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Original article

Nanofluid based grid connected PV/T systems in Malaysia: A techno-economical assessment

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ABSTRACT

In this study, the techno-economic assessment of a Grid-Connected Photovoltaic Thermal (GCPVT) system with nanofluid as base fluid is carried out. The investigation blinds both theoretical and experimental work. The reason why a grid-connected PV is considered is due to grid-connected PV configurations constituting about 86% of the PV tsystem, with 54% of them being centralised while 32% are being distributed, which shows the importance of such systems and the potential they can achieve with PV/T collectors. The study focuses on the electrical and thermal performance of PV/T. The yield and capacity factors are used to investigate the productivity and utilisation of the PV panel, respectively. In addition, the assessment of the cost analysis and economic aspect was conducted through Cost of Energy (CoE) and Payback Period (PBP) calculations. This system was installed, tested, and data has been collected in the green innovation and technology park in UKM, Bangi. Furthermore, an evaluation of the panel production in terms of current, voltage, power and efficiency is presented. The average daily ambient temperature and total global solar energy in Bangi are 38.89 °C and 4062 Wh/m^2, respectively. A MATLAB software code is developed and used for the data analysis. The results of the assessment show that the GCPVT system has an annual yield factor and capacity factor of (128.34–183.75) kWh/kWp and (17.82–25.52)%, respectively. While the cost of energy, payback period, and efficiency are 0.196 USD/kWh, 7–8 years and 14.25%, respectively. Moreover, different nanoparticle mass fractions in the nanofluid were considered and the optimum fraction was found to be 3%. Additionally, different comparisons of this system with other systems and countries are presented to show its improvement and cost-effectiveness. This study indicates how the GCPVT system with nanofluid improved the PV technical and economic performance.

Introduction

Solar energy is shaping to be one of the important renewable energy sources of modern times as this source is abundant and environment-friendly and can be utilised worldwide as a stable source of energy. The solar radiation provides both light and heat, with its light converted to electricity through Photovoltaic (PV) cells, utilising the visual part of its spectrum, while the heat is captured and absorbed by thermal systems in order to produce thermal energy and/or electricity. PV configurations are standalone and grid connected systems. The grid-connected PV (GCPV) is categorised as either a distribution generation (DGPV) or building integrated PV system (BIPV) [1]. Another solar technology is the Photovoltaic/Thermal (PV/T) collector, which capitalises on both heat and light in order to generate electricity and thermal energy in the same area. PV/T is valuable particularly for cold regions allowing consumers to gain electricity and heat at the same time [2]. The efficiency of the PV/T system is the sum of the PV and solar thermal efficiencies, making it higher than the two separately. The thermal aspect is mainly the increase in temperature, which reflects positively on its efficiency. In the same vein, the PV efficiency is reduced as its cell temperature increases. The working fluid within the collector (such as air, water, a combination of the two etc.) is used to absorb the heat from the thermal collector which gains its heat by absorbing it from the PV cell/module/array, and so the output voltage of the PV cell can be maintained, along with its performance overtime. Moreover, the fluid is now heated and ready to be used for various applications [3,4]. The use of water as cooling fluid is attractive, as it reduces the operating temperatures much more than air, yet air presents a simple system design. In literature, it is found that the use of nanofluids as working fluids achieves better cooling efficiency than water [3]. However, in cold

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Nomenclature

G_T	solar radiation ($W.m^{-2}$)
T_i	input temperature (°C)
T_o	output temperature (°C)
T_a	air temperature (°C)
T_{PV}	PV temperature (°C)
T_C	cell temperature (°C)
$\mathring{U}$	water flow rate ($m^3.s^{-1}$)
V_{oc}	open circuit voltage (V)
I_{sc}	short circuit current (A)
A_c	area of the system (m^2)
m	air mass flow rate ($kg.s^{-1}$)
P_T	thermal power (W)
P_E	electrical power (W)
P_O	output power (W)
η_{PV}	PV -Electrical- efficiency (%)
η_T	thermal efficiency (%)
η_S	system efficiency (%)
LCC	life cycle cost ($)
CoE	cost of energy ($/kWh)
PBP	Pay Back Period (Years)
YF	yield factor (kWh/kWp)
R_{PV}	performance factor of PV (%)
YR	reference yield (kWh/kWp)
CF	capacity factor (%)
κ	thermal Conductivity (W/m k)
ρ	viscosity (mPa s)
μ	density (g/mL)
$\dot{m}$	mass flow rate (kg/s)
GPBT	greenhouse gas emissions Payback Time (years)
EPBT	energy Payback Time (years)
EROI	energy Return on Investment
E	embodied energy E (kWh/m^2)
PV	photovoltaic
GCPV	Grid Connected Photovoltaic
GCPVT	Grid Connected Photovoltaic Thermal
SiC	silicon carbide
FiT	Feed-in-Tariff
CED	cumulative energy demand (years)
COP	coefficient of performance
NMAE	normalized mean absolute error (%)
WMAE	weighted mean absolute error (%)

environments, using water as coolant requires adding surfactants in order to avoid freezing conditions [2].

Literature survey

Previous studies indicate that massive research and development is channelled to improving the total efficiency of the PV/T systems by enhancing the thermal and electrical performances [5,6]. In this paper, the focus is shifted to the PV aspect.

The nanofluid is chosen over water due to the Brownian motion of nanoparticles in the fluid, which gives it a higher thermal conductivity. However, if the mass fraction is not chosen wisely it might cause an increase in its density and reduction in viscosity [7]. For this reason, it is important to start with thermophysical property tests for each produced nanofluid sample for various considerations [8–10]. These tests must account for properties such as density, viscosity and thermal conductivity [11–13]. Once the optimum nanofluid concentration is decided, the mixing process is carried-out. It is important to ensure no sedimentation occurs in the produced fluid. Another aspect is to test the pumps in the system for their performance over time, as higher densities and sedimentations might contribute to requiring more maintenance.

Battisti and Corrado [14] numerically evaluated an air heat PV/T system in Italy using the SimaPro 5.1 software. The study presented a calculation of the cumulative energy demand (CED), energy (EPBT) and greenhouse (GPBT) payback time. The EPBT and GPBT were found to be 1.7–2.8 and 1.6–2.8 years, respectively.

Sun Jian et al. [15] tested the thermal and electrical performance of a Compound Parabolic Concentrator (CPC) PV/T with fins, using a numerical simulation. In addition, the study investigated the effect of various parameters on design and operation. The authors claimed that an increase in the thermal and system efficiencies has occurred across the length of the system, while the electrical efficiency decreased. This increase is attributed to an increase in the air mass flow rate, while the larger area covered by the panel increased its electrical efficiency.

Dolara et al. [16] have evaluated and compared between three physical models describing the PV cell with modules used of crystalline material: mono-crystalline and poly-crystalline. The study presented a forecast of output power with an hourly error lower than 15 Wh, while the NMAE% and WMAE% are in the range of 0.5% and 10%, respectively. The authors claimed that accuracy of the model depends on two factors: (i) data used in its calibration and (ii) approach utilised for cell temperature calculation, rather than basing it on the complexity of the model. Refs [17,18] show further work on the performance predictive models of the PV systems, so that the interested reader can return to.

Lv et al. [19] designed and assessed a water based PV/T with glazing. System consideration was based on the measured and simulated parameters. The study concluded that the system presented has achieved a good improvement in electrical and thermal efficiency compared to other systems. In addition, the simulation results showed that there is a real growth in the yearly gained calories and that the total system efficiency achieved is 54.3%.

Salavati et al. [20] evaluated the performance of a flat plate solar collector with SiO2/ethylene glycol (EG)–water nanofluid as working fluid and different volume fractions values (0, 0.5, 0.75 and 1%). The mass flow rates used are 0.018, 0.032 and 0.045 kg/s. The study produces curve characteristics for the collector indicating the effects of particle loading on the enhancement of thermal efficiency. The results show an increment of efficiency of about 4–8% when increasing the nanofluid concentration from 0 to 1%.

Colangelo et al. [21] modified and built a flat panel solar thermal collector then compared the thermal efficiencies of two heat transfer fluids: distilled water and Al_2O_3–distilled water based nanofluid at a high concentration (3.0%) volume fraction of solid phase. The authors utilise a patent design to support the high concentration to reduce the sedimentation of clusters of nanoparticles. The experiments show nanofluid causing an increase of thermal efficiency of up to 11.7% compared to water.

Colangelo et al. [22] investigated the stability, viscosity, thermal conductivity and cluster size of Al_2O_3-Therminol nanofluids in high temperature solar energy systems. The stability was tested using a backscattering technique and the cluster size was analysed through Dynamic Light Scattering (DLS). The effects of volume fraction, temperature and surfactant were examined through the measurement of thermal conductivity. This study shows the importance of these factors for nanofluid related work in solar energy. The surfactant added was shown not to influence the thermal conductivity of the fluid. The DLS measurements show that cluster size is dependent on volume fraction. The study concludes that the viscosity rises when increasing the volume concentration; nanofluids with and without surfactants show a non-Newtonian behaviour and the viscosity of nanofluids rises with increasing cluster size. Further investigative work with regard to the