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Water Based Hybrid Photovoltaic and Thermal (PV/T) Flat Plate Solar Collectors: Status and Opportunities.

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Abstract: The concept of water based Photovoltaic/Thermal (PV/T) system is founded on the premise of temperature reduction of PV units for efficiency enhancement, a noble idea that originated in the late 1970's. PV/T technology combines PVs and solar thermal components into a unitary module to enhance the solar conversion efficiency and make economic use of the space. Mechanisms of absorbing and transferring the residual heat dissipated because of exposure of solar cells to solar radiation have been designed in different configurations and dimensions optimized by different researchers. This study extensively revealed the idea of water heating using this technology, extent of past and ongoing research studies based on the theoretical and analytical techniques, experimental, modeling and simulation, economic and environmental assessments. The outcome of this study enables a better understanding of the status of the PV/T technological enhancements, identification of the impending problems and obstacles, existing standards and regulations with regard to PV/T design and installation, areas of application and the potential research opportunities for further improvements in the performance of the PV/T.

Key Words Hybrid, Water based PV/T, Status and Opportunities

1. Introduction

Solar energy has gained popularity in the recent past because of its sustainability and environmental friendliness but has not been fully exploited to bridge the current energy gaps due to costly harnessing systems. However, there are good prospects that costs may come down soon by developing novel and efficient technologies of conversion of solar energy. One such technology is the hybrid Photovoltaic and thermal application [1]. The Photovoltaic (PV) modules partially convert radiant energy from the sun into electric energy, the remainder of which is engrossed by the module there by generating residual heat. This implies that, in highly insulated systems, the operating temperature of the module is increased, which in effect, may result in efficiency drop of the PV cells (e.g., 1^0C rise in temperature of c-Si cells, causes efficiency drop of 0.4%) and structural damages to the module when exposed to thermal stresses long periods [2,3].

The high temperatures are undesirable for operation of PV modules and need to be controlled to achieve relatively higher efficiencies. Besides the cooling, architectural disparities, and fitting space restrictions on buildings also present operational challenges of individual PV and solar thermal systems; therefore, it is necessary to merge the two systems in one hybrid PV/T to overcome these challenges. A suitable design of a combined Photovoltaic and Thermal system, hence hybrid, eliminates the need for external power source to pump the cooling fluid around the system as is the practice with the conventional PV systems.

Hybrid PV/T collectors simultaneously convert radiant energy from the sun into electric and thermal or heat energy via the combination of both PV and thermal units. They provide an effective and convenient means of obtaining electric power and thermal energy within the same system, maximizing on their total energy output [4].

PV/T systems are categorized according to the working fluid used for heat extraction. The basic types are water-based, air-based and dual water-air based systems. This paper is limited to water-based PV/T systems that generate hot water for varied applications. The water-based types are effectively recommended for use in low latitude regions since the mains water supply temperatures are below 20^{0}C throughout the year and can function best in all climates except for instances prone to freezing [5]. Hybrid PV/T solar systems technology is rapidly developing, but the adoption is still limited to prototypes for demonstration. Despite the cost-effective improvements on solar energy conversion, the uptake rate is still lower than the independent PV and thermal systems [6].

2. The concept of Hybrid PV/T water heating systems.

Electricity production is given priority in PV/T system applications; as a result, it is absolutely preferable to keep PV unit operating temperatures as low as possible to maintain their electrical efficiencies at satisfactory levels.

Hybrid PV/T system consist of a combination of PV and thermal units that generate thermal energy and electricity concurrently attaining a greater energy conversion capability of the captured sunlight. The thermal unit has provisions for circulating a heat removal fluid (in this case, water), in the process, cooling the PV unit [7]. The aspect of generation of both electricity and heat in comparison to conventional individual PV and thermal units is demonstrated in Figure 1.

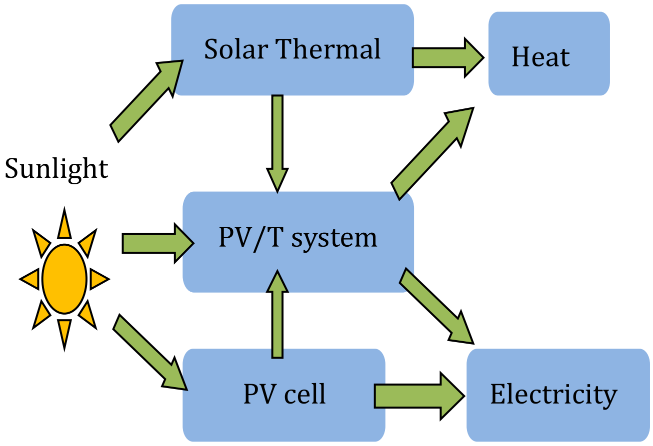

Figure 1: The solar conversion technology tree

These systems are commonly made from Silicon PV units and metal plate heat removal elements having water-flow tubes attached, to prevent direct touch between the flowing water and PV bottom face. The absorber plate contacts the PV unit bottom face in a manner that permits conduction of heat and further transfer to the flowing fluid. The bottom of the absorber component and the module sides are lagged to prevent escape of heat to the surrounding atmosphere. Figure 2 (a) shows a typical flat-plate PV/T water heater with a cut away section to expose the interior configuration. The flow tube profile for most PV/T models studied have adopted the serpentine shape as shown in Figure 2(b). At a closer look, cross section of the plate and tube arrangement shown in Figure 2(c) is often adopted but different profiles have also been tried and attachments between the plate and tubes mode options shown in Figure 3.

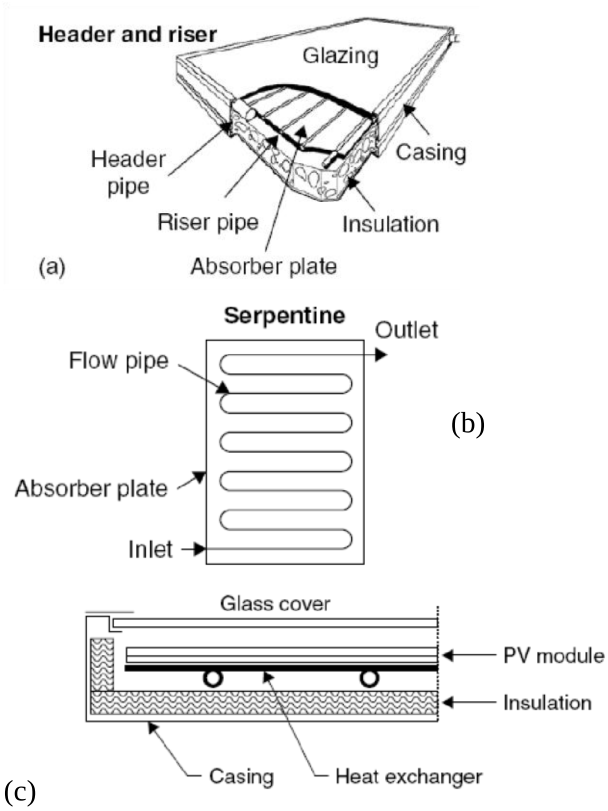

Figure 2: (a) Cut out section showing Header and riser tubes (b) Serpentine profile of the flow tube (c) Cross-section of a water-based PV/T collector [1]

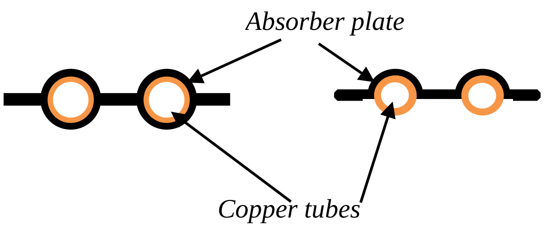

Figure: 3: Tube to plate configuration modes.

The different cross section profiles are shown in Figure 4. These involve the sheet and tube, box channel, channel above and below PV module designs.

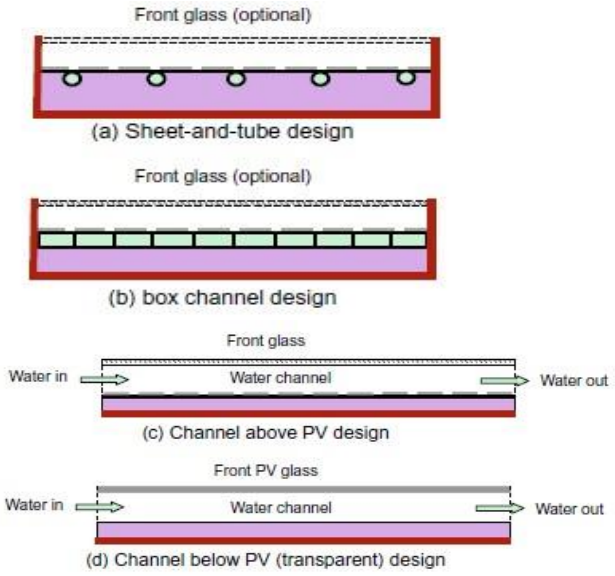

Figure 4: Cross sections of commonly used PV/T water collector designs [2].

The water-based PV/T systems are convenient generally for household hot water needs and can serve efficiently at any time of year, mostly in low latitude regions, because water in communal pipeline is typically below 20°C. Their performance is typified by its thermal and electrical efficiencies which are functions of water temperature, flow rate, water flow channel profile and sizes, PV type, and varying climatic conditions [8].

Studies on PV/T water heating system usually focus on determining appropriate water flow rate and temperature, sizing of water tubes for optimization and structural configurations including parts, components, connections etc. PV/T water heating like any other system has challenges such as continuous rise in water temperatures which severely affect the overall efficiency and heat removal effectiveness. In addition, in very cold climate it may be prone to freezing. The PV/T systems may be thermosiphonic where, makes use of internal convective currents to continuously move the hot water from the heating element to the storage unit or pump operated to assist in water circulation [1].

3. Performance assessment

A PV/T collector principally combines the characteristics of a flat-plate solar (thermal) collector and those of a PV module. Therefore, in assessing the performance of the PV/T, it is prudent to look at the two systems separately, thereafter, consider the overall combined effect.

3.1 Thermal performance assessment of flat plate solar collectors.

The thermal performance of the flat-plate solar collector is defined by the Hottel-Whiller–Bliss thermal efficiency equation [9]. The expression has gained widespread application in the design, modelling and simulation and performance assessment of solar systems. The arrangement in Figure 5 is applied for the analysis in this case.

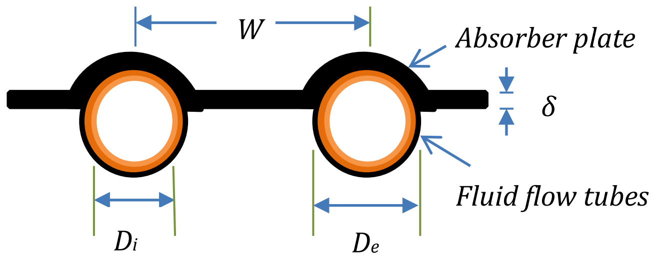

Figure 5: Cross section of the absorber plate and fluid tubes configuration

The aggregate heat absorbed by the collector Q_u is conventionally expressed as the product of mass flow rate $\dot{m}$, specific heat capacity c_p of the cooling fluid and the temperature difference of the fluid at outlet T_{out} and inlet T_{in} as given in equation 1.

$$Q_u = \dot{m}c_p(T_{out} - T_{in}) \tag{1}$$

The heat source for the collector is the solar radiation and therefore, when this is considered, the expression for the useful energy Q_u is given as:

$$Q_u = A_c\left[G(\tau\alpha) - U_L\left(T_{m,p} - T_a\right)\right] \tag{2}$$

Where A_c is the collector area, τ is the transmittance of glazing cover, α is the absorptance of the glazing cover, U_L is the overall thermal loss coefficient, T_a an $T_{m,p}$ are ambient air temperatures and mean absorber plate temperatures respectively. The latter is an intricate function that depends on the collector design, solar insolation and working fluid. Therefore, a modified Hottel-Whiller–Bliss thermal efficiency equation comes into play. This excludes the heat energy converted into electrical energy Q_e as expressed in Equation 3.

$$Q_u = F_R A_c[G(\tau\alpha) - U_L(T_i - T_a) - Q_e] \tag{3}$$

Where F_R is the heat removal factor, defined as:

$$F_R = \frac{GC_p}{U_L}\left[1 - exp\left(-\frac{U_L F\prime}{IC_p}\right)\right] \tag{4}$$

Where F' is the fin efficiency factor of the collector and varies with the type of working fluid used e.g. for water is expressed as:

$$F' = \frac{1/U_L}{W\left\{\frac{1}{U_L[D_e+(W-D_e)F]}+\frac{1}{C_b}+\frac{1}{\pi D_i h_{wm}}\right\}} \tag{5}$$

Where W is the separating distance between the central axes of the tubes, D_e and D_i are the external and internal diameters of the tubes respectively as shown in Figure 5, C_b is the bond conductance between the tube and the fin; h_f is the heat transfer coefficient of the fluid; A is the heat transfer area; A_c is the collector aperture area; h_r is the equivalent radiation coefficient. F is the fin efficiency expressed as:

$$F = \frac{tanh\left\{\sqrt{(U_L/k\delta)(W-D_e/2)}\right\}}{\sqrt{(U_L/k\delta)(W-D_e/2)}} \tag{6}$$

Hence the steady state thermal efficiency η_{th} of a flat plate collector is expresses as the ratio of useful thermal energy, Qu to the total solar irradiation calculated by:

$$\eta_{th} = \frac{Q_u}{G} \tag{7}$$

Where k is the thermal conductivity of the fin

3.2 Electrical performance assessment of photovoltaic generator.

The PV generator consists of a collection of solar cells connected either in parallel or series or combination of both, connecting leads, guarding parts and supporting frame. The solar cell is made of distinctly conditioned semi-conductor material forming an electric field with positive and negative sides on the back and front sides respectively. The preferred semiconducting materials in common use to make PV cells are Monocrystalline and polycrystalline silicon (Si), Gallium Arsenide (GaAs), Cuprous Sulphide (Cu_2S), and compounds of Cadmium Sulphide (CdS). A range of potential materials, like Cadmium Telluride (CdTe) and Copper Indium Diselenide (CIS) are currently in use for making PV modules by some manufacturers. These technologies are fairly inexpensive to manufacture compared to Crystalline Silicon (c-Si) technologies and provide superior module efficiencies [6].

When exposed to the photons of the sun, electrons are energized and released resulting in electron hole pairs. When these two sides of the solar cell are linked by means of a load, flow of electric current (photon current *Ip*) is initiated provided it is exposed to sunlight. On the other hand, in the absence of sunlight, the solar cell is inactive and functions as a diode which when connected to a large external voltage source, produces a dark or diode current (I_d) [1].

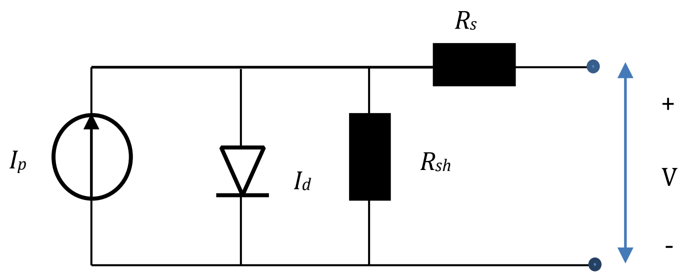

Figure 6: Solar cell circuit representation

The typical PV cell configuration can be represented diagrammatically by Figure 6. As can be seen, there is a current source I_p, a diode and a series resistor R_s equivalent to internal resistance of the cell. The shunt resistance represents the internal resistance of the diode.

The diode current I_d is given as:

$$I_d = I_o \left\{ exp\left(\frac{e(V - IR_s)}{kT_c} \right) - 1 \right\} - \frac{V - IR_s}{R_{sh}} \qquad (8)$$

Where I_o is the temperature dependent dark saturation current (A); e is the electronic charge (1.602×10^{-19} *J/V*); T_c is the cell absolute temperature (K); V is the voltage across the cell and k is the Boltzmann's constant.

However, the load resistance is usually much less than the shunt resistance but much bigger than the series resistance, thus the power dissipated within the cell is negligibly small. Therefore, the series and shunt resistances can be ignored then the expression becomes:

$$I_d = I_o \left\{ exp\left(\frac{e(V - IR_s)}{kT_c} \right) - 1 \right\} \qquad (9)$$

The net current produced is the difference between I_p and I_d given as:

$$I = I_p - I_d = I_p - I_o \left\{ exp\left(\frac{e(V - IR_s)}{kT_c} \right) - 1 \right\} \qquad (10)$$

For a better understanding of the PV cell theory, an
I-V characteristic curve for a solar cell can be generated for a given irradiance G and at fixed cell temperature T_c.

When the cell is short circuited, the short circuit current I_{sc} is maximum and the voltage across the cell is zero. While the circuit is open, the voltage V_{oc} is maximum and current is zero. The power dissipated is the product of current and voltage as follows:

$$P_{max} = I_{max} V_{max} \qquad (11)$$

The maximum power point P_{max} as given in equation 11 is ideal and is impossible to attain in practice therefore, Fill Factor (FF) comes into play. The new expression for P_{max} is given by:

$$P_{max} = I_{sc}V_{oc}FF \tag{12}$$

From which,

$$FF = \frac{P_{max}}{I_{sc}V_{oc}} = \frac{I_{max}V_{max}}{I_{sc}V_{oc}} \tag{13}$$

The correlation between short circuit current I_{sc} and I_o is obtained from equation 10 and can be formulated as:

$$\frac{I_{sc}}{I_0} = exp\left(\frac{eV_{oc}}{kT_c}\right) - 1 \tag{14}$$

From which V_{oc} can be obtained as:

$$V_{oc} = \frac{kT_c}{e} ln\left(\frac{I_{sc}}{I_0} + 1\right) = V_t ln\left(\frac{I_{sc}}{I_0} + 1\right) \tag{15}$$

Where V_t is the thermal voltage (V) expressed as:

$$V_t = \frac{kT_c}{e} \tag{16}$$

The power output depends on the load resistance, R and can be expressed as:

$$P = I^2R \tag{17}$$

Hence, equation 10 can be substituted in equation 17 to give:

$$P = \quad \left[\ I_{sc} - I_o\left\{exp\left(\frac{eV}{kT_c}\right) - 1\right\}\right]V \tag{18}$$

Equation 18 can be differentiated with respect to V and equated to zero to obtain the external voltage, V_{max} that enable maximum output power from the cell. The resultant equation is given as:

$$exp\left(\frac{eV}{kT_c}\right)\left(1 + \frac{eV_{max}}{kT_c}\right) = 1 + \frac{I_{sc}}{I_0} \tag{19}$$

The load current that gives maximum power output can be found by substituting equation 19 into 10 to obtain:

$$I_{max} = I_{sc} - I_o\left\{\frac{1+\frac{I_{sc}}{I_0}}{1+\frac{eV_{max}}{kT_c}} - 1\right\} \tag{20}$$

This can be simplified to give:

$$I_{max} = \frac{eV_{max}}{kT_c+eV_{max}}(I_{sc} - I_0) \tag{21}$$

And P_{max} according to equation 11 becomes:

$$P_{max} = \frac{eV_{max}^2}{kT_c+eV_{max}}(I_{sc} - I_0) \tag{22}$$

Electrical efficiency of the PV panel is defined as the ratio of maximum electrical power output to the incident light power and is inversely proportional to the temperature i.e., it is reduced when the temperature increases. This is expressed as:

$$\eta_{max} = \frac{P_{max}}{P_{in}} = \frac{I_{max}V_{max}}{AG} \tag{23}$$

Where A = area of the cell (m^2)

To demonstrate this effect of temperature on the PV efficiency Duffie [42] presented an expression thus written as:

$$\eta_{max} = \eta_{max,ref} + \mu\left(T - T_{ref}\right) \tag{24}$$

Where $\eta_{max,ref}$ is the maximum power point efficiency of the PV collector at the reference temperature (T_{ref}), μ is the temperature coefficient of PV efficiency at reference conditions (normally a negative quantity), and T is the temperature of PV module. Equation 24 implies that, every PV module generates both electrical and thermal energy when struck by solar radiation. The maximum efficiency in this case is the electrical efficiency of the PV which is also designated as η_e

Substituting equation 23 into equation 24 we obtain:

$$\eta_e = \eta_{max} = \frac{I_{max}V_{max}}{AG} + \mu\left(T - T_{ref}\right) \tag{25}$$

Therefore, a reduction in temperature, results in an increase in electrical efficiency the PV module, as well as taking advantage of the resulting thermal energy to heat water for domestic or industrial applications. This constitutes the concept of a hybrid PV/T system.

The overall efficiency of a PV/T system can thus be calculated as the sum total of the electrical and thermal efficiencies expressed as:

$$\eta_o = \eta_{th} + \eta_e \tag{26}$$

3.3 Performance assessment parameters.

The technical performance of the PV/T systems is usually assessed using several analytical parameters such as overall energy efficiency, overall exergy efficiency, primary-energy-saving efficiency, and solar fraction. While, the economic performance of the PV/T systems is measured with Life Cycle Cost (LCC) and Cost Payback Time (CPT), and the environmental benefit of the system is justified using the Energy Payback Time (EPBT) and Greenhouse Payback Time (GPBT). These parameters are briefly described below:

3.3.1 Overall energy efficiency.

The ratio of collected electrical and thermal energy to incident solar radiation striking on the PV/T absorber gives the overall energy efficiency. In comparison, electrical efficiency of a PV/T module is more inferior to its thermal efficiency. This fact implies that, when the thermal energy conversion efficiency increased, then the overall energy efficiency of the system is also improved. It is worth noting that, the overall energy efficiency disregards or does not consider the difference between heat and electrical energy qualities hence, it is insufficient to completely warrant a good performance by PV/T systems.

3.3.2 Overall exergy efficiency.

In contrast to the overall energy efficiency, the overall exergy efficiency encompasses thermal and electric energy quality difference by converting low quality heat energy into the comparable high quality electrical energy using the theory of Carnot cycle. The overall exergy (e_o) of the PV/T could be written as follows:

$$e_o = e_{th} + e_e = (\xi_{th} + \xi_e)G = \xi_o G \quad (27)$$

Where, e_{th} and e_e are the thermal and electrical exergy respectively; ξ_{th} and ξ_e are the thermal and electrical exergy efficiency; ξ_0 is the overall exergy efficiency.

The thermal exergy is expressed as:

$$e_{th} = \eta_c Q_u = \eta_c Q_{th} G = \xi_{th} G \quad (28)$$

Where η_c is the ideal Carnot efficiency [10]:

$$\eta_c = \left(1 - \frac{293K}{293K + (t_f - t_a}\right) \quad (29)$$

Where t_f is the final temperature of the working medium.

The electrical exergy is expressed as:

$$e_e = \eta_e G = \xi_e G \quad (30)$$

The total of the thermal and exergy efficiencies gives the overall exergy efficiency expressed as:

$$\xi_0 = \eta_c \eta_{th} + \eta_e \quad (31)$$

3.3.3 Solar fraction.

This is defined as the fractional ratio of primary energy saving that a PV/T system can obtain to the overall energy demand [7], and is expressed as:

$$f = \frac{1}{2} x \left(\frac{Q_{L,t-}Q_{Aux,t}}{Q_{L,t}} + \frac{Q_{L,e-}Q_{Aux,e}}{Q_{L,e}}\right) \quad (32)$$

Where, $Q_{L,t}$ and $Q_{aux,t}$ are the overall thermal load and auxiliary heat required respectively; $Q_{L,e}$ and $Q_{aux,e}$ are the total electrical load and auxiliary electricity needed respectively.

3.3.5 The primary-energy saving efficiency.

The principle of primary energy saving efficiency was introduced by Huang *et al*. [11], as a parameter that considers energy quality difference between heat and electricity. This is expressed as:

$$E_f = \frac{\eta_e}{\eta_{th} + \eta_{pgen}} \quad (33)$$

Where η_{power} is the electrical power generation efficiency for a conventional power plant, usually considered to be 0.38. However, this value should be above 0.50, to be comparable to an individual conventional solar hot water system.

3.3.6 Economic and environmental indicators of the PV/T systems.

The economic indicators for evaluation of PV/T are the Life Cycle Costs and Energy Payback Time while the Greenhouse-gas Payback Time offers an indication in the environmental point of view. The details of these indicators are given below.

3.3.6.1 Life Cycle Costs.

Tripanagnostopoulos *et al.* [12] suggested Life Cycle Costing (LCC) as an economic and environmental assessment technique for PV/T systems. It accounts for the capital, installation, operation and maintenance costs for the entire life of the system. Other, factors such as inflation, tax, degradation/wear and tear, discount rates etc. are also considered in the analysis [2]. Cost Payback Time (CPBT) method is commonly applied in assessing economic worth of PV/T systems; however, it disregards the maintenance costs and time related quantities, thus weakens the results accuracy.

3.3.6.2 Energy Payback Time (EPBT)

Chow [2] defined EPBT as the ratio of the quantity of energy necessary to produce the PV/T in its production phase to its annual energy output, expressed as:

$$EPBT = \frac{\sum PVT + \sum BOS + \sum Mtl}{Q_E + Q_{th} + Q_{HVAC}} \tag{34}$$

Where ΣPVT, ΣBOS and Σmtl are the energy required for the PV/T system production, the balance of system and the building materials; Q_{PV} is the annual useful electricity output; Q_{th} is the annual useful heat gain (equivalent), and Qac is the annual electricity saving of HVAC system due to reduction in thermal load.

3.3.6.3 The Greenhouse-gas Payback Time (GPBT).

GPBT as the ratio of the embodied Greenhouse-gas (GHG) or CO_2 equivalent of the PV/T in its production phase to equivalent annual reduction of GHG emission from the local power plant due to the PV/T operation energy output [2] given as:

$$GPBT = \frac{\Omega_{PVT} + \Omega_{BOS} - \Omega_{Mtl}}{Z_{PV} + Z_{th} + Z_{HVAC}} \tag{35}$$

Where Ω_{PVT}, Ω_{BOS}, Ω_{Mtl} represent the embodied

GHG (or CO_2 equivalent) for PV/T, BOS and Materials respectively and Z_{PV}, Z_{th}, Z_{HVAC} are the reduction of GHG emission from the local power plant due to the PV/T operation energy output with respect to electric, thermal and HVAC energy savings.

4. Review of past work on PV/T water-based systems.

Past and ongoing research have recorded considerable gains in hybrid PV/T technology regarding overall system's efficiency improvement. These studies are related but not limited to the performance evaluation of different types of PV/T configurations, geometrical optimization, and operational parameters associated with the PV/T. Design, experimental, simulation and modeling studies have been done using different techniques, software and simulation tools resulting in a common trend of various useful outcomes. Numerous theories have been proposed, design configurations suggested and simulation results obtained. Some of the works are selectively highlighted in the following section and are classified and covered in sections of design studies, experimental studies, theoretical and analytical studies, modeling and simulation studies and finally combination of experimental and simulation studies.

4.1 Design studies

Proper design and sizing of solar system is a multifaceted procedure involving both the anticipated (collector, inverter, battery etc.) and the non-predictable (weather data) components. Studies on the design aspects of PV/T modules involve, design techniques, material combinations, PV cells and thermal plated attaching techniques, and their respective analysis.

Sandness *et al*. [13] examined the behavior of a merged PV/T collector built by attaching single crystal Si cells on top of a black plastic solar heat absorber (unglazed PV/T system). Chow [14] built up a clear exciting model of a solitary glazing flat plate PV/T collector with a sheet and pipe theory which realized an improvement in electrical efficiency of about 2% and an extra 60% thermal efficiency was realized too. Huang et al [11] used p-Si PV to develop an integrated photovoltaic– thermal system (IPVTS)which obtained a primary energy saving efficiency of about 61.3%, while the temperatures difference between the tank water the PV module was around 4 ◦C.

4.2 Experimental studies.

Experimental studies, ranging from single to an arrayed system of modules, have been carried out to measure an assortment of operational parameters such as temperature, flow rates, thermal and electrical power conversion rates. Most notable objectives of these experiments cut across determining the actual performance of the PV/T system in different operational environments, ascertaining the relationships between the theoretical investigations and practical applications, and validating the simulation models.

Tripanagnostopoulos *et al*. [12,15] considered unglazed combined PV/T system having an appropriate thermal contact connecting the module with the collector and further did experimental studies on hybrid PV/T prototypes founded on conventional PV modules of distinct dimensions. Tripanagnostopoulos *et al*. [15] advanced these studies by designing and fabricating a pc-Si dual PV/T unit that used both water and air as cooling media based on the prevailing climatic conditions and thermal load. This enhanced system when equipped with a booster diffuse reflector, attained a growth in total energy output by upto 30%.

Agrawal and Tiwari [16], created a thermodynamic model that described energy, exergy and Life Cycle Cost (LCC) in their analysis of Building Integrated Photovoltaic Thermal (BIPVT) system. The a-Si BIPVT system realized energy and exergy efficiencies in the regions of 33.54% and 7.13% respectively under the complex weather environments prevalent at New Delhi. Agarwal and Grag [17] [17] designed the prototypes of thermosyphonic flat-plate PV/T water heaters. Bergene and Lovvik [18][18] then conducted an energy transfer study on PV/T water system composed of flat-plate solar collector and PV cells, which indicated that an overall efficiency of 60– 80% can be achieved and best suited for domestic applications. Elswijk *et al.* [19] installed large PV/T arrays on residential buildings and established that the use of PV/T would save around 38% in roof area, compared to PV and solar thermal modules arranged side-by-side. More recently, Zondag *et al*. [8] categorized the PV/T water-based collectors into four major types namely sheet-and-tube collectors, channel collectors, free-flow collectors, and two absorber collectors.

De Vries [20] and Zondag et al. [8] carried out testing of a PV/T solar boiler with a water storage tank and found that the covered sheet-and-tube system was the most promising PV/T concept for tap water heating with mean annual solar efficiencies in the range of 34-39%. Chow *et al.* [21] performed an experimental study on a combined centralized photovoltaic and hot water collector on wall that attained thermal and electrical efficiencies of 38.9% and 8.56%. Erdil *et al*. [22] introduced the concept of venting to release excess pressure build up in hybrid PV/T module. A daily 2.8 kWh thermal energy could be stored as preheated water for domestic utilization at the expense of 11.5% electrical energy loss. He *et al.* [23] constructed and tested a thermosiphonic PV/T water heating system with a polycrystalline PV module on an aluminum-alloy flat-box absorber that attained a maximum thermal efficiency of 40%. Following this development, Robles-Ocampo et al. [24] constructed and studied experimental model of a PV/T hybrid system with bifacial PV module with a set of reflecting planes to enhance the electric energy production. This system attained an overall efficiency of 60%, for which the electrical efficiency turned out to be 16.4%.

4.3 Theoretical and analytical studies.

Studies on the theories and analysis of performance of PV/T water heating systems revolve around revealing energy balance and temperature changes through different layers of PV/T materials [25] [25,26]; optimization of the structural/geometrical parameters e.g. dimensions and sizes, connections, shapes and establishing the favorable operating conditions such as fluid flow rates and pressures; energy and exergy analytical models to study the overall energy use and performance of the integrated systems [28]1D, 2D and 3D models for energy transfer calculation across modules and energy efficiencies [29].

In the earlier works on theoretical analysis of PV/T system, Florschuetz [25] extended the HottelWhiller equation to model PV/T collectors and developed a linear relationship to predict the effect of cell operating temperature on the PV/T system efficiency. In relation to this study, Jones and Underwood [30][30] also derived an unsteady-state model expression for PV module temperature in terms of irradiance and ambient temperature. To perform quantitative performance predictions of a hybrid PV/T system Bergene and Lovvik [18][18] developed a physical model that predicted the performance of the system reasonably well obtaining overall efficiency in the range of 60– 80%. Dubey and Tiwari [31] developed an analytical model to describe the performance of multiple PV/T flat-plate collectors as a function of design and climatic parameters. They validated with their experimental results and attained an increased efficiency in the range of 33–64% mainly due to the increase in glazing area. The useful thermal energy yield was about 4.17 to 8.66 kWh and electrical energy yield increased from 0.052 to 0.123 kWh depending on the number of collectors.

Joshi *et al*. [27] determined the ‘‘fill factor’’ experimentally and evaluated its effect on the performance characteristics of a PV and PV/T system founded on energy and exergy efficiencies. They found that the energy efficiency ranged from between 33-45%. The corresponding exergy efficiency for PV/T system was between 11.3–16% and for PV between 7.8-13.8%. In the works of Huang *et al.* [11][11], an Integrated Photovoltaic and Thermal solar System (IPVTS) using p-Si cells was examined in comparison to conventional solar water heater. The typical efficiency on a daily basis reached 38% constituting approximately 76% of that of normal solar water heating unit utilizing glass covered collectors which recorded 50.50%.

Meir *et al*. [32] in their study to determine the performance of solar systems using calorimetric technique, concluded that the method requires minimal monitoring equipment because hardly any parameters require recording and scrutiny. The conformity of solar gain was roughly ±10% which is comparatively on the upper but is adequate in reference to the numerical nature of the boundary conditions for solar problems. A lesser figure is preferred for these systems.

Kalogirou, [7] and Zondag *et al*. [8] presented a month-by-month performance of unglazed hybrid PV/T system based on unnatural approach of function for typical weather state of Cyprus and realized an upsurge in average yearly electrical efficiency from 2.8% to 7.7% and thermal efficiency of 49%. The latter in their comparable studies on similar set up obtained 6.7% and 33% electrical and thermal efficiencies respectively. Following this works, Kalogirou *et al.* [33], in their study of use of PV/T solar systems in industry, found out that PV/T systems comprising of pc-Si and a-Si PV panels assembled with water-based heat abstraction elements are more efficient compared to the amorphous types, but their solar fraction is slightly lower.

Charron *et al*. [34] offered a hypothetical study on double-facades incorporating photovoltaics (PV) and powered blinds in which they investigated the effects of a variety of design parameters with regards to exploitation of solar energy. They realized an increase in overall thermal-electric efficiency of up to 25%, but power production was lowered by 21% whilst PV modules were placed midway in the cavity. Hendrie [26] developed a theoretical model for the flat plate PV/T solar collectors and used it study the thermal and electrical performance of an air and a liquid based
PV/T solar collector and found that when the PV modules were operational, the air and liquid based units obtained slightly lower thermal efficiencies which were 40.4% and 32.9% respectively.

The extent of the existing theoretical models has adequate depth and breadth to expose the PV/T technology, predict its performance, optimize the system's configuration and propose the favorable operating conditions. However, more studies need to be done on dynamic performance under prolonged periods e.g., yearly.

4.4 Modeling and simulation studies

Extensive work on modelling and simulation of PV/T systems have been instigated and carried out by Several researchers which have been based on a simple energy balance of each component of the PV/T system, to identify and analyze various performance parameters.

Kalogirou [7] used TRNSYS software to model and simulate a hybrid PV/T solar system limiting his studies to Nicosia, Cyprus and established that the mean annual efficiency of the PV system improved marginally by 4.8%, e.g., from 2.8 – 7.7% and provided a coverage of hot water needs of 49%. In the overall scale, the annual efficiency of the system was found to be 31.7%. The optimum water flow rate was found to be 25 l/h. [5,33] suggested a hybrid PV/T system having p-Si and a-Si cells PV unit fixed to copper pane and tubing heat removal component. The residential industrial applications of these systems were suitably considered and examined in TRNSYS platform. They observed that the electrical output of p-Si cell is superior to that of but thermally, a-Si cell achieved better solar fraction outcome.

Bergene *et al*. [18] proposed a model of hybrid PV/T system and developed algorithms to be used in simulation. The model predicted the system efficiencies of between 60–80% but experienced difficulties in comparing the simulation and relevant experimental results since the system parameters of their model were not explicitly stated and as a result recommended the system for residential applications.

Da Silva *et al*. [4] used surface response methodology and modular strategy approach available in Matlab/Simulink platform to simulate water heating hybrid PV/T collector solar system made of p-Si cells. Their results recorded solar fraction of 67% annually and interestingly 24% efficient in the overall scale: typically, 9% and 15% electrical and thermal efficiencies respectively.

One-dimensional analytical models to predict the thermal and electrical performances of both liquid and air-based flat-plate PV/T collectors were derived by Raghuraman [35]. The analyses considered the temperature difference between the primary absorber (PV cells) and secondary absorber (thermal) absorber flat plate. Tiwari and Sodha [36] developed a thermal model for an Integrated Photovoltaic and Thermal Solar collector (IPVTS) system and compared it with the model for a conventional solar water heater by Huang et al. [11] The simulations predicted a daily primary-energy saving efficiency of around 58%, which was within good agreement range with the experimental value obtained by Huang et al at 61.3%.

To predict the operational temperatures of the PV module and the heat-removal fluid during periods of fluctuating irradiance and discontinuous fluid flow in a transient condition, Chow [37] developed an explicit dynamic model based on the control volume finite-difference approach for a single glazed flat-plate water heating PV/T collector that attained a maximum overall efficiency of a could be over 70% for a perfect collector and might decrease to less than 60% for a low-quality collector.

4.5 Combination of experimental and simulation studies.

In order to offer detailed insights on hybrid PV/T water heating, researchers have extensively done simulation studies and further carrying out experiment to validate their simulation models [36] analyze errors, evaluate electrical and thermal efficiencies in different climatic conditions [5,11,23,29,36] determine heat removal effectiveness of water as a cooling medium [21], establish optimum fluid flow rates and temperature distribution across various layers [43] In addition to the above highlights, other relevant works from the literature study have been singled out and cited as follows.

Jie *et al.* [38] did validation analysis of a combined PV/T free flow water boiling system. Their assessment outcomes indicated that the normal everyday main energy reserved reached up to 65%. The PV cell lamination factor was 0.63 and forward-facing glazed cover transmissivity recorded 0.83 as soon as the hot water capacity per unit heat absorbing area surpassed 80kg/m^2.

Sandnes and Rekstad [13] simulated temperature distribution, thermal and electrical performance of a PV/T unit made of a polymer solar heat collector attached to single-crystal silicon PV cells, using an analytical model derived from the Hottel-Whiller model and experimentally tested the unit. Their simulation results agreed with the experimental data which showed that the solar energy absorbed by the panel could be significantly reduced (10% of incident energy) by pasting solar cells onto the absorbing surface. They recommended that combined PV/T concept should be applied in relatively low temperatures to give the desired cooling effects.

To sum it up, combined modeling and experimental studies reported are very extensive, and in good agreement with most theoretical results and hence present practicable lead to their real use. However, further study opportunities lie in aspects of measuring of the long-term dynamic performance of the system in varying operational conditions.

4.6 Economic and environmental assessment.

Economic and environmental assessment of PV/T systems related research work covers the comparison of various solar conversion technologies used in isolation and PV/T systems [39], Life Cycle Costing, Energy Payback Time and Greenhouse gas payback time estimation and their applicability, PV/T energy saving prospects and its cost augmentation [12].

Hybrid PV/T system must rise above expenditure constrains for the thermal and PV units to accomplish a balanced merger because price and associated expenditure concerns significantly come to play for energy-system decisions. The Cost Payback Time (CPBT) for ordinary PVs devoid of financial backing ranges between 15–20 years. When PV/T systems temperatures are kept down during operation, their CPBTs are in the region of 10 years, while CPBT is longer for greater system functioning temperature due to reduction in thermoelectric efficiency [12].

Life Cycle Assessment (LCA) method seeks to evaluate the probable effects on the environment, posed by manufactured goods or services offered throughout their entire existence. In every part of the system, environmental parameters must be evaluated beginning with unprocessed material handling to discarding at the stop of existence. The major part, about 99% of the overall effects, emanates from the PV unit, i.e. starting with manufacture of every part, together with BOS.

Even with the discarding period input insignificant, a detailed examination is essential for estimating the prospective gains from a 'controlled' discarding scheme in PV/T collectors plus BOS, hydraulic-circuit, heat removal unit, and extra parts, whilst LCA facts must as well be taken into consideration in PV units manufacture [12].

Krauter *et al*. [40] studied a CO_2 complete stability in a PV power unit lifecycle and established that the real PV system impacts, in relation to residual CO_2 cutback is the difference between the summation of electricity output associated with the neighborhood distribution network and cost recovering and the summation of the manufacturing needs and the transportation discharges.

Fthenakis and Kima [41] examined solar and nuclear electrical energy production technologies power generation entire lifecycle; CO_2 and the rest of the gases given off throughout the removal, generation, and discarding of allied products and evaluated greenhouse gas (GHG) release, specifically, Carbon dioxide, Methane, oxides of nitrogen and CFCs because of resources and energy paths all through the life cycle phases of solar and nuclear electricity production machineries.

Environmental and economic assessment to this end seems sufficiently covered considering the PV/T technology's performance economic and environmental aspects have been sufficiently assessed to indicate its carbon benefits. More work may be required to extend to long term systems' performance assessment under varying climatic conditions.

5. Application of Photovoltaic/Thermal Collectors.

PV/T collector technology is an emerging technology in its initial stages of implementation and has attracted immense attention. A review of literature has shown extensive opportunity for application in different areas, notably, in the industry and agriculture.

5.1 Application of water-based PV/T collectors in industry.

Solar plants application in industrial establishments is presently less than 1% weighed against their application in domestic households, restaurants, and other commercial ventures. Hybrid PV/T systems are potential components for extensive utilization and adaptation to numerous industrial processes like distillation, cleaning, disinfecting, pasteurizing, aeration, steaming, refining, polymerization, etc. since most of these activities require both electric power and heat. Just a minor fraction can be fulfilled majorly because the thermal and electricity demands are generally excessively great to be provided absolutely using solar energy systems. The electricity requirements can be provided by PVs without difficulties because they match definite voltages and rated powers. While for heat, the working temperatures are significant considerations therefore the PV/T would be suitable only if it attains the required temperatures [5].

PV/T systems are suitable for numerous industrial processes operating under moderate temperature range, between 60–80 °C and mostly less than 50 °C. For instance, water-based PV/T systems may well provide hot water suited for cleaning activities. Additionally, less costly reflectors, like brightly coated faces and non-concentrating reflectors may well improve the heat energy yield [15].

5.2 Application of PV/T in buildings.

PV/T in its right configuration can be applied in both residential and commercial buildings to provide hot water needs and warming in cold environments. [33]. Besides water the electricity requirements are also offset depending on the size and demand.

5.3 PV/T in agriculture

In the agricultural segment, PV/T collectors are used in conservatories, hatcheries, preservatories, aeration, saline water purification etc., giving the necessary thermal and electric power. Greenhouses usually require warmth during winter and aeration in summer therefore PV/T collectors could provide these loads, whereas illumination controls in the internal opening is essential nearly throughout the year. Drying is another farming activity in which PV/T collectors play significant part. Additionally, saline water purification and recovery to be used in irrigating land are further potential PV/T collector application areas [45]

5.4 Application of PV/T collectors in combination with other renewable energy sources.

In several circumstances, a single energy source may be insufficient or uneconomical to meet the demand, hence, ought to be merged with supplementary resources. Solar thermal system combines well with geothermal power as well as biomass boiler to satisfy built environment energy requirements for heating or cooling demands. PV/T collectors provide novel prospects for efficient blending of solar powered heating and superficial well geothermal plants. For this situation, the fairly warm temperatures of underground water may be improved using PV/T collectors, whilst the generated electric power by the PVs to take care of electric load requirements [6].

Combined PV/T collector-biomass boiler system provides a compatible and efficient pairing in terms of power outputs. The boiler meets the major heat demands while the PV/T preheats the boiler feed water to boost steam generation rate in the boiler. Therefore, the conventional fuel consumption is optimized, and steam output maximized [6].

PV/T collectors when paired, mostly with low-scale wind turbines, reliably serve to provide satisfactory energy yields. In PV/T/Wind Turbine system configuration, the output from the solar element relies on the sunlight period while wind-turbine section productivity is largely always determined by the prevailing wind speeds, e.g., daytime or night-time. Hence, these subsystem combinations complement one another in built environment electric power demands while surplus heat energy obtained heats water stored in tanks or used directly for hot water needs [6].

6. Opportunities for advancement of PV/T water heating.

Considerable amount of research and studies have been conducted on PV/T water heating systems as is evident in this review. However, there are more opportunities and widespread areas of growth for this technology as summarized in this section.

There is need to advance dynamic simulations under real conditions to reflect the fluctuating nature of climatic parameters on which the performance of PV/T systems are premised. Factors such as fluctuation in ambient temperatures, solar radiation, and wind speeds are crucial to the system’s performance and are not easy to predict with regard their respective long-term effects. This has a bearing on the economic and environmental analysis, which is presently restricted to simulation in laboratories, and hence the need for long-term measurements. To increase the PV/T systems attractiveness, it is vital to formulate a universal thermal model that can be used for all varying climatic conditions.

Further improvements, such as inclusion of vacuum or low-pressure noble gases to replace PV cell encapsulations, with a view of improving module emittance and ensuring that the air is not oxidized or degraded can be done. Moreover, simulation and subsequent experimental validation studies of evacuated flat- plate PV/T collector is still an area that has not been studied. This work is currently being undertaken by the authors as part work of the research project.

Although considerable amount of work has been done on optimization and sizing, there is also need to enhance geometrical and dimensional parameters of the PV/T with a view of improving their thermal and electrical performance. The concept of sheet and tube is by now more established as the most effective configuration adopted for PV/T heat exchange, there is still an opportunity to establish more ways of improving here transfer. An optimal design configuration of PV/T system would function to provide electricity and hot water cost-effectively compared to isolated PV and solar thermal units.

7. Conclusions

The concept of PV/T water heating is founded on the premise of temperature reduction of PV units for efficiency enhancement, a noble idea that originated in the late 1970's. PV/T technology combines PVs and solar thermal components into a unitary module to enhance the solar conversion efficiency and make economic use of the space. Mechanisms of absorbing and transferring the residual heat dissipated because of exposure of solar cells to solar radiation have been designed in different configurations and dimensions optimized by different researchers. This study has extensively revealed the idea of water heating using this technology, extent of past and ongoing research studies based on the theoretical and analytical techniques, experimental, modeling and simulation, economic and environmental assessments. The outcome of this study enables a better understanding of the current status of the PV/T technological enhancements, identification of the impending problems and obstacles, existing standards and regulations with regard to PV/T design and installation, areas of application and the potential research opportunities for further
improvements in the performance of the PV/T,

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