is the primary energy saving efficiency, η_{el} is the PV conversion efficiency, η_{Tpower} is the conversion efficiency of a conventional thermal power plant (assumed to be 38%), and η_{th} is the thermal efficiency of the PVT system.

2.3. Low temperature desalination system

Mass and heat balances around the evaporation chamber (EC) yield the following coupled differential equations, where the subscripts refer to the state points shown in Fig. 2. The variables are defined in the Nomenclature.

Mass balance on volume of water in EC:

$$\frac{d}{dt}(\rho V) = m_2 - m_6 - m_3 \tag{11}$$

Table 1
Model parameters used in simulations for PVT collectors

Parameter		Parameter	
Cell material	Mono-Si	Material of absorber	aluminum
PV/T module area (m^2)	variable	Absorption factor, PV cell	0.9
Total PV/T module area (m^2)	20–30	Radiation factors, cover glass-ε_g and absorber ε_a	0.05, 0.75
Cell efficiency (%)*	17.5	Absorption factor, cover glass-ε_g and absorber ε_a	0.05, 0.16
Coefficient of temperature inversion (%/°C)	0.5	Collector fluid ($kg/hr/m^2$)	Water, 1-80

*At $T_a = 25°C$, $I_s = 1{,}000\ W/m^2$.

Mass balance on solute in EC:

$$\frac{d}{dt}(\rho VC)_{EC} = m_2C_2 - m_6C_6 \tag{12}$$

Heat balance for volume of water in EC:

$$\frac{d}{dt}(\rho Vc_pT)_{EC} = Q_{in} + (mc_pT)_2 - (mc_pT)_6 - m_3h_{L(t)} - Q_{l}, \tag{13}$$

where Q_{in} is the rate of heat input to the EC and Q_l is the rate of heat loss from the EC. The heat input to the EC is the useful heat extracted from the PVT collectors and stored in thermal energy storage tank and is given by:

$$\frac{v\,d(\rho c_pT)s}{dt} = Q_u - Q_{in} - Q_{lo} \tag{14}$$

where v is the volume of the storage tank, C_{ps} is the specific heat of the water in the storage tank, T_s is the storage tank temperature, Q_{in} is the heat supplied to the EC and Q_{lo} is the energy losses from the storage tank.

Actual amount of thermal energy supplied by the TES to the evaporation chamber, Q_{in} can be written as:

$$Q_{in} = m_SC_{ps}(T_S - T_{EC}) \tag{15}$$

where m_s is the mass flow rate of water from TES with specific heat C_{ps}

Desalination efficiency is defined as

$$\eta = \frac{Mh_{L(T)}}{\sum(Q_{in}\Delta t) + Q_p}, \tag{16}$$

where

$$h_{L(T)} = 3.146 - 2.36(T + 273) \tag{17}$$

and Q_p is the mechanical energy (pump) required for heat transfer.

Evaporation rate as a function of pressure and temperature [34]:

$$m_3 = A_{EC}k\left[f(C_{EC})\frac{p(T_{EC})}{(T_{EC}+273)^{0.5}} - \frac{p(T_5)}{(T_5+273)^{0.5}}\right] \tag{18}$$

where

$$p_{(T)} = [\exp(63.02 - 7139.6/(T + 273) - 6.2558\ln(T + 273))] \times 10^2\ \mathrm{Pa} \tag{19}$$

The above equations were solved using Extend (ImagineThat Inc., San Jose, CA) simulation software. This simulation software is widely used by many professionals around the world in academic, business and engineering projects to derive solutions for real world, scientific and technical processes and problems [35]. Heat losses and latent heat dissipation through the condenser and the design procedure are presented elsewhere [20,23].

3. Results and discussion

3.1. Integrated PV-Thermal desalination system

Numerical simulations have been performed for a site in southern New Mexico. Solar insolation and ambient temperature data were extracted from Renewable resource data center, NREL, USA [36]. Parameters used in numerical simulations are presented in Table 1 for the PVT collector system. The solar insolation and ambient temperatures on a summer day in June varied between 225 and 1,100 W/m^2 and 16–33°C, respectively. Hourly solar insolation and the ambient temperatures for a typical summer day in the month of June are shown in Fig. 3. The temperature profiles for the PVT system are shown in Fig. 4. The absorber plate temperatures reached up to 68.7°C while the collector fluid temperature reached 64.5°C in the middle of the day. The average temperature of the collector fluid was 60.8°C which maintains the absorber area at lower

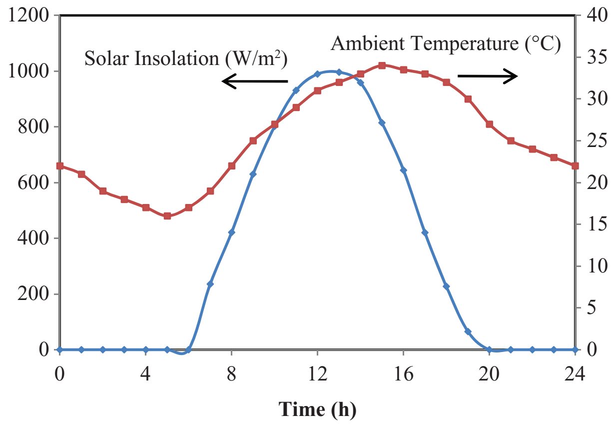

Fig. 3. Hourly solar insolation and ambient temperature profiles for a summer day in June.

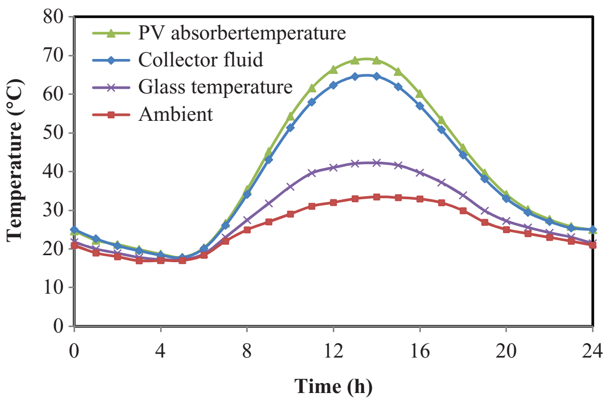

Fig. 4. Temperature profiles of the PVT system in a day.

temperatures. The temperature of the absorber plate will be much higher without the collector fluid circulation as discussed later in Section 3.1.2. The glass cover was in contact with the ambient air and reached a maximum temperature of 43.1°C while the maximum ambient temperature was 33°C. In this simulation, the mass flow rate of the circulating fluid was 40 kg/h m^2. The volume of the TES was 1 m^3 with a volume to collector area ratio of around 40 L/m^2.

Thermal and electrical energy production rates and their efficiencies during sunlight hours are shown in Fig. 5. Thermal energy is the useful energy extracted by the circulating fluid in the PVT collector. Total PVT system efficiency of 59.4% and thermal efficiency of nearly 50.5% is predicted. These results are comparable with the previous studies [7,37,38]. The primary energy saving efficiency of PVT system is predicted as 72.7%, which considers the total energy that will otherwise be required to generate the electricity by a conventional power plant. A photovoltaic collector (Sharp NT-S5E1U,

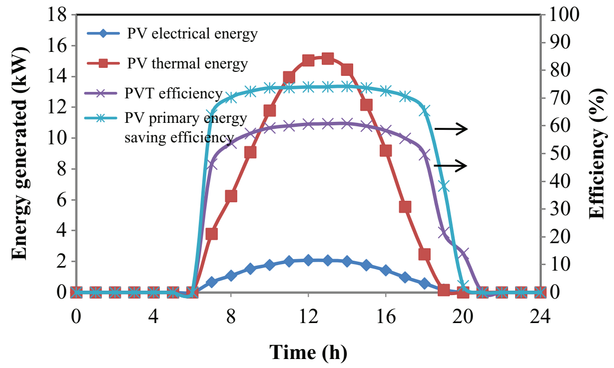

Fig. 5. Energy and efficiency profiles of the PVT system in a day.

cell efficiency 17.5% and module efficiency 14.2%) was used in these simulations. It is well known that the PV cell efficiency would decrease with increasing absorber plate temperature. The electrical efficiency of the PVT system varied between 12.5% and 8.5% during the sunlight hours.

3.1.1. Low temperature desalination system driven by PVT system

Useful energy extracted from the PVT system was used as the heat source to drive the desalination system. Process parameters used in the numerical simulations are presented in Table 2. The mass flow rate of the circulating fluid between the TES and the evaporation chamber was fixed at 60 kg/h m^2 in these simulations. The resulting evaporation temperatures in the desalination system and freshwater and ambient temperatures are shown in Fig. 6. The maximum saline water temperature in the evaporation chamber is predicted as 51.2°C at the maximum TES and ambient temperatures 57.2 and 33°C, respectively. The saline water temperature decreased with the collector fluid temperature and eventually reached ambient temperatures during non-sunlight hours. The useful energy supplied to the evaporation chamber and the energy utilized for evaporation of freshwater is shown in Fig. 7. The energy losses from the evaporation chamber ranged between 10% and 20% of the total useful energy supplied resulting in 80–90% evaporation efficiencies. The hourly freshwater production rate is shown in Fig. 8. As expected, the evaporation rate increased with increase in the heat source temperature and a maximum evaporation rate of 15 kg/h is obtained. The cumulative amount of freshwater produced from the desalination system under the specific conditions was 120 kg/d. The mechanical energy required to circulate

Table 2
Model parameters used in simulations for desalination system

Parameter		Value	Parameter		Value
Evaporation chamber (EC) area	m^2	1–5	Solar insolation	W/m^2	200–1000
Condenser area	m^2	1–5	Seawater concentration	%	3.5
Water depth in the SEC	m	0.05–0.1	Seawater density	kg/m^3	1,020
Height of SEC	m	0.5	Seawater, TES reference temperature	°C	25
TES volume	m^3	1	Ambient temperature	°C	−3 to 35

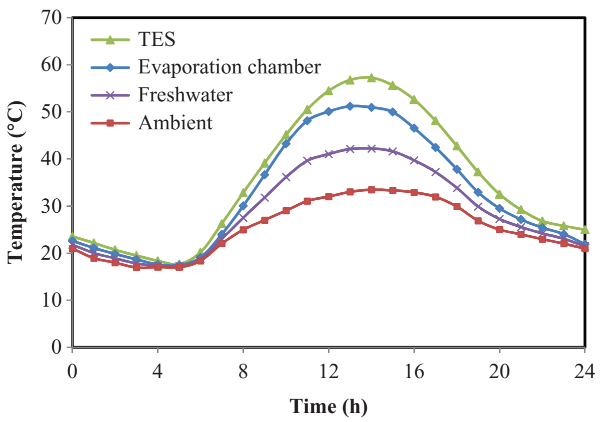

Fig. 6. Temperature profiles of the low temperature desalination system driven by PVT system during a day.

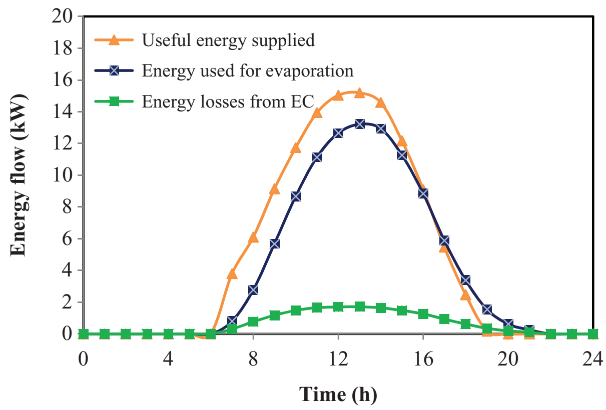

Fig. 7. Energy supply and utilization in evaporation chamber during a day.

the collector fluid is calculated as 4 kJ/kg of freshwater produced.

3.1.2. *Optimization of circulating fluid mass flow rate*

The key parameter that influences the design and operating costs of the PVT system is the circulating fluid flow rate. It is very important to optimize the mass flow rate of the circulating fluid to gain the maximum thermal and electrical energy efficiency of the integrated PVT Desalination system. The effect of circulating fluid mass flow rate was studied through simulations in the range of 1–80 kg/h m^2. In many previous theoretical and experimental studies, a range of circulating fluid rates (5–100 kg/h m^2) was used in other applications [39–42]. The effect of the circulating fluid flow rate on the integrated PVT-desalination system is shown in Fig. 9. Fig. 9a shows the effect of mass flow rate (water) on the PVT collector temperatures. The absorber plate temperature reached a value of 101°C at a flow rate of 1 kg/h m^2 which is also known as the stagnation temperature. Since this is a glazed type PVT collector, the heat will be trapped in the collector within glass cover if the mass flow is not adequate. Electrical efficiencies of the photovoltaic cells will be adversely affected and probably resulting in damage of cells. As the mass flow rate was increased, the absorber panel and the circulating fluid temperatures decreased. At the same time, when there was little to no mass flow rate (∼1 kg/h m^2), the TES and evaporation chamber temperatures were in the range of 25–32°C which are not suitable for low temperature desalination. As the mass flow rate increased, the TES and evaporation chamber temperatures increased (50–57°C) as thermal energy was extracted from the PVT collectors. However, it should be noted that the mass flow rate had significant effect on the circulating fluid, TES and EC temperatures only until the flow rate of 40 kg/h m^2, above which the effect was minimal. Similar trends were observed for thermal and electrical efficiencies of the PVT system (Fig. 9b). They increased with increase in mass flow rate up to 50 kg/h m^2 and remain unchanged at higher mass flow rates. The effect of mass flow rate on the freshwater production is shown in Fig. 9c. Similar to temperature and efficiency profiles, the freshwater production rate increased up to the mass flow rate of 50 kg/h m^2, above which thermal energy available for desalination from TES was not significant. A maximum hourly fresh water production rate of 15 kg/h with a cumulative product of 120 kg/d was observed at this flow rate. Based on the above analysis, an optimum mass flow

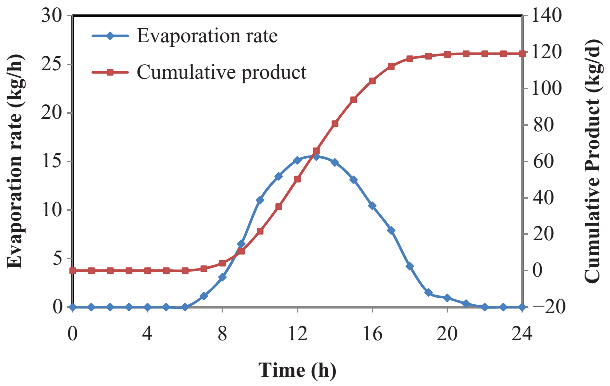

Fig. 8. Freshwater production rate and cumulative product during a day.

rate of circulating fluid (water) would be in the range 40–50 kg/h m^2. Since this flow rate is determined based on summer conditions, the same flow rate is sufficient for winter conditions as well, as the temperature gradient in the circulating fluid will be even higher.

3.1.3. Annual performance of the PVT system

It is important to understand the energy production rates from the PVT system on an annual basis. Design considerations for a PVT system for electricity production depend on the local availability of other energy supplies. If the system has to be stand-alone or off-grid, then the capital costs for the system can be high since the system needs to be designed to account for low solar insolation rates and cloud cover effect during winter conditions. However, if a local energy source is available such as grid energy, the PVT system can be designed to meet the energy needs based on summer weather conditions.

3.1.4. Annual thermal and electrical energy production

The average solar insolation for the City of Las Cruces in southern New Mexico has a minimum of 250 W/m^2 and a maximum of 620 W/m^2. The ambient temperature can be as low as −3°C and as high as 35°C. Average monthly thermal and electrical energies generated by PVT system under the above conditions are shown in Fig. 10. Annual thermal and electrical efficiency of the PVT system is shown in Fig. 11. As expected, both thermal and electrical energies produced by PVT system are low during the winter due to lower solar insolation rates and ambient temperatures, and higher wind and cloud cover effects. Therefore, it is necessary to design a PVT system based on winter conditions for remote applications. However, it should be realized that capital costs for such system will be much higher producing additional thermal and electrical energies in summer conditions. For economical design, an optimum collector area should be determined which is 30 m^2 having the capacity to produce electrical energy 14–18 kWh/d and freshwater production capacity of 90–150 kg/d. This collector area is 15–20% higher than the minimum required based on summer conditions to account for weather conditions in the winter.

3.1.5. Energy and carbon emissions payback period

Production of PV modules involves utilization of energy and material resources. Energy generation and manufacturing process, ultimately, result in environmental pollution and greenhouse gas emissions. A summary of energy cost requirements and the CO_2 emissions for PV module manufacturing are presented in Table 3. However, once in operation, by using PV modules CO_2 savings in the range 270–1,050 g/kWh can be achieved depending on the regional fossil fuel mix and solar irradiance [43,44]. An average savings value of 662 gCO_2/kWh was used to calculate the payback period for the PV module area under study. The payback period for recovering the energy investment is around 5.5 years even with 50% of the design capacity and so is the carbon emissions payback period. These calculations are based on the electrical energy generated by the PVT collectors alone; the payback periods will be much lower if thermal energy production rates are taken into account.

3.2. Desalination cost analysis

An analysis on the cost requirements of the desalination system has been performed. Rather than investing in new PVT collectors, the simple way to convert the existing PV module is to incorporate heat exchanger to extract thermal energy [45]. Total capital and equipment costs are shown in Table 4 for construction of a glazed type PVT collector area of 30 m^2. Desalination costs are determined based on the assumption that the investment is financed at an annual interest rate of 5% over the lifetime of 25 years for the desalination system [46–48]. The following equations can be used to calculate the unit cost of the desalinated water produced from the integrated PVT-desalination system.
where a is the amortization factor, n is the life time of the plant, i is the annual interest rate (%), f is the plant availability and M is the quantity of produced water (kg).

Amortization factor	Annual capital and operating costs	Unit product cost
$a = \frac{i(1+i)^n}{(1+i)^n - 1}$	$A_{total} = A_{fixed} + A_{replacement} + A_{O\&M}$	$A_{unit} = \frac{A_{total}}{(f^*M)^*365}$

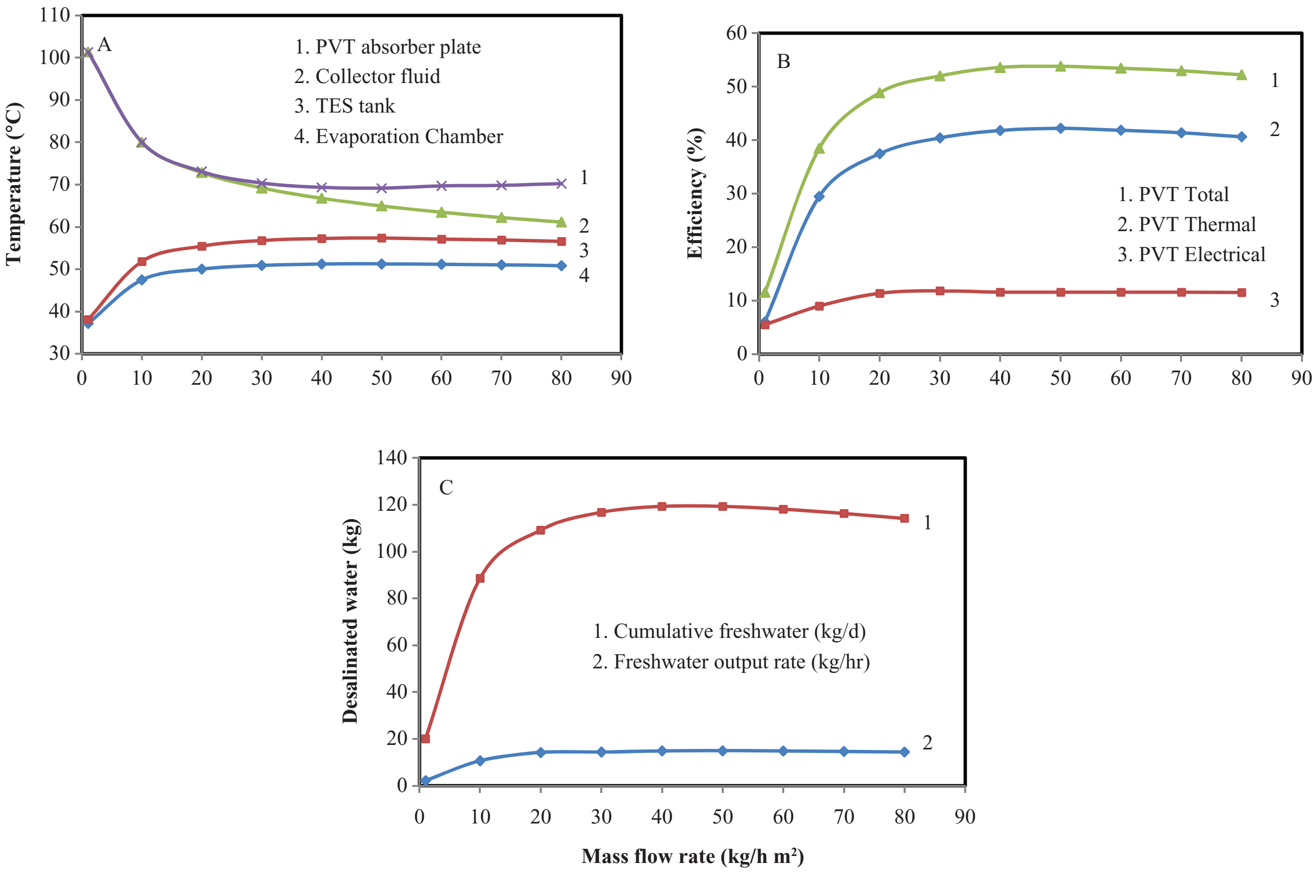

Fig. 9. Effect of mass flow rate on the integrated PVT Desalination system.

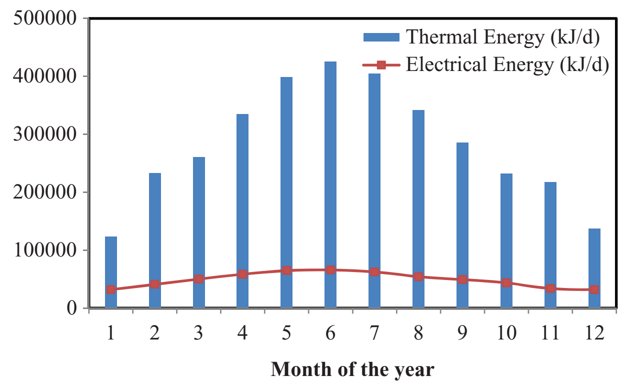

Fig. 10. Annual thermal and electrical energy production.

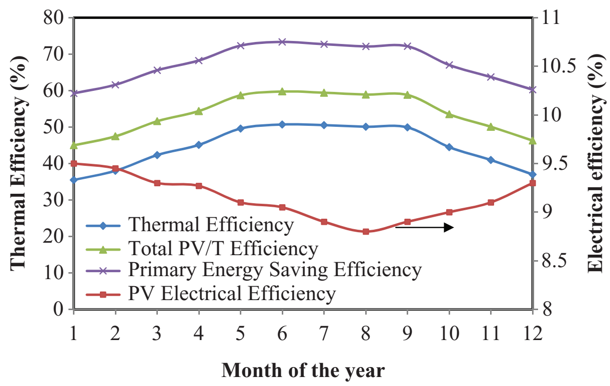

Fig. 11. Annual thermal and electrical energy efficiency of the PVT system.

Based on annual performance and above economic analysis, average cost for unit desalinated water is determined as 1.3¢/L or 13$/m^3 for a single stage low temperature desalination unit. Seasonal variation in desalinated water cost is shown in Fig. 12. Desalination cost can be improved with multi-effect operation of the process similar to multi-stage flash distillation (MSF), and multi-effect distillation (MED) processes. A comparison of desalination cost with other conventional desalination processes powered by renewable energy sources is shown in Table 5 [47,48].

4. Conclusions

The feasibility of integrating a PVT collector system to drive a low temperature desalination

Table 3
Energy and carbon emissions payback period

Description	Unit	Value
Energy cost of the PV module	kWh/m^2	600
CO_2 emissions in energy production	kg/kWh	0.66
CO_2 emissions generated to manufacture PV module	kg/m^2	397
Total PV area in this study	m^2	30
Total energy required to produce PV modules	kWh	18,000
Total CO_2 emissions	kg	11,916
Total electricity generated per day (Design capacity)	kWh	18
Annual energy production (100% design capacity)	kWh	6,570
CO_2 emissions eliminated in a year	kg	4,349
CO_2 emissions payback time	yr	2.7
Energy payback time	yr	2.7
Annual energy production (50% design capacity)	kWh	3,285
CO_2 emissions eliminated in a year	kg	2,175
CO_2 emissions payback time	yr	5.5
Energy payback time	yr	5.5

Table 4
Costs to modify the existing photovoltaic modules and for desalination unit

Item description	Cost ($)
Additional cost due to modification	2,000
Heat exchanger, evaporator and condenser	2,000
Pumps	300
Storage tank	300
Total equipment cost	4,600
Annual interest rate (%)	5
Plant life expectancy (Years)	25
Operation and Maintenance (%)	10
Replacement costs (%)	10
Total investment ($)	5,500

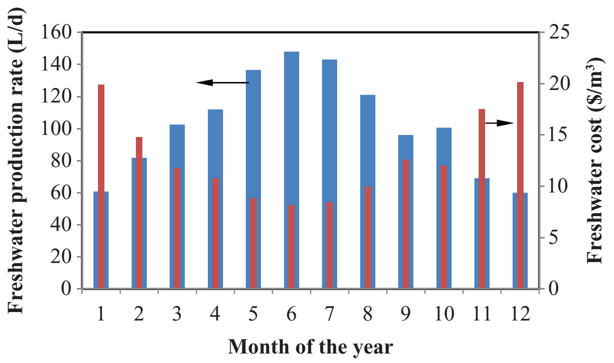

Fig. 12. Seasonal variation in the desalination costs of the integrated process.

Table 5
Desalination cost comparison with other desalination processes

Process	Capacity (m^3/d)	Cost ($/$m^3$)
Solar Still	0.5–1	12–12.50
Multi effect distillation (MED, solar)	85	7–10
PV-Reverse Osmosis	1	12.05–15.60
Membrane Distillation (solar)	<1	13–18
PV-Thermal desalination (single stage)	<1	12.9

system has been studied. A glazed type PVT collector was used in the simulations with a thermal storage tank to provide the thermal energy needs for desalination. The mass flow rate of the circulating fluid was optimized based on the performance of both the PVT collector and desalination systems. It was observed that a mass flow rate of 40–50 kg/h m^2 was sufficient to drive both the systems at maximum efficiencies. A case study was performed to analyze the annual performance of the system. The integrated PVT desalination system was able to provide a household with both energy and freshwater needs. The combined system could provide a household a maximum of 18 kWh/d of electrical energy and 150 L of freshwater. The energy and carbon emissions calculations show that the integrated system has a payback period of less than 6 years even when operating at 50% of the design capacity based on electrical energy production alone. Freshwater costs for single stage desalination unit were found to be round 13 $/$m^3$ which is an acceptable value for a small size desalination plant. The integrated system best utilizes solar thermal energy harvested by providing it as a heat source to the low temperature desalination system and is a viable option for remote and rural applications.

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Nomenclature

A	area [m^2], annual costs
c_p	specific heat capacity of saline water [kJ/kg°C]
C	solute concentration [%], specific heat capacity [kJ/kg°C]
d	diameter of the circulating fluid tube [m]
F	heat removal factor [dimensionless], packing factor [%]
$f(C)$	correlation factor for the presence of solute concentration [%]
h	latent heat [kJ/kg], heat transfer coefficient (convective) [kJ/h m^2°C]
I	solar insolation [kJ/h m^2]
m	mass of water [kg]
Q	energy flow [kJ/hr]
q	evaporation rate [m^3/s]
Re	Reynolds number
Pr	Prandtl number
Nu	Nusselt number
T	temperature [°C]
U	heat loss coefficient [kJ/h m^2°C]
V	volume of water in EC [m^3]
x	length of the circulating fluid route [m]

Subscripts

a	ambient, amortization factor
c	cell, collector, specific heat
d	desalination system
e,E	electrical, evaporation, evaporated
el	electrical
EC	evaporation chamber
f	fresh, circulating fluid exit, amortization factor
g	glass
i	inlet
I	solar insolation
In	supplied
l,lo, ls, L	latent heat, losses
p	panel, photovoltaic, absorber plate, pressure and pump
pv	photovoltaic module
pes	prime energy saving
PVT	photovoltaic thermal collector
r	radiative, absorber
s	saline water, solar energy, storage tank, surface
std	standard or reference
T_{power}	power plant efficiency
u	useful
w	withdrawal
v	volume of storage tank

Greek Symbols

α	absorptivity [dimensionless]
α_m	an experimental coefficient [10^{-7} – 10^{-6} kg-$K^{0.5}$/m^2-Pa-s]
ρ	density [kg/m^3]
τ	transmitivity of glass [dimensionless]
ν	volume of the thermal energy storage system [m^3]
ε	radiation factor
σ	Stefan-Boltzmann constant, (5.7×10^{-8} W/m^2K^4)

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