January - February 2020
ISSN: 0193 - 4120 Page No. 9168 - 9175

Solar Photovoltaic Thermal System Heat Transfer Analysis

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Abstract:
Photovoltaic Thermal (PVT) /Hybrid collectors are an integration of Photovoltaic (PV) as well as solar thermal (ST) collectors. This propitious technology is integrated by generating heat together with electricity simultaneously. This technology elevates the overall system efficiency and diminishes the price of solar electricity. The outcome of those electricity and heat generations recommends that this technology could be pertinent for utilization in buildings, specifically at the time of limited installation area. To retain the operational efficacy of the PV system, heat must be eliminated from its surface, thereby leading to the emergence of PVT. Recently, thermal energy (TE) storage scheme attracted increasing attention connected to thermal applications like space, waste-heat usage, water heating, air-conditioning, and cooling, etc,. Here, a comparative study betwixt solar devices is proffered. Such devices encompass: i) PVT System, ii) Hybridized PVT collectors, iii) PVT air collectors, together with iv) PVT water collectors. The PVT-heat transfer (HT) methodologies associated recent papers are also examined. The central purpose of this research is to elevate HT rate of the PV cell (PVC) to attain higher electrical efficiency (Eeff). Finally, the top-notch methodologies comprising HT are contrasted by considering temperature as a parameter.

Keywords: Photovoltaic Thermal, propitious technology, solar thermal.

I. INTRODUCTION

The solar energy (SE) is an eco-friendly, renewable, and freely existing energy source on earth. In modern years, the contribution of this renewable energy (RE) to the universal sustainable development and environmental conservation has been commonly recognized [1].

Its application shields the environment from its deterioration and simultaneously, its use would make sure the conservation of energy resources. Amongst all existing RE choices, SE seems utmost propitious sustainable energy resources. Hence, the SE centered schemes could face energy demands and also could balance the ecosystem. Solar radiations (SR) could be transmuted to electrical energy (EE) or TE or else both.

SE collectors are a unique category of heat exchangers which transmute SE into an internal energy of transporting medium. The chief constituent of this solar scheme is a solar collector. This collector absorbs the inward SR, transmute it in to heat, and after that, alter the heat to a fluid (normally water, oil or air) which flows via the collector. The SE thus gathered is carried as of the circulating fluid to the space conditioning or hot water equipment directly or TE storage tank which is drawn for using it at cloudy days

January - February 2020
ISSN: 0193 - 4120 Page No. 9168 - 9175

and/or night [2, 3]. Consumers and policymakers paid maximum attention on SE centered technologies which are a viable solution to growing energy demands [4].

SE could be captured in 2 fundamental ways like i) photo-reaction and ii) heat. The controlled SE might be categorized as per the applications, like solar fuel manufacture, solar heat, PV electricity, and ST electricity. Amongst these domains, the solar technologies are a) PV - directly transmutes sun-light to electricity; b) Concentrating solar power -TE as of the sun is utilized for running utility-scale turbines to create electricity; and c) ST-solar heat is employed for generating hot water. Aside from those conventional strategies for producing SE, a new hybridized approach that assimilates the solar PV with ST [5-7] on a single unit (termed as PVT) is attaining eminent day to day. The SE conversion approaches along with their inter-relation are delineated in Fig1,

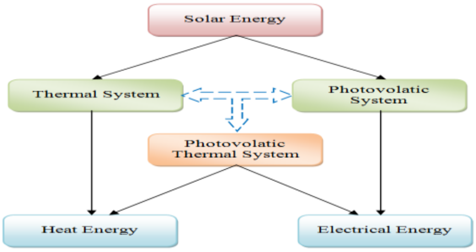

Figure 1: SE Conversion Technologies [8]

1.1 Concept of Photovoltaic-Thermal (PVT) System

In a component termed PVT collectors, the PV produces electricity and act as the thermal absorber. Both power and heat are created simultaneously in this manner, [9]. PV technology is the utmost propitious RE technologies [10]. Solar PV indicates power system that intended to contribute usable solar electricity by PV effect [11].

The hybridized PVT air collector comprises principally of single crystal silicon (Si) PV device and PV module (PVM) for the discharge of the heat of the air stream generated by the transformation of SR. The heated airflow cools the PVM to elevate its electric performance.

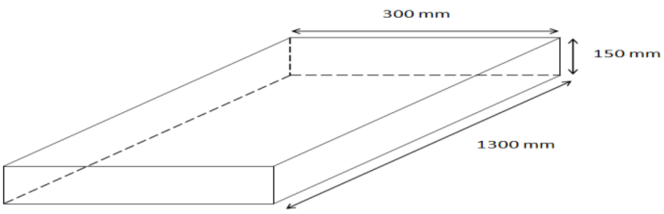

Figure 2: Dimensions of the PVT System

PV technology is centered on the photoelectric effect (PEE) and it is revealed in 1839 by Edmond Becquerel which was delineated and affirmed as the law of PEE by Albert Einstein in 1905. PVCs encompass semi-conductor constituents that embrace a p-n junction [12]. A meta-stable electron-hole pair which exists merely for a brief time prior to re-combining is developed by absorbing the incident photons of sun-light in PVCs. The re-combination of the light-created carriers is evaded via spatially isolating them with a p-n junction, as if linked, directs to the holes and electrons for gathering a p-type as well as n-type poles, correspondingly. This stimulates voltage differences which force the light-created carriers to run via an external circuitry generating direct current (DC) electricity (provided in fig 3). PV power system applies solar panels (as well termed as PVM), where each encompassing countable solar cells (SCs) interlinked for generating required power.

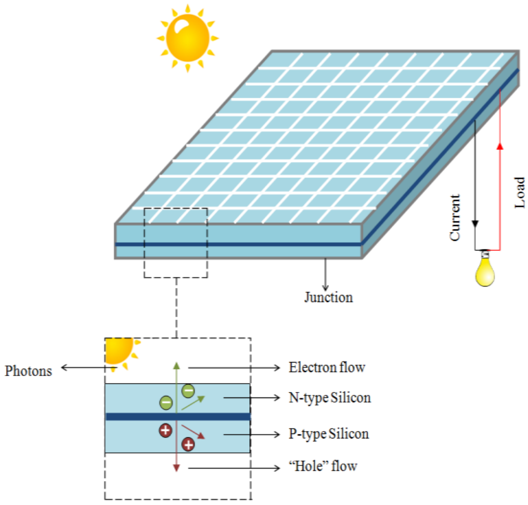

Figure 3: The Photovoltaic Effect

The concurrent cooling of a PVM sustains E_{eff} at a reasonable level and hence the PVT collector proffers an enhanced mode of employing SE with maximal overall efficacy. There are variant methodologies in PVT integration. Amongst them, there could be selections on i) water, evaporative or else air collectors, ii) thin-film SCs or else poly-crystalline Si (pc-Si) /mono-crystalline Si (c-Si) /amorphous Si (a-Si), iii) concentrator or flat-plates, iv) unglazed/glazed panels, v) forced/natural fluid flows, vi) building-integrated/standalone features, et cetera. A central R&D practice the PVT approach in the earlier period with a steady elevation in the degree of actions.

The striking traits of the considered PVT scheme are:

a) Dual-purpose: Here, the same scheme could be utilized to create heat and electricity.
b) Flexible and Efficient: In this, the combined efficiency is constantly higher on utilizing 2 independent schemes and as well it is specifically effectual in developing integrated PV whilst the roof-panel spacing is restricted.

January - February 2020
ISSN: 0193 - 4120 Page No. 9168 - 9175

c) Wide application: the output heat employed for cooling and heating applications (i.e. desiccant cooling) is contingent on the seasons and it is almost relevant for the domestic-related applications.
d) Practical and cheap: it is simply retrofitted/integrated to build without any notable modification. Then replace the roofing component with this PVT scheme to diminish its payback period.

II. RELATED WORK

2.1 Photovoltaic Thermal System

Chung et.al [13] intended and optimized the PVT parameters integrated with reflectors. Furthermore, it delineated the achievement of E_{eff} and thermal efficiency (T_{eff}) on the PVT after embedding 2 reflectors on the north as well as south sides and by altering the water circulation scheme. For experiential planning, Taguchi orthogonal arrays where the optimum parameters were examined for E_{eff} and T_{eff} were utilized. To ascertain the imperative parameters, and PCA point of every experiment, the respective ANOVA and PCA ('principal component analyses') were implemented. The outcomes were implemented to build a response surface strategy. Lastly, the steepest descent strategy was employed to attain the optimum parameters. Then, the reflector theory was propounded to evaluate the elevation of SR quantity following the reflector addition. Furthermore, this elevation was transmitted to the TRNSYS software for simulating the water temperature and electric power output from the water storage. The assenting tests of the 4 seasons ascertained that the EE after addition of reflector elevated by 0.117–0.183kWh, whilst the TE augmented by $1.7^0\,\mathrm{C}$ to $2.6^0\,\mathrm{C}$. The test affirmed that it possesses the prediction error of at most <4%.

Zhongbing et.al [14] proffered a dynamic design for a PVT-TEV (PVT-compound thermoelectric ventilator) scheme, in which PVT collector creates electricity amid winter and concurrently pre-heats the fresh-air to attain inclusive SE utilization. The pre-heated fresh air was again heated using the TEVs and subsequently infused into an inside room. Also, the proffered PVT-TEV comprises the functions like i) sun-shade, ii) power generation, iii) waste heat revival along with iv) supplying fresh-air for houses. This model was verified by the data congregated as of PVT-TEV under existent climatic criteria. The outcomes disclosed that the simulated value was compatible to the experiential value. This PVT-TEV's performance in disparate working scenario was also examined by utilizing the propounded model. Elevating the clean air-mass flow rate (MFR) could augment the heating and electrical performances of PVT-TEV scheme. Moreover, the PVT-TEV's total performance coefficient (COP_{total}) doesn't develop whilst the fresh airflow rate rises from $93\,{m^3}/{h}$ to $123\,{m^3}/{h}$ and $153\,{m^3}/{h}$ owing to the fan power increase. The TEV system's heat gains and the PVT-TEV's fresh-air O_T (outlet temperature= O_T) are increased by a working current. The maximization of interior temperature could augment the PVT-TEV's performance. The suggested design of PVT-TEV scheme proffered a base for the structural model and PVT-TEV's yearly performance optimization.

Wafa et.al [15] propounded the utmost valuable 2 dimension numerical prototype. This thermal/electrical model computed the net EE and TE centered on the EB (Energy Balance) of CPV-T receiver. The numerical outcomes were contrasted and experiential studies were proffered to validate the feasibility of this propounded prototype. The outcomes exposed that the numerical prototype well-forecasted the output power utilizing the experiential data with low-level mean percentage errors. Certainly, the parameters influenced the system's performance and they were briefly delineated. The simulation method has evaluated the CPV-T power generation. It also executes an inclusive economical analysis under Chambery together with Tunisia scenarios. The CPV-T scheme has confirmed its viability specifically in zones with maximal SR.

Ali and Mahmoud [16] recommended a cooling methodology for concentrator PV scheme utilizing ample micro-channel heat-sink (MCHS) with nanofluids. An inclusive 3D prototype was introduced. The model paired the 2-phase ('Eulerian-Eulerian') and multi-phase prototype for the conjugate HT of nano-fluid flow in an ample MCHS using the concentrator PV thermal prototype. This prototype was simulated numerically and verified with the prevailing numerical and experiential data. The nanoparticle types, volume fractions (VF), together with coolant flow Reynolds number (FRN) highly influenced the SC performance parameters. Outcomes signify that utilizing SiC-water nano-fluids acquires low-level cell temperature contrasted to Al_2O_3-water nano-fluids. The elevation of nano-particles VF ratio incredibly diminished the SC temperature and enhanced the EE and temperature uniformity. Additionally, raising the FRN to a specified value notably augments the net EE. Furthermore, an elevation of the FRN brings an imperative diminution in the cell net gain power. Utilizing 4% SiC-water nano-fluid, the diminution in maximal local SC temperature lied betwixt

$8^0 C$ and $3^0 C$ coned with clean water by varying the FRN as of 12.5 - 250 when 'solar concentration ratio' = 20.

Steffen et.al [17] paid attention on the performances proffered by the un-covered PV-T collectors with a removable PVM on the macroscopic air gap effects and heat exchangers. Thin film components encompassed frameworks were constructed without utilizing heat conductive paste/adhesives or Si glue. Gauged on sun simulator of electric open-circuitry sort, the thermal '0'-loss efficacies for the adhesive-less collectors were $\eta_{0,M} = 66.80\%$ (copper pipe meander laser weld on alumina sheet) and $\eta_{0,M} = 69.20\%$ (alumina roll-bond) in respect of gross regions. Those outcomes were identical or excellent on considering the efficacies of commercial collectors. Owing to the air gap's thermal resistance, the computed temperature differences of 12K is maximal betwixt heat carrier and absorbing sheets, which have to be concerned whilst assessing the electrical attainment by simulations. A framework of 'roll-bond heat exchanger' along with 'intensively thin adhesive layer' was developed for comparison. Therefore, the attained optimized HT was ($\eta_{0,M} = 76.80\%$). Utilizing numerical 2D frameworks, it could validate the efficacy measures and ascertain the influences of model and boundary scenarios on HT strategies in the recommended collectors. At last, Simulations exposed excellent experiential outcomes and proved to be an effectual tool for optimization.

Table 1: Analysis of Solar Photovoltaic Thermal System

Researcher Name and year	Model Used	Purpose	Limitations
Peng et.al [18]	Concentrating PVT utilizing beam splitting approach.	Solar Energy	It eliminates 71 percent of the un-preferred radiation and also it proffers 30% of SE at a higher temperature
Cheng et.al [19]	Concentrating PVT with the physical and mathematical framework.	Electrical Efficiency	EE chiefly depends on entransy loss coefficient and entropy generation.
Xue et.al [20]	Concentrating PV/Concentrating Solar Power	Electrical efficiency	The solar-to-EE decreased as of 44% to 36.80%.

2.2 Hybrid Photovoltaic Thermal Collectors

Hassan and Mohammad [21] modeled a hybridized PVT-PHP collector (PHP- Pulsating Heat Pipe) aimed at ameliorating the EE, via diminishing the PV panels' temperature, and exploiting the TE. An experiential arrangement of intended collector was developed, and its operation parameters were quantified. Those parameters embrace a) SR intensities, b) ambient temperature, c) filling rate, d) inclination angle, d) PV temperature, e) open-circuitry voltage, f) short-circuitry current, g) condenser inlet & outlet-temperature, h) water flow rate, i) fill factor, j) heat delivery, k) E_{eff} and l) integrated efficacy. The outcomes exposed that this recommended design has proffered an excellent EE and TE contrasted to the conventional PVT and PV.

Longsheng et.al [22] propounded a conception of PVT water collector wherein SC was located on the base of the glass cover. A numerical framework of this PVT was propounded and verified by experiential tests. With numerical examination, it was discerned that at a covering factor, the PVT-SC's electricity transmutation efficacy surpasses the conventional PVT's efficacy by almost 10% whilst its T_{eff} was approximately 30 percent lower on considering the traditional PVT's T_{eff}. As the covering factor varies as of 0.050 to 1, the T_{eff} drops almost 70.00%. When the water mass in the tank rises up, the T_{eff} of the both PVTs elevate. In the interim, the ultimate water temperature of the conventional PVT collector diminishes $>17^0 C$, whilst it diminishes $<6^0 C$ for the novel PVT, when the water mass elevates as of 100kg to 300kg.

Bosheng et.al [23] recommended a CCHP scheme by integrating concerted PVT technology with a superior air-handling method that brings sovereign regulation of humidity and temperature. The resulted heat as of a PV-T was utilized for desiccant re-production in a 2-phase liquid desiccant cycles amid hot season, and could be straightly supplied to adjacent users amid winter. In 2002, an office under climatic scenarios at Beijing was undertaken to discern its disparate energy needs. Owing to an effectual utilization of SE, i) annual energy saving rate and ii Carbon-di-oxide emission reduction rate was forecasted to be 73.280 and 74.550 percent, correspondingly. 2 intense scenarios ascertaining that if the surpass heat as of the PVT was utilized were contrasted to delineate the bottom and top limits of economical performances. The incorporated

January - February 2020
ISSN: 0193 - 4120 Page No. 9168 - 9175

performance, energy, pondering environment, and economical factors, attain 37.480% when no surplus heat as of PVT was utilized, and it could be ameliorated by thermal storage or regaining the surplus heat for generating other certain products. Moreover, it proffered a solar-utilization mechanism and also finer integrated performance for tri-generation.

Bosheng et.al [24] recommended a liquid desiccant scheme incorporated with a concerted PVT for deep de-humidification. The resulted electrical power makes a vapor compression chiller to cool the desiccant solution for a 2-phase de-humidification, and then the resulted heat as of the collector was employed for the desiccant re-generation. Simulations specified that the recommended scheme has the utmost power saving competency of 55.650% on contrasting with the classical one, in addition to the equivalent power generation efficacy reaches 8.70 percent in the base model scenario. A relative driven force examination exposed that the 2-phase de-humidification has a good comparative driven force on contrasted to the single-phase liquid desiccant de-humidification, therefore directing to a minimized irreversible loss of 65.430%. Sensitivity specified that the de-humidification temperature decisively impacted the system's performance. The energy efficacy reached maximal 13% value as the de-humidification temperature was 22.30 °C. The economical works exhibited that an investment on the concentrated PVT has the huge share of the total primary investment, and a notable impact on the payback period. This period could be lessened if the upside of the clean development approach was concerned.

Hafsia et.al [25] propounded the designing of a hybridized PVT collector grounded on the thin films SC of CdTe, and then resolve the temperature intensities of the disparate layers via the introduction of the EB sheet that embraces the heat exchange betwixt the disparate constituents of the collector to examine its thermal and electrical performance, and lastly contrast their efficacy with that of the PVT collector grounded on cSi.

2.3 Photovoltaic Thermal Air Collectors

Kasaeiana et.al [26] endeavored to design and optimize an air PVT scheme. There were certain parameters that influence the efficacy of a PV-T solar scheme say a) glass thickness, b) Tedlar, c) inlet flow temperature, d) SC temperature, etc. The equations were derived for a thermal collector and PVC. By implementing genetic algorithms (GA), T_{eff} and E_{eff} of this system might be well-optimized. The parameters employed in GA could be varied, and the SR which is a non-changeable parameter can't be utilized in this algorithm. By contrasting to other methodologies, it was found that the GaAs were intensively effectual to appraise the design parameters of PVT solar schemes.

Kim et.al [27] intended an air-centered PVT using a mono-crystalline PV, and its T_{eff} and E_{eff} was examined with the experiential outcomes. The results specified that the average of T_{eff} and E_{eff} for the PVT collector were, 15% and 22%, respectively.

Lippin et.al [28] recommended a framework for a solar hybridized PVT air collector. The outcome exposes that in the suggested design 20 percent enhancement in overall performance was attained on contrasted to conventional solar hybridized PVT air collector.

Farshchimonfared et.al [29] paid attention on the air distribution (AD) scheme using PVT air collectors with the target of optimizing the AD duct diameter, channel depth ('*D'*), and air MFR /unit collector region in respect of the complete performance. A weighed effectual TE output that encompasses EE and TE. Also, fan power utilization was employed to scrutinize the entire system's energy performances. This study designs PVT air collectors comprising [10m^2, 15m^2, 25m^2, and 30m^2] collector areas (A_c) and [0.5, 1.0, 1.5 and 2.0] length (L) to width (W) ratios (*L/W*) connected to an AD scheme of a house in a mild winter (example. Sydney). For a constant increase of temperature (10^{0}C), and elevating the rates of effectual TE output per unit A_c (Q_{eff}) sent to the building, the optimum '*D'* (D_{opt}), the flow of air-mass (*m*) per unit A_c (m/A_c), together with the AD duct's diameter were utilized optimally. The m/A_c's optimal value was constant and it is approximately equivalent to $0.021 kg/s\ m^2$. D_{opt} value differs as of 0.09 to 0.026 *m* and the optimum AD duct varies as of 0.3m to 0.5m. D_{opt} elevates as the L/W and A_c augments.

Juwel et.al [30] recommended an air type single pass PVT scheme where innumerable thin rectangular fins were developed for heat dissipation. The PVT performance was examined using a scheme that was incorporated by a TFMS (thin flat metal sheet). Subsequently, the temperature parameters were gauged and then contrasted with innumerable operational states. Analytical expression was resulted as of the EB equations for all design components. Average temperatures as of the rear/top PV surfaces, and collector's back wall surface and O_T or inlet temperatures (I_T) were recorded under [0 to 4] fins, MFR [0.02kg/s- 0.14kg/s] and SRs [200 to 700*W/m*^{2}].

January - February 2020
ISSN: 0193 - 4120 Page No. 9168 - 9175

Those readings were utilized in computing the E_{eff} and T_{eff} of the recommended PVT system. The maximal T_{eff} and PV efficacy were attained about 56.190% and 13.750% correspondingly for 4 fins at 0.14kg/s of MFR and 700W/m^2 of SR. Besides, i) the root mean square, ii) percentages of deviation (e) and iii) correlation coefficient (r) were utilized for verifying the outcome whilst delineating the uncertainties. The work would be valuable for designing thermal collectors. It proffers helpful information concerning performance enhancement methodologies in PVT schemes.

2.4 Photovoltaic Thermal Water Collectors

Niccolo et.al [31] proffered the framework of a covered PV-T collector with i) a roll-bond flat plate absorber, ii) thin film PV expertise, as well as iii) a simulation prototype, build via the delineation of innumerable mathematic equations, for appraising the performance offered by covered PVT water collectors. Lastly, works on a yearly and daily production of the recommended PVT collector, contrasted to a standard PV, were elucidated.

Sobhnamayan et.al [32] proffered the solar PVT water collector optimization which was centered on exergy conception. Thermal examination of PVT is contingent on its electrical scrutiny; thereby, 5-parameter current-voltage (I eV) design was utilized to attain electrical parameters like open- and short- circuit voltages, current and voltage at the scenario which has maximal electrical power, EE, etc.. For attaining exergy efficacy of PVT, exergy together with energy examination are requisite. Concerning exergy balance for disparate constituents PVT, then attain the expressions that exhibit the exergy of the disparate PVT collector parts. Certain corrections were executed on a specific expression to acquire a modified exergy efficacy equation for the PVT water collector. A computer simulation was introduced to acquire the measure of electrical and thermal parameters GA was utilized to optimize the exergy efficacy of PVT collector (water). Pipe diameter and optimal inlet water velocity were $4.8\,mm$ $0.09\ ms^{-1}$, respectively. Maximal exergy efficacy was 11.36%. Lastly, certain parametric examinations were made to find the impacts of climatic exergy efficacy parameter.

Feng et.al [33] propounded the thermal and PV performances of PVT water collector along with water heater in houses. Centered on the EB equations, certain performance parameters, encompassing the PV efficacy, the SC temperature, the water's O_T, the HT rate and PV power. The effect of the series-linked PVT number, the water's I_T, and the MFR on the thermal and PV performances were delineated and examined. The strategies of enhancing the thermal as wee as PV performances were deduced. The outcomes specified that the less series-linked PVMs, the higher MFR, and also the lower inlet water temperature brought the higher PV efficacy.

2.5 Photovoltaic Thermal System Heat Transfer Enhancement Methods

Chang et.al [34] tackled disparate parameters prevailing for twisted taps. On contrasting friction factor (f) with the Nusselt number of twisted tape with former correlation were formed to assess the turbulence prototypes employed. Impacts of the clearance and twist ratios of [C=0 {tight fit}, 1, 0.7, 0.5, and 0.2] and [γ=41.7, 25, 15.6, 5.0, 2.5] correspondingly on HT rate (Nu), f were scrutinized under non-uniformed heat flux utilizing molten salt in place of testing fluid. Additionally, the grid generation impacts on prediction outcomes were as well registered. Numerical evaluations were executed with FLUENT code 6.3.2, for the gamut of Reynolds' number [7485 to 30553]. The outcomes exposed that the inserted twisted tape could notably augment the uniformity in temperature dissemination of molten salt and tube wall. Moreover, the diminishment of twisted rate 'γ' and clearance rate 'C' could augment the HT rate effectively. Specifically whilst C was '0', it was the 'HT enhancement' (HTE) effect with tight-fit twisted tape. Simultaneously, the reduction of C and γ, increases the f. Such methodologies and outcomes could be extended to the HTE of the entire solar receivers.

Table 2: Analysis of PVT HTE Methods

Researcher Name and Year	Model Used	Purpose	Limitations
Chang et.al [34]	ST	HTE	More power is requisite for pump power consumption.
Shuang et.al [35]	PVT system	HT	The pressure elevates rapidly in contrast with the condition of non-radiation coupling.

January - February 2020
ISSN: 0193 - 4120 Page No. 9168 - 9175

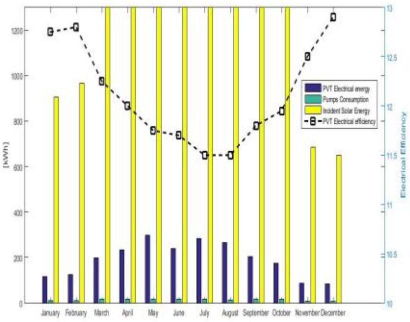

Figure 4: EE Produced by PVT Plant, Consumed by the Pumps, Incident SE and E_{eff} [36]

Discussion: Figure 4 [36] depicts the EE measures linked to PVT plant: the EE created is the AC energy with pump consumptions. The SR which is a portion of the complete radiation is incident with the PV surface (which is, 73%). So, E_{eff} is the ratio betwixt those 2 quantities. Hence, the lesser values during summers (whilst SR and ambient air temperature are maximal) are owing to the E_{eff}, sensitivity of crystalline Si cells and their temperatures.

III. CONCLUSION

PVT hybrid solar collectors are sometimes termed as hybrid PVT systems. PVT is a system that transmutes the SR to TE and EE. This system integrates a SC which transmutes sunlight to electricity utilizing an ST collector which detains the remaining energy and eradicates waste heat as of the PVM. PVCs suffer as of a fall in efficacy with the elevation in temperature owing to the increase in resistance. In the recent decennium, PVT installations have transformed as of largely project-centered developments to comparatively standard schemes. The market is still extremely compact contrasted to the ST and PV markets, but innumerable commercial products are presently existent. Disparate categories of systems have attained ground in various countries centered on the composition of the former markets for ST and PV, but also contingent on the achievement of individual firms. This paper proffers a survey on latest researches, (i.e.,) solar PVT scheme, PV – air collectors, PV – water collectors, etc, and also delineated on PV-HTE methodologies which may encourage more installers to select PV/T schemes in support of clean PV or ST schemes.

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January - February 2020
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