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# Humidification–dehumidification desalination process driven by photovoltaic thermal energy recovery (PV-HDH) for small-scale sustainable water and power production

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## HIGHLIGHTS

- Recovery of thermal energy from PV panel in a theoretical HDH desalination setup.
- The PV-HDH system produces 833 L/m$^2$PV of water and 278 kWh/m$^2$PV of electricity.
- The PV-HDH showed 83.6% reduction in environmental impacts when compared with PV-RO.

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## ABSTRACT

Humidification–dehumidification (HDH) desalination technology with the use of recovered photovoltaic (PV) thermal energy could be viable for the production of small-capacity sustainable water and improvement of PV electric power generation efficiency. This paper investigates the technical feasibility and environmental friendliness of an air-cooled PV system integrated with ambient seawater inflow into a HDH desalination system. The technical analysis of the PV-HDH desalination process was carried out through the modeling of the physical and thermodynamic properties involved in the recovery of PV thermal energy and determination of the effect of this recovery on water produced under the environmental conditions of Abu Dhabi, UAE. The results showed that the heat recovered from the PV resulted in the production of a daily average of 2.28 L of fresh water per m$^2$ of PV. On the other hand, the environmental impact assessment of this PV-HDH power and desalination technology was also carried out for the first time in order to determine its viability for small-scale sustainable water and energy production. The PV-HDH system resulted in 83.6% decrease in environmental impacts when compared with PV-Reverse Osmosis (PV-RO) system. In conclusion, the integrated PV-HDH desalination technology is promising and expected to play a key role in the field of water desalination.



## 1. Introduction

The adverse outcomes of the exploitation and application of fossil fuels have necessitated the development of renewable energy sources for seawater desalination [1]. In particular, solar humidification–dehumidification (HDH) process can provide a small-scale clean energy source for water production [2,3]. In solar HDH process, ambient air or water is heated by a solar heat source and the circulating air humidity is increased to near saturation in the humidifier, at the required design temperature. The humidified air is then passed through a condenser (or dehumidifier) to condense out part of the air humidity as distillate. HDH cycle is preceded by the solar still technology, as a direct solar desalination technology where only heat (and not electricity) is obtained from solar radiation [4–6]. Some theoretical and experimental analyses have shown the suitability of solar stills for sustainable water production [7–9]. Interesting research results have been obtained using the solar still and continued efforts have been made to optimize this technology. In order to improve system productivity, different design configurations and operating conditions of solar still technology have been tested such as multi-stage stacked tray design [10], a double-condensing chamber [11], use of energy storage element [12], use of a concave wick evaporation surface [13], and basin type systems [14]. In the solar still of Fath et al.[2], for example, the system productivity was partially improved from 5.2 to 5.3 L/m$^2$ by decreasing airflow rate from 0.1 to 0.001 kg/s using natural circulation system. Also, Velmurugan et al. attempted to improve solar still productivity by 29.6% by integrating fins at the still basin [4].

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**Nomenclature**

| | |
|---|---|
| $b$ | breadth of PV module = 0.45 m |
| $c_a$ | specific heat capacity of air = 1005 kJ/kg · K |
| $h_i$ | specific enthalpy of stream $i$ |
| $h_{p1}$ | penalty factor due to the presence of glass cover = 0.9782 |
| $h_{p2}$ | penalty factor due to the presence of interface between glass plate = 0.58 |
| $I(t)$ | incident solar intensity (W/m$^2$) |
| $L$ | length of the PV panel = 1.2 m |
| $P_a$ | total pressure of moist air = 101.2 kPa |
| $P_{air}$ | partial pressure of dry air |
| $P_{s,i}$ | vapor pressure of air in stream $i$ |
| RH | relative humidity of air |
| $S_{w2}$ | salinity of seawater into the humidifier = 35,000 ppm |
| $S_{w3}$ | salinity of brine out of the humidifier |
| $T_a$ | ambient temperature |
| $T_{air,in}$ | inlet air temperature into air gap |
| $T_{air,out}$ | outlet air temperature from air gap |
| $T_c$ | temperature of solar cells |
| $T_{dh}$ | temperature of dehumidified air = 293.2 K |
| $T_f$ | average temperature of air inside the air gap |
| $T_p$ | temperature of glass plate at the back side of PV |
| $U_{bp,a}$ | overall heat transfer coefficient from back plate to ambient |
| $U_l$ | heat transfer coefficient from PV cells to ambient through top and back surfaces (W/m$^2$) |
| $w_i$ | specific humidity of air in stream $i$ |
| $m_a$ | mass flow rate of air into PV gap and humidifier = 4.0 kg/h |
| $m_{da}$ | mass flow rate of dry air into humidifier |
| $m_{w2}$ | mass flow rate of seawater into humidifier = 3.6 kg/h |
| $m_{w3}$ | mass flow rate of brine out of humidifier |
| $\alpha_c$ | absorptivity of solar cells = 0.9 |
| $\alpha_p$ | absorptivity of back glass plate 0.8 |
| $\beta_c$ | packing factor of solar cells = 0.83 |
| $\beta_o$ | temperature coefficient of solar cells 0.0045 |
| $\eta_0$ | reference or solar cell efficiency = 15% |
| $\eta_{el}$ | electrical efficiency of solar cells |
| $\tau_g$ | transmittivity of glass cover of PV panel 0.95 |

The solar still technology, however, offers very little chance for large-scale and widespread use in the seawater desalination market due to its low efficiency and Gain Output Ratio (GOR). This is because most of the latent heat of condensation of water vapor is lost at the cover of the still and all the main processes of heating, evaporation and condensation take place within a single component [15,16]. HDH process, however, separates the humidification and dehumidification processes into distinct processes in different components [17–19] where improvement in each process can take place. On the other hand, when PV panel is used to generate electricity, heat is dissipated together with the electrical energy produced [20]. This heat will normally build up due to resistance to heat transfer provided by the heat transfer surfaces in the PV panel, thereby leading to reduction in electrical efficiency of the PV [21]. However, the heat can be recovered by cooling the PV panel through the use of cooling medium such as air or water [22,23]. The recovery of thermal energy would lead to the reduction of temperatures of the heat transfer surfaces in the panel and increase in panel's efficiency [24]. For example, for a standard PV panel operating at temperature over 25 °C, the electrical power drops by about 0.5% for every 1 °C increase in temperature. In the PV-HDH system studied in this paper, the thermal energy recovered from the PV panel is used as the heat source to desalinate saline water through HDH process. This PV-HDH hybrid system consists of two units: PV panel cooled by circulating air, and the HDH desalination system. Like distillation processes, PV-HDH ensures pure water production from saline water.

According to Lattemann and Höpner, some of the key issues which pose threats to the environment in a thermal desalination process include the emissions of air pollutants from the fuel source during thermal energy generation and other impacts from the inputs and wastes from the process [25]. In the present study, the environmental sustainability of the PV-HDH method has also been carried out in order to evaluate the adverse impact of this method on the environment. The environmental sustainability of the PV-HDH system has been studied, while accounting for the electrical and recovered thermal energy of the PV which are available for use. The technical modeling of water and energy production from the integrated system has been carried out in order to estimate the operational feasibility of the system. The environmental impacts of the system have also been compared with those of current conventional PV-RO system. According to our literature search, this environmental impact assessment has been carried out in this paper for the first time. This paper considers the use of PV-HDH system as an alternative desalination method for small-scale applications, most particularly in areas not connected to the grids powered by conventional fuel sources.

In the present PV-HDH system, PV air cooling takes place in the air gap at the back of the PV panel and saline water is fed to the humidifier where it is partially evaporated by the heated air from the PV gap. Consequently, the heated air from the PV gap becomes saturated moist air in the humidifier. The saturated moist air from the humidifier outlet is then fed to the dehumidifier where the moisture (pure water) is partially condensed and collected.

## 2. System description

Fig. 1 illustrates the studied PV-HDH system. The analyzed system has been designed as a simple unit in order to reduce the capital costs. A closed air and open water cycle was used for the system. Air was considered to be fed to the air gap at the back of the PV through an electric fan. The air would then cool down the PV panel, become heated in the air gap and humidified by sprayed saline water in the humidifier. The air outlet from the humidifier was considered to be saturated with moisture and passed to the dehumidifier shell where it would be dehumidified by cooling it down to another saturation point (designed as 20 °C) with the aid of cooling water (CW) fed to the tubes inside the dehumidifier shell. This would ensure the partial condensation of the saturated vapor in the air and production of fresh water in the dehumidifier. The partially dehumidified air can then be recirculated to the back of the PV panel to continue the cycle.

## 3. System simulation

The mathematical modeling of the PV-HDH system was carried out using the environmental conditions in Abu Dhabi, UAE. UAE was selected because it is one of the countries where desalination is particularly relevant, although the methods used are applicable beyond UAE. Apart from this, the high solar intensity in the country resulting to arid climatic conditions was of interest. The environmental data for Abu Dhabi, UAE, was obtained from the weather station at Masdar City, Abu Dhabi. This data contained the values of each of the environmental variables – solar irradiance, ambient temperature and relative humidity – for every hour of the entire year. These environmental variables were used as the input variables in the model equations. Since the values of these input variables have been provided in the environmental data for every hour of the year, the average hourly values of these variables for each month have also been computed using MATLAB R2014b. This computation was carried out so that the average hourly variation of output variables in each month can be obtained. Because of the aridity and stable environmental conditions in UAE, there are negligible variations in the environmental data every year. The design simulation was