Applied Energy 120 (2014) 115–124

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

# Optimizing limited solar roof access by exergy analysis of solar thermal, photovoltaic, and hybrid photovoltaic thermal systems

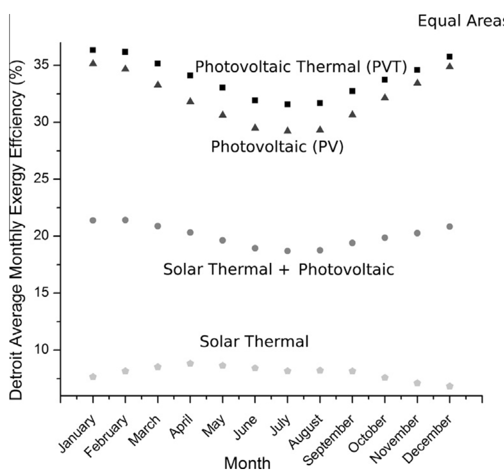
M.J.M. Pathak [a], P.G. Sanders [b], J.M. Pearce [b,c,*]

[a] Department of Mechanical and Materials Engineering, Queen's University, Kingston, ON, Canada
[b] Department of Materials Science and Engineering, Michigan Technological University, Houghton, MI, USA
[c] Department of Electrical & Computer Engineering, Michigan Technological University, Houghton, MI, USA

## HIGHLIGHTS

- Rigorous theoretical exergy model developed to compare solar energy systems.
- Compared photovoltaic solar thermal hybrid (PVT) systems.
- Also side by side photovoltaic and thermal (PV + T) systems.
- Also photovoltaic (PV) systems and solar thermal (T) systems.
- PVT systems are superior in exergy performance in representative climates.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

*Article history:*
Received 16 April 2013
Received in revised form 9 January 2014
Accepted 11 January 2014
Available online 14 February 2014

*Keywords:*
Exergy
PVT
Solar energy
Solar thermal
Photovoltaic
Photovoltaic thermal hybrid

## ABSTRACT

An exergy analysis was performed to compare a conventional (1) two panel photovoltaic solar thermal hybrid (PVT x2) system, (2) side by side photovoltaic and thermal (PV + T) system, (3) two module photovoltaic (PV) system and (4) a two panel solar thermal (T x2) system with identical absorber areas to determine the superior technical solar energy systems for applications with a limited roof area. Three locations, Detroit, Denver and Phoenix, were simulated due to their differences in average monthly temperature and solar flux. The exergy analysis results show that PVT systems outperform the PV + T systems by 69% for all the locations, produce between 6.5% and 8.4% more exergy when matched against the purely PV systems and created 4 times as much exergy as the pure solar thermal system. The results clearly show that PVT systems, which are able to utilize all of the thermal and electrical energy generated, are superior in exergy performance to either PV + T or PV only systems. These results are discussed and future work is outlined to further geographically optimize PVT systems.



## 1. Introduction

Fossil fuels cannot indefinitely sustain the energy needs of the earth's growing human population due not only to finite supplies,

* Corresponding author. Address: 601 M&M Building, 1400 Townsend Drive, Houghton, MI 49931-1295, USA. Tel.: +1 906 487 1466.
*E-mail address:* pearce@mtu.edu (J.M. Pearce).

http://dx.doi.org/10.1016/j.apenergy.2014.01.041
0306-2619/

but also the adverse effects of anthropogenic greenhouse gas emissions on global climate [1,2]. It is therefore necessary to look for alternative renewable forms of energy [3–6] such as solar energy, which have previously been shown to be a sustainable solution to society's energy needs [7,8]. Currently there are two common systems that utilize the sun's energy for human use: (1) the solar photovoltaic (PV) cell, which converts sunlight directly into electricity and (2) the solar thermal (T) collector, which converts solar energy into thermal energy. As the levelized cost of PV has dropped quickly [9] to become competitive with conventional grid electricity in specific regions, available roof top space with open solar access tends to drop precipitously in those same regions as they are covered with PV. Thus, when attempting to meet all of a building's internal electricity and heat loads with energy from the sun, roof area becomes a significant limiting factor [10]. A hybrid solar system, called a solar photovoltaic thermal hybrid system (PVT), provides a potential solution to this challenge [11–13]. PVT systems exploit the heat generated from the PV system, which is normally wasted, to produce useful thermal energy along with the electricity from the PV.

There have been several methods to compare PVT systems using economics, carbon dioxide emissions, energy produced and exergy efficiency [14–18]. Both Erdil et al. [19] and Kalogirou et al. [20] calculated the economic feasibility of a PVT system and concluded that their systems were cost effective. However, economic analysis is usually used to determine the cost viability of the system, but is limited because of the arbitrary nature of the current economic system [21,22]. The proposal of using carbon dioxide ($CO_2$) emissions, particularly the dynamic life-cycle emissions [4], as a way to rate energy systems is useful particularly in the context of stabilizing global $CO_2$ concentrations. However, trying to make a system more energy efficient would reduce the $CO_2$ emissions of the system in a given location, which eventually reduces the complexities of varying geographic emission intensities due to fuel mix in a region [4]. Energy analysis has shown that PVT systems produce more energy than either a PV or thermal collector system per unit area [23]. Through this work, studies have tested using different flow rates, glazes and designs to determine if PVT systems are superior [24–27]. However, like the other two comparisons, energy lacks the ability to compare electrical energy and thermal energy since energy analysis only looks at the quantity of the energy and not the quality as well. Exergy, defined as the maximum useful energy in a specific reference state, typically the surroundings, analyzes both the quantity and quality. This further allows for an improved analysis and optimization of systems since exergy, unlike energy, is not conserved, but rather destroyed by irreversibilities in real processes [28].

There have been several studies comparing PV, T and PVT systems using exergy. However in these studies, the exergy analysis uses a simplified model by multiplying the Carnot cycle by the thermal energy efficiency [29,30]. Other exergy analysis work has focused on specific systems to try to optimize operating settings [31–33]. A meticulous exergy analysis comparing PV, thermal and PVT systems has not been undertaken. Thus, this paper provides a more rigorous theoretical exergy model by building on previous detailed exergy models [31–33] but going further to compare a conventional two panels PVT (PVT x2) system to a side-by-side (PV + T) system, two modules PV (PV x2) only system, and a two panels T (T x2) only system to determine the technically superior system for applications with limited roof area. In this study all four solar energy systems were analyzed for the same total area to ensure an unbiased comparison in three locations with varying climatic conditions: Detroit, Denver and Phoenix.

## 2. Nomenclature

Table 1 contains the nomenclature for the equations in Section 3–6. The equations used in these appendices are from the renowned account of solar engineering of thermal processes [34] unless otherwise stated.

## 3. Material and methods

Models, detailed in the sections following, of the four solar energy systems (PVT x2, PV + T, PV x2, and T x2) shown in Fig. 1, were created and analyzed in Scilab, an open-source numerical simulation tool [35]. The National Renewable Energy Laboratory National Solar Radiation Data Base 1991–2005 update Typical Meteorological Year 3 (TMY 3) data was used for the three locations: Detroit City Airport (725375), Denver Intl AP (725650) and Phoenix Sky Harbor Intl AP (722780) [36].

All three locations are Class I data sets with the highest quality of solar modeled data with a complete data set. These three locations were chosen due to their distinct and representative average ambient temperatures and irradiance values, with Detroit representing both low temperatures and low solar flux (9.2 °C and 3.63 kWh/m$^2$/d), Denver presenting low temperatures and high solar flux (8.2 °C and 4.58 kWh/m$^2$/d), and Phoenix representing both high temperatures and high solar flux (16.9 °C and 5.48 kWh/m$^2$/d) [37]. The hourly air temperature, wind speed and solar irradiation were used in the simulation. The wind speed was recorded at ten meters off the ground and therefore the systems are assumed to be at that elevation. As shown in Fig. 1 each individual system (PVT x2, PV + T, PV x2, and T x2) has the same total area. The following sub-sections describe the evolution of the models to analyze the systems. The PVT system was model as an air heater with a PV panel as the absorber since air systems are typically preferred due to the lower operating costs and minimal use of material [38]. The solar thermal system was modeled as a tube and sheet system but with air as the fluid to have the same medium as the PVT system for a more direct comparison.

## 4. PV model

### 4.1. Solar photovoltaic cell model

In this simulation, the solar PV cells are modeled with a five-parameter equivalent electric circuit which describes the cell as a diode [39,40]. The starting equation for the model of the solar cell describes the solar cell as a diode and can be seen in Eq. (1).

$$I = I_L - I_D - \frac{V + IR_s}{R_{sh}} = I_L - I_o\left[e^{\frac{V+IR_s}{a}} - 1\right] - \frac{V + IR_s}{R_{sh}} \quad (1)$$

where $I$ is the current, $I_L$ is the leakage current, $I_o$ is the reverse saturation current, $V$ is the voltage, $R_s$ is the series resistance and $a$ is the modified ideality factor. A circuit depiction of Eq. (1) can be found in Fig. 2.

To solve for the five parameters, the initial conditions were applied to Eq. (1). At the short circuit current conditions, the current, $I$, is equal to the reference short circuit current ($I_{sc,\ ref}$) and the voltage is equal to zero. Furthermore, the slope of the current with respect to the voltage is equal to the negative inverse of the shunt resistance ($R_{sh}$). In the open circuit conditions, the current equals zero and the voltage equals the reference open circuit voltage ($V_{oc,ref}$). At the maximum power condition, the current equals the reference maximum power current ($I_{mp,ref}$) and the voltage equals the reference maximum power voltage ($V_{mp,ref}$). Furthermore the change in the maximum power is zero.

When these conditions are applied to the diode equation, Eq. (1), the following five equations are produced (2–6).