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Design, performance and economic analysis of a nanofluid-based photovoltaic/thermal system for residential applications

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ABSTRACT

Photovoltaic thermal systems (PVT) have higher electrical efficiencies than photovoltaic systems because they bring down solar cell temperature, thereby increasing the electrical yield of solar cells, while simultaneously providing thermal energy in the form of hot fluid. Use of nanofluids in such systems have become increasingly popular due to the superior thermal properties of nanofluids. A nanofluid-cooled photovoltaic/thermal system is designed to meet the electrical demands of a residential building for the climate of Dhahran, Saudi Arabia. Optimum collector design is selected through computational fluid dynamics after which daily and yearly performance evaluation of the system is analytically performed through Engineering Equation Solver. Additionally, an economic feasibility study is performed to demonstrate the financial benefits of the proposed system. Results show an increase of 8.5% in the electrical output of a water-cooled PVT system over a PV system and an increase of 13% in the thermal output of a nanofluid-cooled PVT system over a water-cooled PVT system. Furthermore, the cost of energy from the proposed system is 82% less than the domestic price of electricity in Saudi Arabia and the system could prevent the release of 16,974.57 tonnes of CO_2 into the atmosphere.

1. Introduction

The challenge of meeting the impending energy crisis is becoming increasingly formidable due to increase in population and the rapidly depleting fossil fuel reserves. The Kingdom of Saudi Arabia is seeing a rapid expansion in its infrastructure, especially with regard to residential buildings, because of a rise in population coupled with high levels of economic growth [1]. Energy consumption in residential buildings accounts for 52% of the total electricity consumption in Saudi Arabia [2]. Buildings are also responsible for a substantial proportion of the global greenhouse gasses (GHGs) emissions. Since the Eastern Province accounts for one-third area of the country, it is important to address the energy needs of that area. The potential for solar energy to meet the energy demands of the Kingdom has been excessively researched [3–5]. The climate of Saudi Arabia is characterized by high levels of solar radiation; however, the elevated ambient temperatures also affect the performance of solar cells.

In any type of solar cell, the electrical performance of the cell deteriorates with increase in temperature. Results of Van Dyk [6] indicate that the maximum PV power output decreases with increasing temperature at a rate of 0.4–0.5%/°C. Experimental studies report a drop in the maximum power of 0.446%/°C [7] to 0.48%/°C [6] for a monocrystalline cell, 0.387%/°C [7] to 0.46%/°C for a polycrystalline cell [6]. Since less than 50% of the absorbed solar radiation can be converted to electricity [8], it is important to remove the remaining energy or it will lead to extreme cell temperatures. Photovoltaic thermal collectors (PVT) combine photovoltaic modules with solar thermal collectors in such a way that it cools the solar cells and improves their performance while simultaneously increasing the energy yield per unit panel area by providing thermal energy in the form of a hot fluid, which may be used for various purposes.

Over the years many different types of PVT collector design have been suggested ranging from flat-plate to concentrating collectors, forced convection (active) to free convection (passive) systems, monocrystalline/polycrystalline or any other type of PV panel. Polycrystalline cells have lower efficiencies than mono-crystalline cells but are simpler to produce with lower manufacturing costs and less wastage of silicon. A concentrating PVT system, requires reflectors or lenses to focus sunlight onto the PVT system along with high-efficiency solar cells (second-generation or third-generation solar cells) and complex sun tracking mechanism which increases the expenses and complexity of the system [9]. In the absence of pump, passive systems offer more electrical power but less control and lower convective heat transfer coefficients than active systems. Compared to channel PVT systems, sheet and tube PVT systems are simpler, easier to manufacture and analytical results [10] show that the thermal efficiency of sheet and

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Nomenclature

α	PV absorptance
A_c	collector area (m^2)
β	collector tilt angle (deg)
COE	cost of energy (US$/kW.h)
$CPBT$	cost payback time (years)
DCF	discounted cash flow (US$)
Δp_{total}	total pressure drop (Pa)
δ_g	glass thickness (m)
Ex	rate of exergy destruction (W)
η_{mp}	maximum power point efficiency
η_{ex}	exergy efficiency
h_r	radiation heat transfer coefficient ($W/m^2.K$)
I_{mp}	maximum power point current (A)
i_{ec}	inflation rate of domestic electricity price
I	incident radiation (W/m^2)
IC	investment cost (US$)
I_b	beam radiation (W/m^2)
I_d	diffuse radiation (W/m^2)
I_T	total radiation (W/m^2)
i_d	discount rate
i_e	inflation rate
k	Boltzmann constant ($m^2\,kg\,s^{-2}\,K^{-1}$)
K_g	extinction coefficient of glass (m^{-1})
μ_{Isc}	temperature coefficient for short circuit current (A/K)
μ_{Voc}	temperature coefficient for open circuit voltage (V/K)
m_{fluid}	mass flow rate of collector fluid (kg/s)
m_w	mass flow rate of cooling water (kg/s)
NPV	net present value (US$)
n_g	refractive index of glass
ϕ	latitude (deg)
P_{mp}	maximum power (W)
Q	thermal power (W)
ρ_g	ground reflectance
R_b	ratio of radiation on tilted surface to that on horizontal surface
S	absorbed solar radiation (W/m^2)
τ	glass transmittance
T_a	ambient temperature (C)
T_{cell}	cell temperature (C)
T_g	glass temperature (C)
T_i	collector fluid inlet temperature (C)
T_o	collector fluid outlet temperature (C)
T_p	absorber plate temperature (C)
U_L	overall heat loss coefficient ($W/m^2.K$)
V_{mp}	maximum power point voltage (V)
WS	wind speed at reference height (m/s)

tube design is only 2% lower than that of the channel below PV design.

The fluid used to cool the PV cells has a significant impact on the overall performance of PVT system. Earlier designs of PVT system used either air or water as a coolant. The use of low thermal conductivity fluids in solar systems such as water or ethylene glycol limits the thermal efficiency of such systems. One of the techniques used to overcome this limitation is the use of nanofluids as heat transfer fluids in solar collectors. Nanofluids consist of nano-sized particles suspended in base fluids such as water or oil. Owing to their small size the nanoparticles always remain in suspension and even the introduction of a small fraction of nanoparticles greatly enhances the thermal properties of base fluids. However, the introduction of nanofluid increases the cost and complexity of the system. Many different types of nanoparticles such as Carbon based nanoparticles (Carbon Nano Tubes) [11] and magnetic nanoparticles [12] have been successfully used in solar collectors. However, the use of metal-based nanoparticles to enhance the thermal conductivity of heat transfer fluid in solar collectors is more common. Among metal-based nanoparticles, the addition of silver (Ag) nanoparticles to water have resulted in high-thermal conductivity nanofluids [13], consequently, silver/water nanofluids have been successfully implemented in experimental studies for both Flat Plate Solar Collector [14] and PVT systems [15].

It was the consumer's demand for energy that triggered research on PVT systems, hence the success of PVT systems can only be judged in context with real scale project applications. A significant amount of research [16–19] on actual full-scale implementation of PVT systems, especially related to buildings, has been performed giving rise to the term Building Integrated PVT (BIPVT) systems. According to PVT roadmap [20], the major market potential for PVT system lies in the domestic sector, and therefore to convince domestic or commercial users to invest in PVT systems, one has to accentuate the potential economic benefits from PVT systems. To this end, considerable studies have been performed to demonstrate the economic feasibility in the implementation of a PVT system [21,22].

The objective of current study is to design a flat-plate, sheet and tube, polycrystalline photovoltaic/thermal system with active PV cooling through silver/water nanofluid to meet the electricity demands of a residential building for the climate of Dhahran, Saudi Arabia. The study uses computational fluid dynamics for the selection of optimum collector design after which daily and yearly performance evaluation of the system is performed through the use of validated analytical models. Finally, an economic feasibility study of the system is performed through Life Cycle Cost analysis.

2. Numerical models for analysis

2.1. Assumptions

- Altitude of system is 10 m above ground.
- Perfect thermal contact is assumed between PV and collector.
- Charge controller is assumed to be equipped with MPPT.
- Hellman coefficient is assumed to be 0.40 for stable air above flat open coast.
- The fraction of radiation reflected from ground is assumed to be 0.2.
- The PV module is assumed to be fixed, i.e. no solar tracking, tilted at an angle equal to the Dhahran latitude ($\beta = 26°$) and facing south, i.e. azimuth angle is 0°.
- The cold cooling water and the hot nanofluid in the heat exchanger are assumed to have a mass flow rate ratio of 4:3 [23]. Both mass flow rates are assumed constant throughout the year.
- Battery efficiency, inverter efficiency and power factor are assumed to be 0.85, 0.9 [24] and 0.8 respectively.
- Daily electrical load profile assumed to be constant throughout the year [25].
- Thermal residential load in Saudi Arabia is covered with an electric water heater.
- 100% of the total investment cost is paid at the beginning.
- Annual maintenance cost, *MC*, is assumed to be the sum of 2.76% of PV cost, 2.3% of heat exchanger cost and 0.7% of pump cost [26].
- Battery and inverter are to be replaced after 7 years [21].

2.2. Absorbed radiation and optical model

Incident radiation values for each hour of the representative date of each month for Dhahran, Saudi Arabia can be determined from Appendix D. Since, incident radiation (I) values were measured using a horizontally-set pyranometer and the PVT collector is tilted at an angle, it is necessary to calculate total radiation (I_T) and absorbed radiation (S)