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To cite this article: B Anand and S Murugavelh 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **312** 012030

IOP Conf. Series: Earth and Environmental Science **312** (2019) 012030 doi:10.1088/1755-1315/312/1/012030

Techno-economic analysis of solar trigeneration system

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Abstract. In this work, a techno-economic analysis of concentrated photovoltaic/thermal collector (CPVT) driven desalination and cooling plant is presented. The system comprises of a CPVT collector, a humidification-dehumidification (HDH) desalination unit and vapour compression refrigeration (VCR) unit. The CPVT collector having 10 m^2 aperture area and a triple junction PV panel placed at the receiver supplies required hot water to the HDH desalination system. Chilled water generated from 0.5 hp compressor operated VCR unit is supplied to the dehumidifier of HDH desalination. The process of cooling and dehumidification using chilled water result in increased desalination yield and resulting air is suitable for air conditioning purpose. The work is aimed to evaluate the annual performance of the trigeneration plant and to estimate the unit cost of fresh water and payback period. The annual performance of the plant is evaluated for the typical metrological year data for the location of Vellore, India. Results show that the annual desalination, electricity and cooling output are 4.2 m^3/ yr and 3.46 MWh/yr and 0.788 MWh/yr respectively. The daily average desalination and cooling output are 11.12 L/day and 2.47 kWh/day respectively. The annual electricity consumption of the solar cogeneration plant is 6570 kWh/yr. The estimated unit cost of fresh water is ₹10/L. By considering the interest rate of 9 % and total life time of the plant as 20 years, the payback period is estimated to be 6.5 years.

1. Introduction

The solar cell efficiency drops with increase in temperature of solar cell. The solar cell efficiency also depends on solar radiation. The commercial solar cell efficiency varies from 10 % to 20 % and remaining energy is wasted as heat loss [1]. A well proven method to improve the conversion efficiency is recovering the waste through process integration [2]. A Photovoltaic/Thermal panel (PVT) simultaneously generates electricity and thermal energy. This is achieved by circulating a cooling medium such as air, water behind the PV panel [3]. The cogenerated heat from the PVT panel is also used in domestic application such as space and water heating [4]. A concentrated PVT system is combination of solar concentrating collector and PVT panel. The PV panel in CPVT collector is triple junction PV panel and it can withstand temperature up to 240 °C [5]. The CPVT coupled with water desalination performance better than other solar desalination technologies [6]. A solar heating and cooling system based on CPVT operated vapor absorption chiller resulted in high primary energy savings [7]. A novel heat pump integrated with PVT system, result in average COP of 4.8 while generating hot water at 70°C [8]. A high concentrating CPVT collector integrated with space cooling system having combined efficiency of 87.5 % [9]. From the literature studies, the CPVT technology perform better than individually operated system. Further, very few studies are carried out to integrated cooling and desalination. This result in increased desalination and resulting air suitable for air conditioning. But, these technologies require hot water for desalination and electricity to run VCR (Vapor Compression Refrigeration) unit. In such cases PVT collector will require more land are and the hot water from PVT panel are at low temperature. In this case, CPVT collector with high conversion efficiency, and high hot water temperature will make the plant self-sustained. In this work, a detailed mathematical modelling and CPVT operated desalination and cooling plant is carried out. Further, a detailed economic analysis of the plant is also carried out to evaluate the unit cost of fresh water and payback period.

2. Plant description:

The schematic process flow diagram of CPVT operated desalination and cooling plant is shown in figure 1. The plant consist of a CPVT collector, a HDH desalination unit, a vapour compression refrigeration unit, a blower and pump. The CPVT collector is made of 10 m^2 aperture area, a triple junction solar cell placed at the receiver. The HDH unit consists of a humidifier and dehumidifier. The humidifier receives required hot water from CPVT collector and the dehumidifier receives chilled water from the VCR unit. Initially the temperature of the solar cell is high as the concentrated solar radiation is focused on it. At high temperature the electrical conversion efficiency of the solar cell is very low. In order to reduce the cell temperature a cooling medium is supplied to the heat transfer pipes attached back of the PV panel. This result in increased electrical conversion efficiency and hot water suitable for thermal desalination process. The CPVT system is modelled based on the hot water and electricity requirement of the desalination and cooling plant. The temperature of the solar cell and hot saline water to humidifier can be controlled by controlling the saline water flow rate. A blower supplies air at ambient condition from bottom of the humidifier. After heat transfer in CPVT collector, the hot saline water enters the humidifier where simultaneous heat and mass transfer occurs between air and hot water. This result in heating and humidification of air. The hot humid air leaving the humidifier is then entering the dehumidifier. In dehumidifier, the moisture content in the hot humid air is cooled and dehumidified using chilled water. This result in increased desalination yield and air coming out of the dehumidifier is at low temperature suitable for air conditioning.

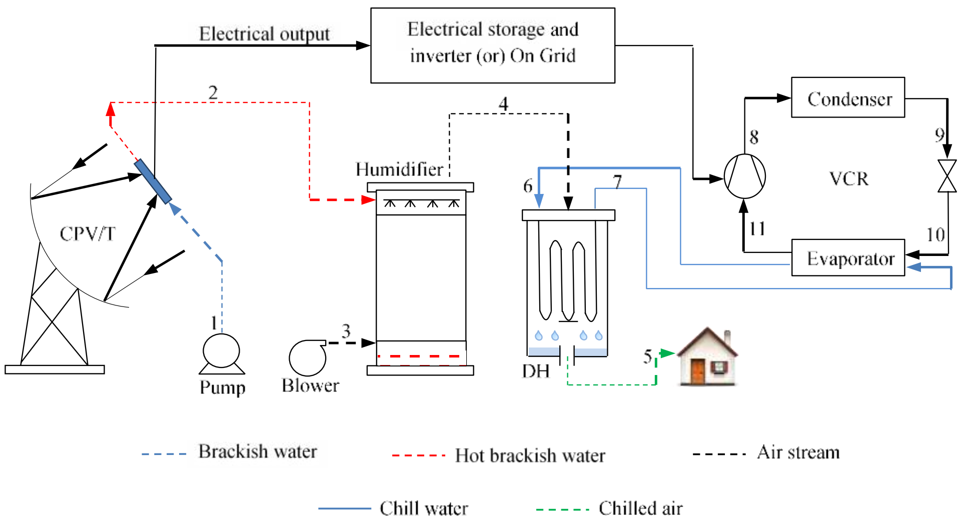

Figure 1. Schematic view of CPVT operated desalination and cooling system

3. Economic analysis of solar tri-generation plant

In this section, a detailed economic model is developed to estimate the unit cost of fresh water payback period of CPVT operated desalination plant. The total direct capital cost the plant is given in table 1 and the details of financial parameters considered in this work is shown in table 2. The unit cost of the fresh water (C_{FW}) is the ratio of annual total cost of the plant (ATC_P) to the annual fresh water yield (FW_y) and it is expresses as

$$C_{FW} = \frac{ATC_P}{FW_y} \tag{1}$$

The annual total cost of plant includes annual capital cost (AC_P), operation & maintenance cost (OMC_P) and annual salvage value of the plant (ASV)

$$ATC_P = AC_P + OMC_P - ASV \tag{2}$$

The annual capital cost is product of total capital cost (M) and CRF

$$AC_P = M(CRF) \tag{3}$$

Where CRF is the Capital Recovery Factor and it is calculated from eq. (4)

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{4}$$

Since the plant also produces cooling output, the equivalent electrical energy (AER_C) required to produce the same annual cooling output (AQ_C) from conventional air conditioner is calculated from eq. (5) by considering COP_{ac} as 2.5

$$AER_c = \frac{AQ_c}{COP_{ac}} \tag{5}$$

The annual salvage value of the plant (ASV_P) is product of future salvage value (SV_P) and sinking fund factor (SFF_P)

$$ASV_P = SV_P(SFF_P) \tag{6}$$

Considering future salvage value of the plant as 20 % of total capital cost (M), the sinking fund factor is estimated from eq. (7)

$$SFF = \frac{i}{(1+i)^n - 1} \tag{7}$$

Further, the operation and maintenance cost of the plant includes energy cost, labor cost, periodic cleaning of salt deposition etc. Considering the cost of electricity as 6.5 /kWh the O&M cost is calculated as

$$OMC_P = C_e\left(AEC_P - (AEG_P + AER_c)\right) + 0.15(AC_P) \tag{8}$$

where, AEC_P is the annual electricity consumption and AEG_P is annual electricity generation from the plant.

Table 1. Components of solar tri-generation plant and its capital cost

Components	Description	No's	Cost
CPVT collector	CPVT collector with aperture area of 10 m^2 and triple junction solar panel placed at the receiver.	1	1,10,474[a]
Humidifier	• Made of SS 304 material of 1.5 m height and 0.30m in diameter. • Corrugated plastic sheet is used as packing material	1	23,000
Water cooled Dehumidifier	Shell and tube heat exchangers with tube diameter of 0.012 m and 0.5 m length.	1	10,000
Water chiller	0.5 hp compressor operated chiller unit	1	25,000
Air blower	Centrifugal blower with 500 m^3/h discharge capacity	1	3,000
Pump	Discharge: 33.6 LPM, Head:6-26 m	2	6,000

Piping cost	All the pipelines are constructed using CPVC pipes	-	3,000
Others	Rotameters, valves, gasket, bolt and nuts	-	6, 250
	Total direct capital cost		1, 86, 724
Unit cost of fresh water			₹ 10/L
Payback period			6.5 years

[a] Total cost including 30 % subsidy offered from MNRE, India.

Table 2. Financial parameters of solar tri-generation plant

Parameters	Description
Direct capital cost	1,86,724
Service life of the plant	20 years
Interest rate	13 %
subsidy	30 %
Transportation and insurance	5 % direct capital cost
Cost of contingency	5 % of direct capital cost
Salvage value	20 % of direct capital cost
Total capital cost of the plant	2,05,396

4. Results and discussion

The monthly average global horizontal irradiation and mean ambient temperature in Vellore, India is shown in figure 2. The monthly average radiation in the month of January is around 5.5 kWh/m^2day and it increases gradually and reaches highest value of 7 kWh/m^2day in April month. Then the radiation and ambient temperature drops towards the December month.

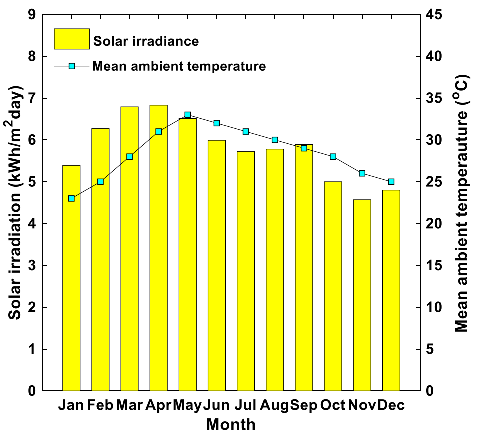

Figure 2. Monthly averaged GHI and ambient temperature in Vellore, India

The annual desalination yield, electricity production and cooling output are shown in figure 3. The total desalination yield and electricity production are high during the months of higher solar radiation. This is because higher solar radiation results in higher hot water temperature into the humidifier. Meanwhile more electricity is generated as high amount of radiation is available for the electrical energy conversion. The cooling output is also high at higher solar radiation. At higher radiation the hot humid air leaving the humidifier is at high temperature. This increases load on dehumidifier and resulting air is also at high temperature. Meanwhile, the temperature difference between ambient and chilled air is high this result in high cooling output. In winter, the ambient temperature itself at low level, so the changes in temperature of air is not much high compared with summer time. The highest average desalination yield is achieved in the months of April and May.

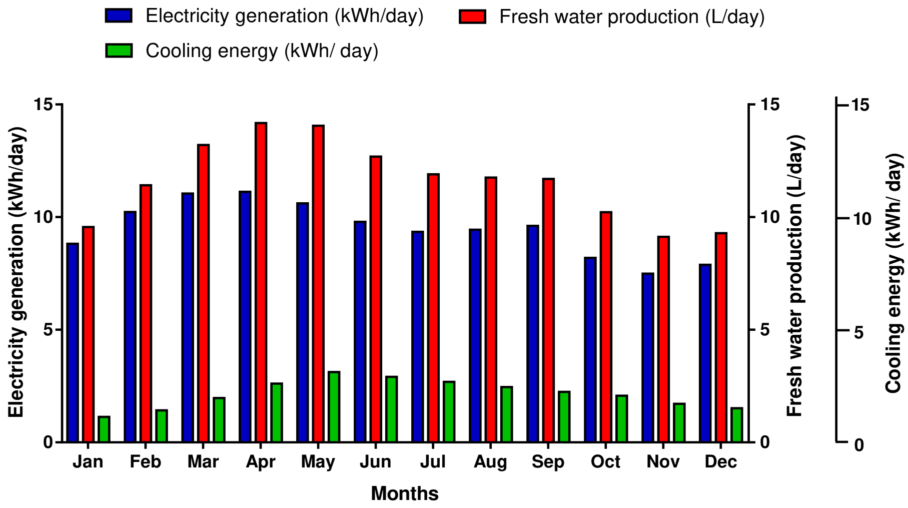

Figure 3. Monthly averaged desalination output, electricity production and cooling output from the CPVT operated system

The detailed economic model is presented in section. 3, based on the model developed and total capital cost the unit cost of fresh water and payback period are calculated. Assuming the interest rate as 9 % and energy cost as ₹ 6.5/kWh the unit cost of electricity and payback period are calculated as ₹ 10/L and 6.5 years.

5. Conclusion

The concentrated photovoltaic/thermal operated desalination and cooling plant is modelled and simulated for the annual desalination, cooling and electricity output. The annual desalination, cooling and electrical energy output are 4.2 m^3/yr, 3.46 MWh/yr and 0.788 MWh/yr respectively. The highest desalination yield, electrical output and cooling are achieved in the month of April/May. The highest monthly average desalination, electricity and cooling outputs are 14 L/day, 11.5 kWh/day and 4 kWh/day respectively. From the economic study, the unit cost of desalination and payback period are calculated to be ₹ 10/L and 6.5 years respectively.

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