Decision Tree Based Approach to Control the Efficiency of a Hybrid PV/T Solar System in Bangladesh

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ABSTRACT

The Hybrid PV/T solar system is a combination of the photovoltaic (PV) module with a solar thermal collector. The system can provide electrical and thermal energies; and therefore increase both the total energy output and the overall system efficiency. For the experiment, a modified PV/T solar system was set with a water heat exchanger; so that excess heat, which is generated in the system and can hinder the PV module electrical efficiency, is removed upon reaching an optimal temperature. At the same time, the thermal efficiency can be improved. Further analysis has been carried out using the statistical correlation method and decision tree based data mining approach.

Keywords*:* Solar cogeneration, solar CHP, PV/T hybrid system, solar energy, PV panel, data mining, decision tree, PVT improvement.

INTRODUCTION

The Hybrid PV/T or simply PVT system commonly referred to as photovoltaic thermal hybrid system, where circulating air or/and water—of lower temperature than that of PV module—are heated. It is a solar energy system which combines two different methods of energy conversion: Photovoltaic which converts electromagnetic radiation into electricity and heat energy which absorbs and utilizes solar energy mainly for heating purposes. Thus the whole plant can be considered a solar co-generation or combined heat and power (CHP) system. The improved PV/T systems have key energy-efficiency advantages and could be used instead of separate installation of plain PV modules and thermal collectors.

The Hybrid PV/T solar system consists of PV modules coupled to water and/or air heat extraction devices. The heat extraction method is not only introduced for PV cooling, but also for other practical heating applications such as solar heating, water desalination, solar green-house, solar still, solar heat pump, air-conditioning system etc. This system is simple and suitable for building integration or providing hot water/air depending on the season and the thermal needs of the buildings.

About 5-15% of the incoming solar radiation is converted into electricity and a greater portion is converted in heat energy by the PV module [1]. When the solar radiation falls on the PV module, electricity is generated due to the photoelectric effect. The photons from the solar radiation need to have a minimum frequency, which is known as threshold frequency, while hitting the PV module. At the same time, the electrons need to receive sufficient energy to be released from the PV cells in order to produce electricity. Insufficient photon frequency or energy will give rise to the heat energy. Again, if the photons have more energy than the energy needed to release the electrons, then the excess energy will give rise to the heat energy. In both cases, there will be some heat generation in the system, which will act as resistance to the electricity generation and give electrical efficiency loss of the PV modules. It has been found there is a drop of efficiency after a certain optimal temperature. In hybrid PV/T system, extracting the heat through the thermal part of the system in order to keep temperatures lower and consequently lowering resistance can minimize the problem [1, 2].

A wide range of literature can be found on theoretical and experimental studies of hybrid PV/T systems with air and/or water heat extraction from PV modules. The initial studies were presented in the papers of Kern and Russel (1978)[3], Florschuetz (1979)[4] and Raghuraman (1981)[5]. Following them, Lalovic (1987)[6] proposes novel transparent type cell as a low cost PV/T improvement, Garg and Agarwal(1995)[7] present same aspects of a water type PV/T system and Bergene and Lovvik (1995)[8] give results for liquid type PV/T systems.

Design concepts, prototype construction and test results for water and air cooled PV/T systems are included in the work of Tripanagnostopoulos et al (2002) [9]. The study of the dual type PV/T system based on the water or air heat extraction (Tripanagnostopoulos et al, 2001) [10] and the results of an economic analysis comparing water cooled PV/T systems with standard PV and thermal systems (Tselepis and Tripanagnostopoulos, 2002) [11] are also two works, that are referring to the improved water cooled PV/T solar systems.

Water cooled PVT systems are practical systems for water heating in domestic buildings but their application is limited up to now. Air cooled PVT systems have already been applied in buildings integrated usually on their inclined roofs or facades. This system keeps the electrical output at sufficient level covering building space heating needs during winter and ventilation needs during summer avoiding also building overheating.

In PV/T system applications the main priority is to produce electricity so the operating temperature of the PV module should be within certain range to keep the electrical efficiency at sufficient level. For this, enough provision should be introduced to remove the excessive heat from the system. To improve the heat transfer some modification on the Hybrid PV/T system is done in the project, which includes using of Thin Metallic Sheet and Painted Black Corrugated Ribs. The modifications have been discussed in details in the section 2.2 of this paper.

Though both water cooled and air cooled heat exchanging methods have been included in the experimental setup, the analysis has been kept limited in the water cooled system only. It has been focused on the mass flow rate of the cooling water to understand how much heat the water can extract from the system. By controlling the water flow rate, the electrical efficiency of the PV module can be controlled and the thermal efficiency of the water can be improved.

In this article, both experimental results and decision based simulation results are presented. Thus, electrical efficiency variation and the determination of the optimal temperature for different setups have been discussed based on experimental data sets. Next we describe decision correlation scatter plot with multiple parameters and a decision tree for different electrical level using the data-mining tool 'R'. Then a simulation has been carried out in 'Simulink' platform with solar cell models to test the different decisions made by the tool. Temperature distribution diagrams in the PV/T solar system at different nodes have been figured out based on the decisions made for those nodes. An approximation of the mass flow of cooling water has been determined to control the optimal temperature considering the simulation results and the amount of excessive heat needs to be taken out, so that the electric efficiency of the PV module could be maximized.

EXPERIMENTAL SETUP

Components of the Setup

The various components of the setups are discussed below in details.

Solar photovoltaic panel. For this project Polycrystalline-Sillicon (pc-SI) PV panels were used with a rating of 50 watts and 0.45m^2 aperture area, having approximate dimensions of (839*537*50) mm. The selection of the pc-Si PV panel is discussed in next *section.* To facilitate the experiment and available PV panel got the above mentioned dimensions and aperture area.

Copper tube. For circulating water, copper tubes were used in the project as copper has the higher thermal conductivity, which was a necessary requirement of the project. The optimum diameter, which was selected for the high rate of heat transfer and sufficient rate of flow, was taken as 0.5 inch.

Nylon Pipe. For carrying the water in the copper tube, nylon pipe was used. The optimum diameter had been taken as 1 inch. In nylon pipe, bends are so gentle that the fluid flow is smooth and continuous. The nylon pipe carried water from the storage and after circulating in the system it returned back to the storage device.

GI Sheet. For the thin flat metallic system (TMS) and ribs, 22 gauge galvanized iron or GI sheets were used. The GI sheets were painted black to increase the heat absorptivity, which will improve the heat transfer with air and water. The shape of the ribs were varied in the three setups to observe the variation in heat transfer rates and thereby the performance of the setups. The shapes of the ribs were triangular, sinusoidal and rectangular, which can be clearly distinguished from the setup diagrams given in Figure 1, Figure 2 and Figure 3, respectively.

Thermocouple. For measuring the heat in the corrugated ribs, thermocouples were used. In the experiment, 23 thermocouples were used (7 for each setup and 2 for the inlet and outlet water temperature). K-type (chromium, nickel-chromium) thermocouples were used. In every setup, thermocouples were attached to the selector switch and from there temperature was taken with the help of a digital thermometer.

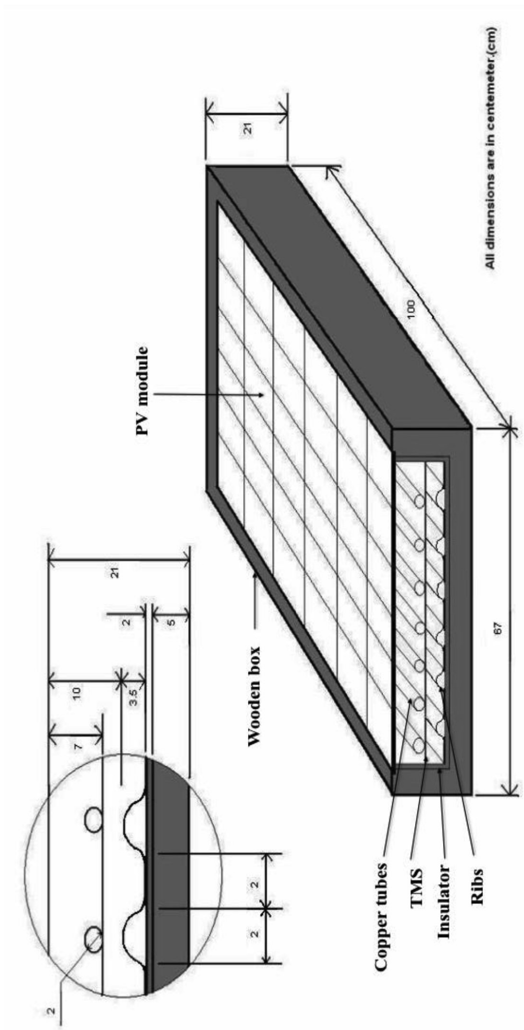

Figure 1. Schematic diagram of setup 1 using the sinusoidal rib (observable at the macroscopic view).

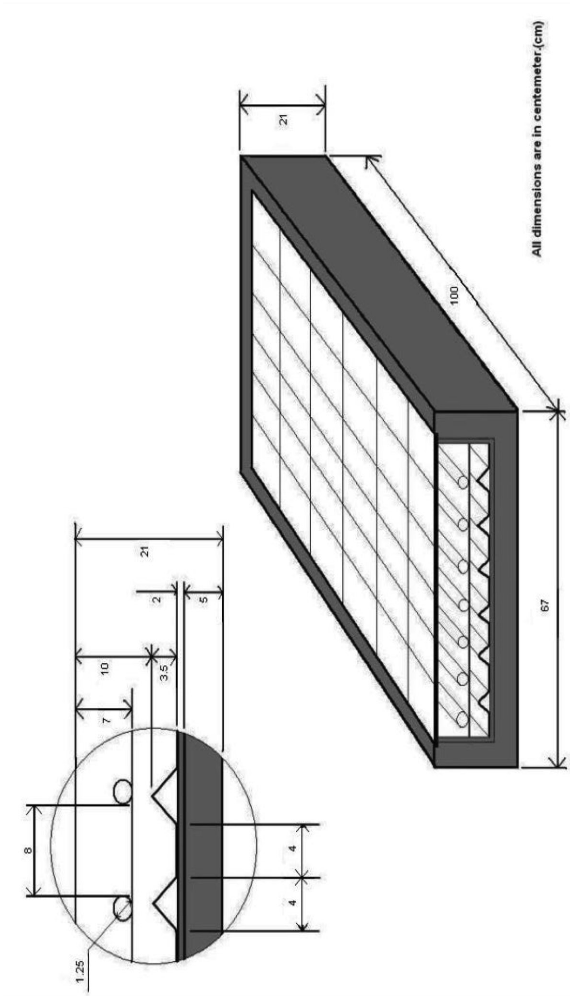

Figure 2. Schematic diagram of setup 2 using the triangular rib (observable at the macroscopic view).

Insulating Material. As the insulating material, glass wool was used which is easily available and suitable for the project. The glass wool was applied in the inner surface of the wooden box to minimize heat transfer to and from the setup, which might decrease the efficiency of the PVT system.

Wooden box. The whole setup was constructed in wooden box with the dimension suitable to the dimensions of the PV panel. Gamari wood was used for better longevity of the setup.

Modifications of the PV/T system

The PV/T system needs special arrangements to achieve the heat extraction or cooling required to increase the system efficiency. To improve the design, a dual PV/T collector was considered where both water and air heat exchangers (WHE and AHE correspondingly) are together in the same device [1]. For the hybrid PV/T system, air and water are circulated through the rear surface of the PV panel in the system, which gives the combined air and water heat extraction method. The concepts of designing such an arrangement are discussed below. Fig. 1 depicts the concept.

In the design of the PV/T system, water circulation was done by flowing water through pipes in contact with TMS element placed in thermal contact with the PV module rear surface for the WHE. Forced and controlled water circulation is preferable in order to increase the heat transfer rate. But extra components had to be added, which would make the system bulky and more expensive. In the system, natural circulation of water was designed which would collect heat and flow by the thermosyphon mood.

An air channel was provided and air was inserted through the channel at the back of the PV modules for the AHE. Generally natural convection of air is preferred than forced, tough the operation of PV/T system with high rate of forced airflow gives satisfactory result regarding heat extraction as the flow rate in forced airflow is higher than that of natural airflow applications [1, 10-12]. Air flow is dependent on the temperature difference between the inserting air in the channel and the PV module for the AHE. The heat transfer in the low temperature air is used for both PV cooling and thermal energy collection.

Larger surface area of TMS in the air channel to promote the convection heat transfer to the circulating air can increase the heat transfer

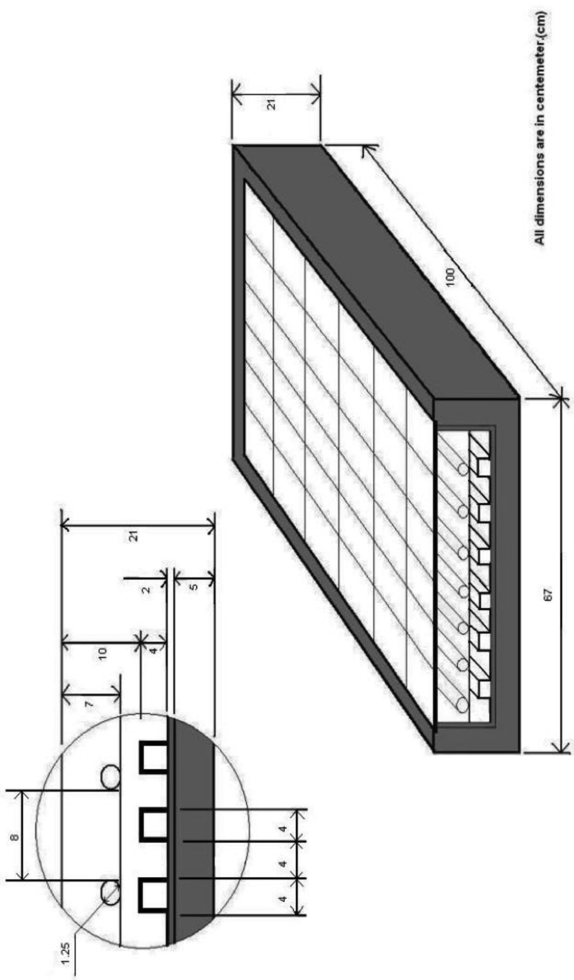

Figure 3. Schematic diagram of setup 3 using the rectangular rib (observable at the macroscopic view).

by air. In order to increase radiation heat transfer, the PV rear surface as well as the opposite channel wall surface should be of high emissivity to transform the infrared radiation to convection heat transfer mechanisms and to heat efficiently the circulating air. It can be further improved if larger heat exchanging surfaces are used in the air channel.

Based on the above investigated design concepts by Tripanagnostopoulos (2007) [1], the combination of WHE and AHE elements were used applying some modification in the collector for the design improvements. The first modification was the positioning of the TMS element in the air channel (PVT/dual—TMS model). And in the second modification the TMS element was combined with roughened opposite channel wall by small ribs (PVT/dual—TMS/RIB model).

In PVT/dual –TMS model a GI sheet as TMS element was placed with parallel to the air flow attaching the water tubes just above it. The position of the sheet was selected as the middle of the air channel. The upper side of the TMS element facing towards the PV rear surface was painted mat black and the lower side was left unpainted. This modification was done to obtain a higher radiation transmission to the upper side of the TMS element due to the higher emittance in the upper side comparing to lower side [1]. The TMS temperature was raised by the absorbed heat and hence thermal efficiency was increased.

In the second modified model, the PVT/dual—TMS/RIB model, a TMS element with ribs of small size was placed on the opposite air channel wall [1]. The heat transmittance was increased due to the radiation from TMS back surface to air channel wall by painting the ribs as black. Three experimental setups were constructed varying the ribs shapes to observe the variations of heat transmittance and the improved efficiency with change of the shape of the ribs. The rib shapes were triangular, sinusoidal and rectangular as mentioned in section 2.1 and the variations can be observed from Fig. 1, Fig. 2 and Fig. 3. Different shapes of the ribs resulted in different surface area of the TMS element with ribs varying the heat transmittance.

Usually PV panels are constructed with:

- Crystalline-Silicon (c-Si)
- Poly-crystalline Silicon (pc-Si)
- Amorphous-Silicon (a-Si)

There is a variation in the ratio of the additional cost per PV module and the cost is almost double for a-Si compared to c-Si or pc-Si PV modules [1]. So for cost effectiveness pc-Si had been selected for this project.

METHOD FOR COMPUTATIONAL ANALYSIS

Data Mining

Data mining is a computer driven data exploration method that tries to find out pattern in a data set in steps. Various application domains implement data mining methods when big data is under concern. The purpose of such an analysis can lead towards intelligent decision making based on previously obtained data. Advent of modern computational techniques provides opportunity to collect, store and analyze overwhelming amount of data. Data mining is a step by step process that starts with data cleaning and finishes after discovering knowledge in it. The steps are iterative. See Figure 4. Discovering knowledge can also be expressed as fitting a model in data. Knowledge discovery process is often associated to preset threshold values. These thresholds are defined either by the users or by the pattern recognition algorithms used in data mining process. [14]

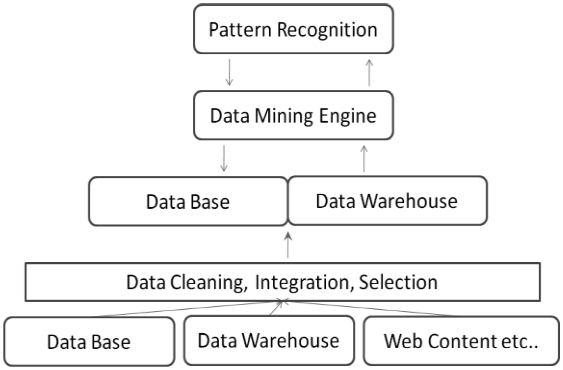

Figure 4. Hierarchy for the data mining platform.

The data mining steps include data cleaning, integration, selection, and deploying pattern recognition algorithms. Data cleaning is a pre processing routine that eliminates unwanted values, fills up missing values, smoothes noises, resolving inconsistent parameters etc. For data mining application cleaning is very important. With this cleaned data,

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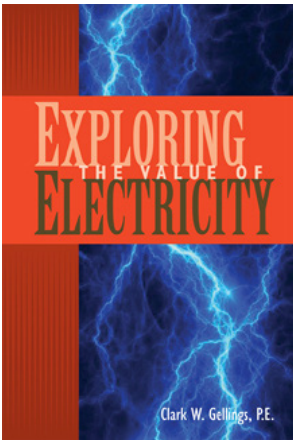

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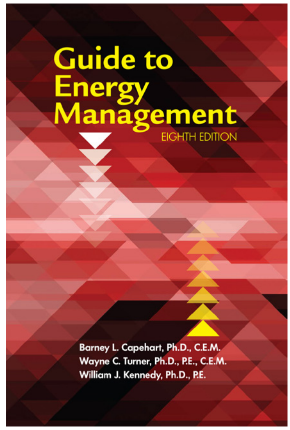

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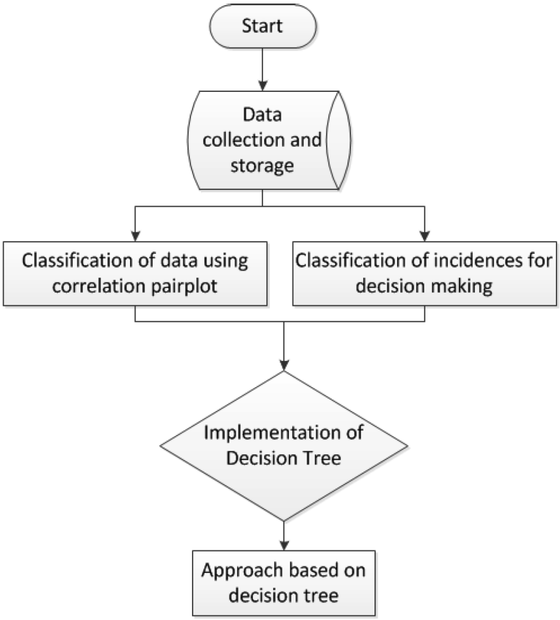

Figure 5. Algorithm for the computational analysis.

pattern recognition algorithms are trained to find out patterns or manual classifications. The most important part of data mining is pattern recognition tools or algorithms. Pattern recognition algorithms use instance based attributes. The assigned labels or assigned attributes carry different meanings and interpretations based on different instances. The pattern recognition algorithms use these attribute values at different instances to discover patterns. Out of different pattern recognition algorithms decision trees are pretty common in knowledge discovery action. In this paper decision tree has been used to make decisions based on stored data of different instances collected from the PVT Models. [14] [15] [16]

Correlation Scatter Plot

Correlation scatter plot is used in this paper to demonstrate the classification of PV data based on correlation coefficient. There are different methods available to understand the impact of correlation studies or dependence between multiple variables. Pearson's correlation is one of the most common methods out of those. It can be calculated with a process of dividing the covariance by the product of standard deviations of the two variables. If 'A' and 'B' are two different variables then the correlation between them can be obtained by

$$\rho_{A,B} = corr(A,B) = \frac{cov(A,B)}{\sigma_A \sigma_B} \quad (1)$$

Here σ is the standard deviation. Pearson's correlation is applicable for standard deviations that are non-zero and have finite values.

Project Work Flow

The algorithm prepared for this research project is as following. Refer to Figure 5.

The process starts with stored data from PVT models. Then classification is prepared with correlation analysis. A second incidence based classification is also carried out. This classification is post incidental analysis, which depends on different clusters of PVT cell data. The incidences are fictitious by nature and can be associated to any number of the practical scenarios. For this project the purpose of selecting fictitious incidence is only to show how decision-making process is implemented on PVT data to take different kinds of operational decisions. Here only numbers from one to five has been proposed instead of detailed scenario based incidents. Once a decision based routine is set it can be interpreted with any numbers of practical use cases. Finally decision tree algorithm is used to trace a pattern from both of these classifications. The data collection and storage part also consists of data cleaning, data integration etc. in other words data preprocessing for the mining process.

RESULTS AND DISCUSSIONS

Performance Assessment

For the performance test of the hybrid PVT system, the three setups were tested simultaneously at outdoors under sunny weather conditions. Two whole days were selected to perform the experiments depending on the intensity of the solar radiation—one was at intense sunny day and the other was at moderate sunny day.

The electrical performance assessment of a PVT system is straightforward [13] since the use of electricity can be immediate while it is

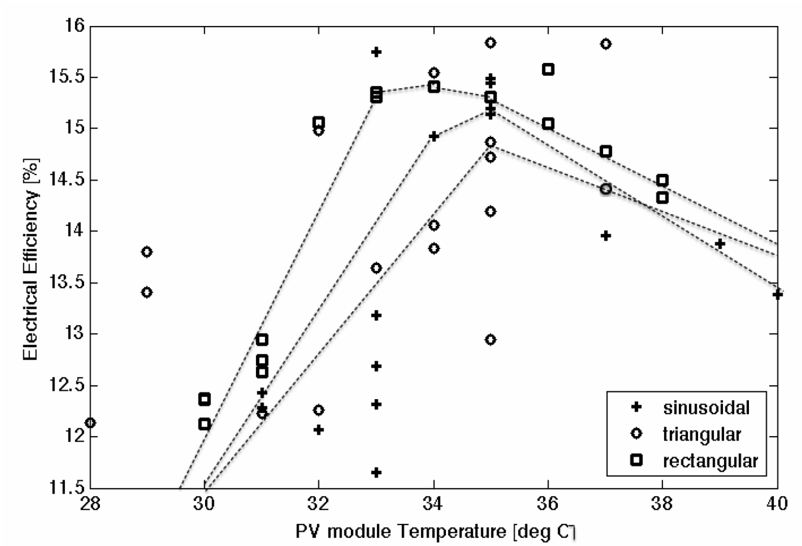

Figure 6. The PV module electrical efficiency as function of its operating temperature for the three different corrugated ribs in the experiment.

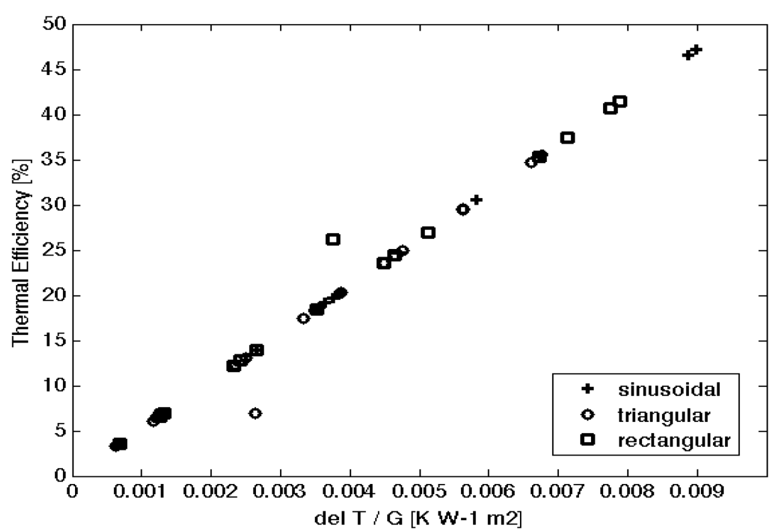

Figure 7. Steady state results for thermal efficiency of PVT/dual—TMS/RIB type collector regarding water and air heat extraction using three different corrugated ribs.

different for thermal performance. Different terminologies were used to determine the efficiencies. They are input mass flow rate of fluid (m), specific heat of the fluid (C_p) fluid temperature (T_{in}), output fluid temperature (T_{out}), ambient air temperature (T_a), air channel opposite wall temperature (T_w), Air temperature in air channel (T_{air}), PV module temperature (T_{PV}), incoming solar radiation on PV module (G), aperture are (A_a), current at maximum load (I_m), and voltage at maximum load (V_m)

The thermal efficiency and electrical efficiency of a hybrid PVT system, respectively, given by:

$$\eta_{th} = \frac{mC_P(T_{in} - T_{out})}{A_a G} \tag{2}$$

$$\eta_e = \frac{I_m V_m}{A_a G} \tag{3}$$

The electrical efficiency is related to the cell efficiency η_{cell} by the ratio of the cell surface area A_{cell} to the aperture area (which is known as the packing factor β), in that

$$\eta_e = \frac{\eta_{cell} A_{cell}}{A_a} \tag{4}$$

The thermal efficiency is conventionally shown as a function of the reduced temperature, which is defined as

$$T^* = \frac{(T_{in} - T_{out})}{G} \tag{5}$$

Experimental results from the modified hybrid PVT systems

To summarize PVT system experimental results, Figure 6 plots electrical efficiency (η_e) of the PV module as a function of the operating temperature (T_{PV}). The plot is shown for the three different shapes of ribs. Though there is a little noise in the data set, it can be said that the electrical efficiency starts to decrease linearly with the temperature increase after 35~36 ^{0}C approximately. The variation in efficiency from the three setups is due to the difference in the surface area and heat transfer capacity of the TMS sheets with different ribs.

For thermal collectors, thermal efficiency (η_{th}) is determined as function of the ratio ΔT/G, where $\Delta T = T_{in} - T_{out}$ is determined for water flow operation. Figure 7 shows the steady state test result of the modi-

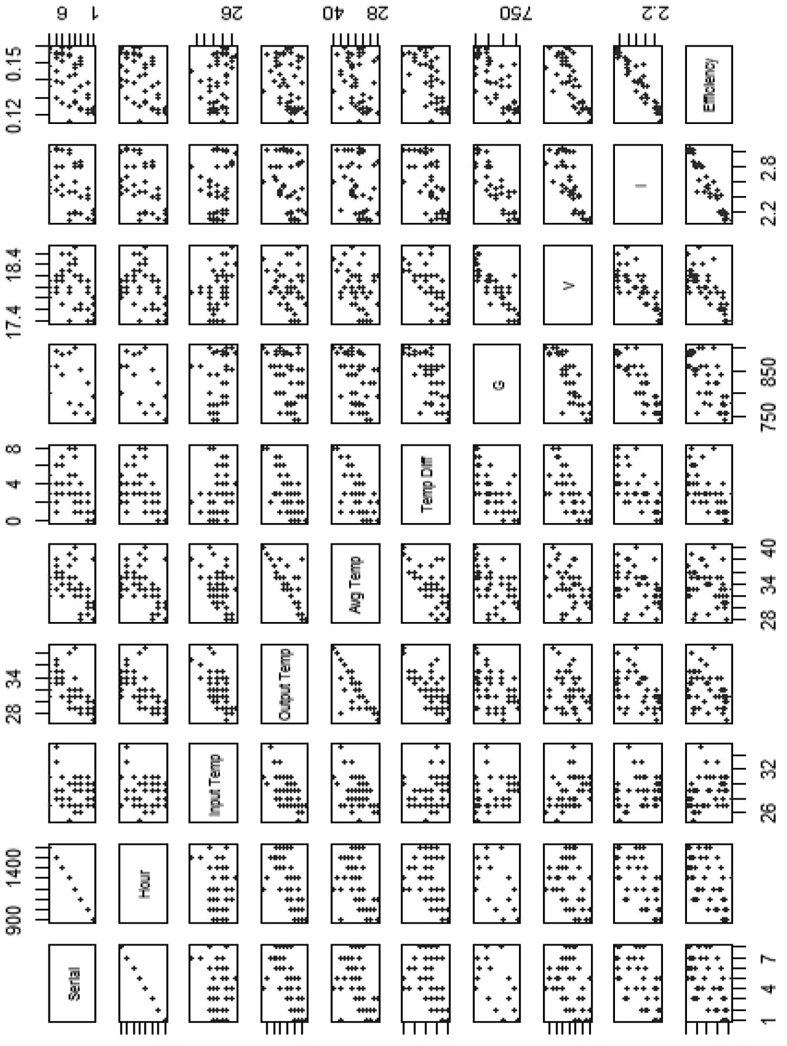

Figure 8. Correlation scatter plot with multiple parameters

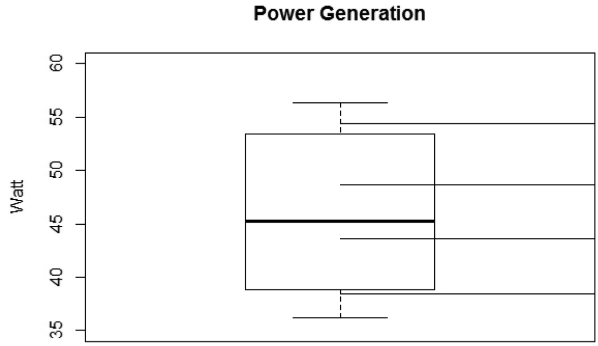

Figure 9. Five different clusters in the boxplot of the power generation data

fied PV/T models. Here, a linear relationship between η_{th} and $\Delta T/G$ is observed. It is seen that the thermal efficiency from all the three setups increase linearly and approximately in the same path with the increased $\Delta T/G$ ratio depending on the solar radiation intensity on the PV panel from time to time. It provides information that there is negligible difference in the thermal efficiency from these different setups with different ribs, which can be considered as same heat transfer rate to the water tubes from all the three setups and it is possibly due to the small area of the experimental wooden box providing negligible air heat extraction.

Experimental results from the statistical and data mining algorithms

The PVT modules produced different sorts of data mentioned at section 3.1. These data then are preprocessed or in other words cleaned and again stored in the database of the data-mining tool used in this project called 'R'. Once the preprocessed data is stored a correlation scatter plot is established based on the correlation coefficient of any two different variables. The purpose of using a scatter plot is to comprehend the relations between data within a shorter scope.

Based on the correlation scatter plot presented in Figure 8, a relation has been traced between different parameters of the database. From the scatter plot representation incoming solar radiation (G) and PV/T module temperature have been chosen for input data to the data-mining platform.

Next, a power generation based boxplot (Figure 9) is proposed to represent different incidents. Each power generation cluster is the key towards one decision-making phase [17]. Based on these power gen-

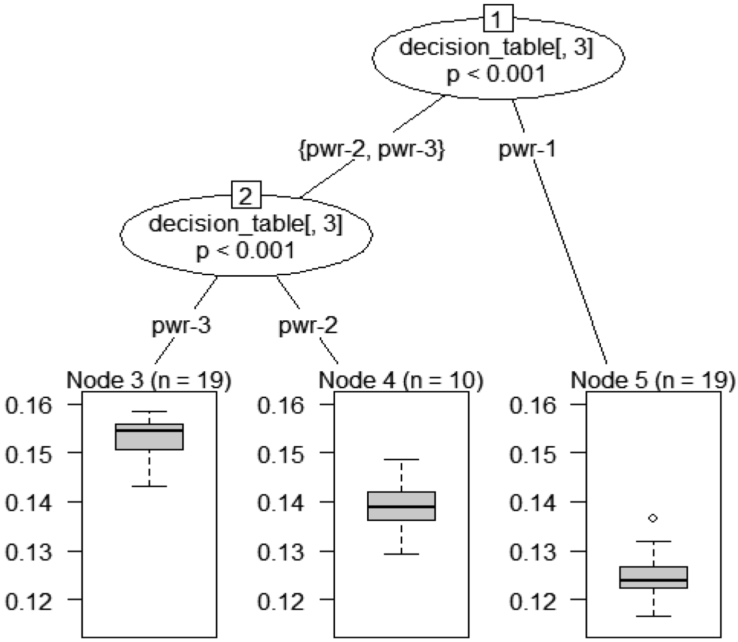

Figure 10. A decision tree for different electrical efficiency levels

eration clusters a typical decision is proposed suitable for that scenario. Here five incidents have been proposed to demonstrate the overall application of the algorithm implemented.

Decision tree based on electrical efficiency

Once the data are classified with coefficients involved in both power generation and other aforementioned input data, a data frame is fed to a decision tree algorithm to propose a suitable operational decision [18] [19]. Below a decision tree (Figure 10) is constructed out of randomly chosen time window from the data frame. The time frame chosen has shown a certain pattern on the PV module temperature (T_{PV}), incoming solar radiation on PV module (G) data and the power quintile prepared earlier in Figure 9. Based on those patterns the decision tree is prepared. The decision tree would lead the experiment to take some crucial decisions such as mass-flow control of the cooling water.

In this part of the experiment the purpose of building a decision tree is to find out the optimal conditions to operate the system in maximum electrical efficiency. The method chosen is to control the incoming

Table 1. Thermal properties of the solar cell

First order temperature coefficient for Iph	0.06785	1/Kelvin
Energy gap	1.11	eV
Temperature exponent for diode saturation current	3	
Temperature exponent of the resistance	0	
Initial temperature	303	Kelvin
Irradiance	1000	(w/m2)

water mass in kilograms per unit second. The time window or data array changes the tree shape specially the nodes. The tree is triggered when the system exceeds the temperature when maximum efficiency is observed. The temperature is chosen around 36° Celsius from the Figure 7. The algorithm selects the individual threshold of each node and when a certain threshold exceeds a new child node or nodes, new final decision classes are obtained.

The final nodes are the decision nodes, in other words the key classifications. Figure 10 shows a decision tree that results in five decisions with different threshold values. Once the thresholds are set and bottom nodes are defined, physical decisions can be made using this decision tree.

Here the physical decision will be to maintain proper average temperature of the entire system that includes PV panel and the associated structure. To test the decision process one simulation has been carried out in 'Simulink' platform with 'solar cell models'. The corresponding equation that has been used to model these panels is shown below [20];

$$I = I_{ph} - I_s \cdot \left(e^{\frac{V+I\cdot R_s}{N\cdot V_t}} - 1 \right) - I_{s2} \cdot \left(e^{\frac{V+I\cdot R_s}{N_2\cdot V_t}} - 1 \right) - \frac{V + I \cdot R_s}{R_p} \tag{6}$$

Here: $I\,ph$ is the solar-induced current that can be further explained by $I\,ph = I\,ph0$ X $Ir/Ir0$ Ir is the irradiance in W/m^2, $I\,ph0$ is the solar current obtained for irradiance $Ir0$; Is and $Is2$ are the saturation currents of the Diode-1 and Diode-2 inside; $N1$ and $N2$ are the quality factors

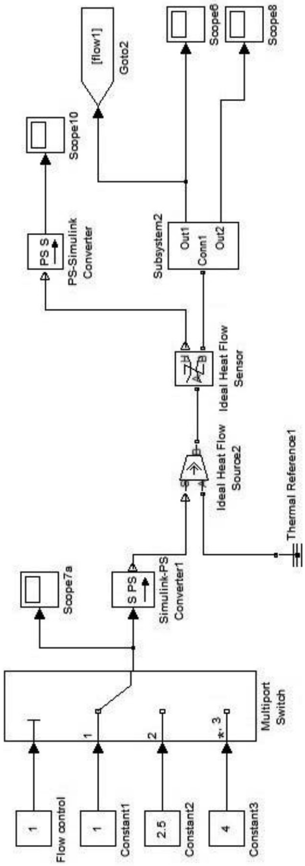

Figure 11. Simulink model for the system

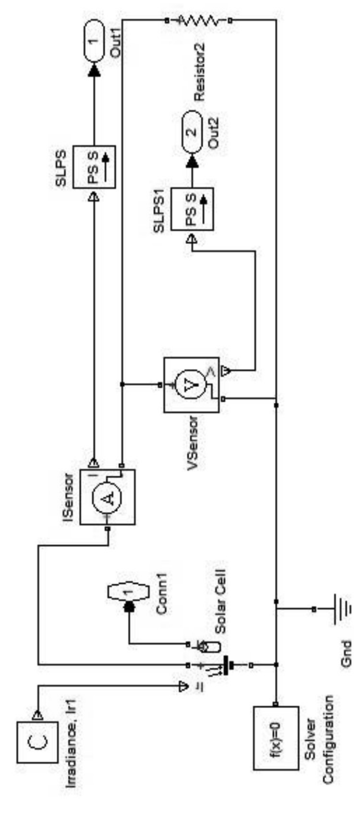

Figure 12. The subsystem for the solar cell module, Subsystem2 in Figure 11.

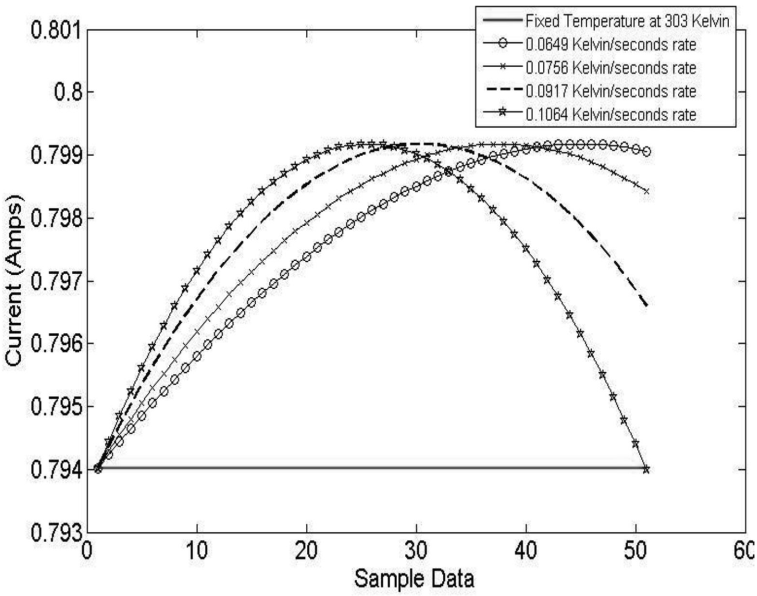

Figure 13. Different current ratings based on increment of average temperature of the system

diodes; $Vt = kT/q$ is the thermal voltage, (k is Boltzmann constant, T is device temperature in Kelvin); Rs and Rp are the series and parallel resistances; V is the terminal voltage. The thermal parameters chosen for the model are shown below in Table 1; with these parameters cell efficiency reaches to maximum value at around 36° Celsius.

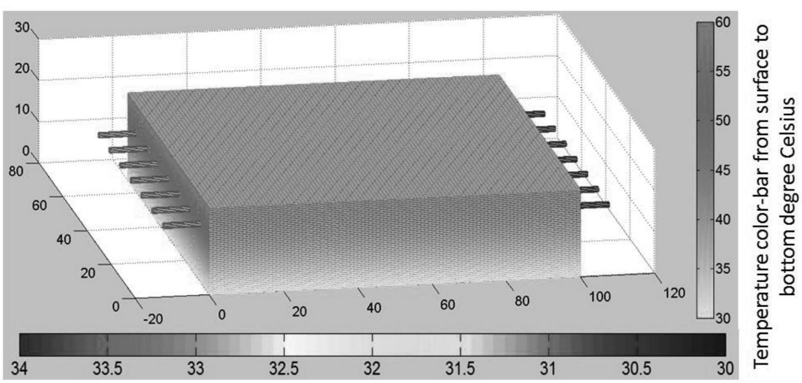

Figure 14. Temperature distribution during decision node-4

Temperature variation in the PV system has been modeled by the heat flow module of 'Simulink' (Figure 11 and Figure 12). The thermal efficiency is calculated from Figure 7. At $\Delta T/G = .002\ KW^{-1}m^2$ the efficiency is obtained 10%. The simulation is carried out with a static 10% thermal efficiency.

Figure 11 shows that the heat flow module and temperature control in the form of temperature increment, whose unit is Kelvin/seconds. Thus the heat flow manipulates different current levels. The manipulation is straight forward. If the temperature increment is faster, then the output current reaches to the maximum level faster. It means if the panel temperature keeps increasing then the output current will soon fall down to its initial starting point which is far below its maximum. On the other hand, a slower increment in temperature will restrict the current level from falling of its maximum point very fast. The current output at different thermal incremental rate is shown in Figure 13.

Figure 13 also shows the comparison between current outputs with respect to the output while the entire system temperature remains fixed. The horizontal line (Current = 0.794 Amps) represents a constant system temperature throughout the period. The current has been chosen as the indicator of efficiency considering that the output voltage is constant throughout the period. From Figure 13 it is certain that the decision tree would be used to control the average temperature of the system at a point where output current is constant. The physical process of taking such a measure would be to control the mass-flow of incoming cooling water. The maximum current considered is 0.7991 Amps.

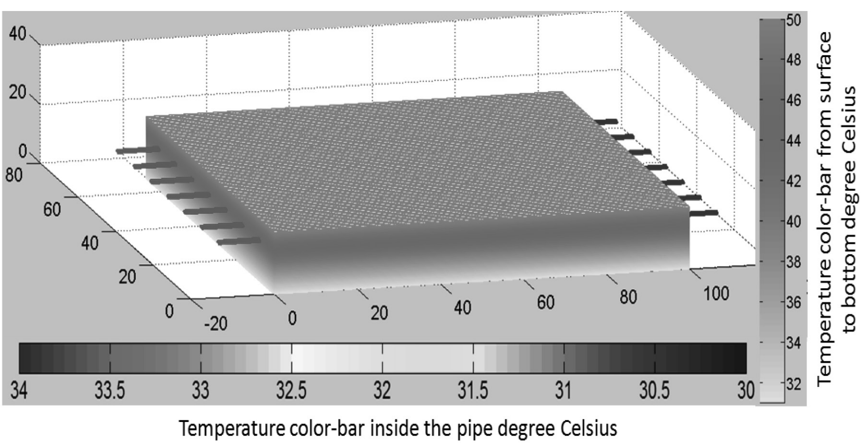

Figure 15. Temperature control after reaching at node-3

The maximum current and the maximum efficiency are obtained in the simulation at around 36°~37°C system temperature. Here a 36°C means the average temperature of the entire PV/T system including its boundaries. The first decision class or namely node-3 of this experiment shows a maximum level of efficiency, which is the optimum condition. So, the decision process will be involved only to the class-2 (node-4) and class-3 (node-5) branches. When a class falls under either node-4 or node-5 the operational decision is made to control the level of fluid dispatch through the inlet-outlet pipes.

The initial temperature distribution for the node-4 is shown in Figure 14. The temperature distribution is considered linear from top surface to the bottom and maximum temperature is assumed 51°~52°C max and minimum is assumed 27°-28°C in the simulation, where the average temperature is considered 40°~42°C.

After the fluid flow is controlled the expected temperature distribution should be scattered unlike the linear distribution assumed before the fluid flow has been controlled.

The specific heat of water (4179 Joules/kg/Kelvin) and specific heat of silicon (7030 Joules/kg/Kelvin) have been used in the process of calculating the water flow required to control the overall temperature. The target average temperature of the system is 36°~37° Celsius and the target surface temperature is 42°~44° Celsius. To compare the simulation with the actual system the pipes have been designed to have 31° Celsius at inlet and around 33° Celsius at outlet on an average. During the heat

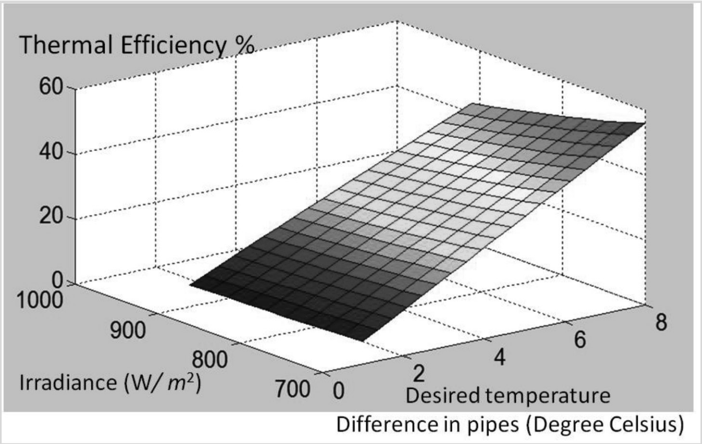

Figure 16. Thermal efficiency based on different parameters

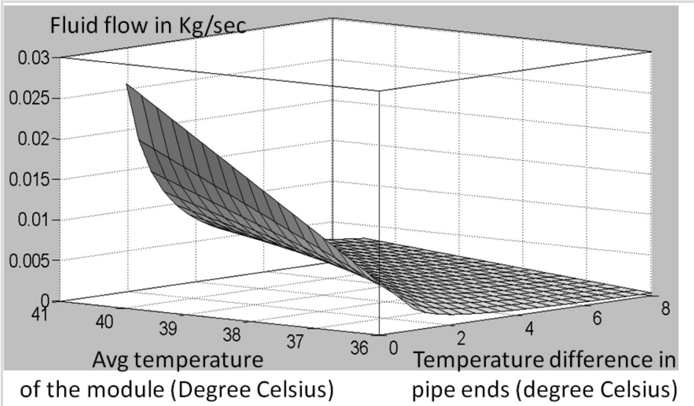

Figure 17. Water mass flow based on different parameters

distribution from top to bottom the maximum heat is dissipated through the water pipes.

The mass of the solar panel is around 6.64 Kg, which is calculated from the volume and the specific mass of silicon. Each water pipe can carry 0.107 Kg of water, which means seven pipes are carrying around 0.749 Kg of water. 36° Celsius is the temperature at the decision node-3, at which no action is carried out. When the temperature again rises up and crosses the threshold set by the decision tree, fluid flow is again controlled based on the decision node that has been appeared from the most recent data obtained. The temperature levels at decision node-3 after the fluid has been controlled to maximize efficiency are shown in Figure 15.

During the calculation process, gradual increment of the surface temperature from sunlight has been avoided, which would introduce a non-linearity in the overall calculation.

Modified decision tree

From the above discussion, it is quite clear with fixed thermal efficiency and irradiance, decision making to maintain maximum electrical efficiency is straight forward. But in the actual experiment multiple levels of nonlinearity were observed. For example irradiance is a variable quantity; surface temperature is also variable and at the same time demand of electricity and demand of hot water are erratic in nature. Thus the requirement of electrical efficiency and thermal efficiency are random. This scenario demands an optimized fluid flow for heat exchange. Which lead the experiment towards modifying the previous decision tree. The modification process is carried out considering two

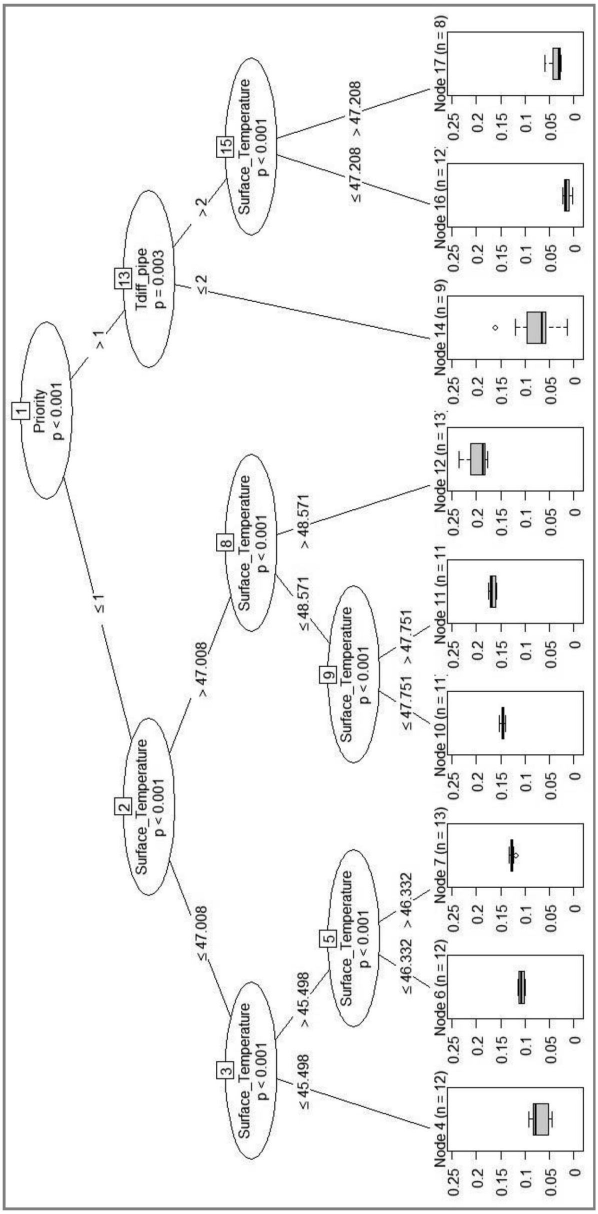

Figure 18. Decision tree classes for controlling fluid mass flow

sets of relations. The first important nonlinear relation is among thermal efficiency mentioned in Equation 5, instant irradiance, and the desired temperature difference between inlet and outlet points of the water pipes. Figure 16 shows the apparent relation between these parameters. The second set of relation is based on surface temperature of the PV/T module thus the work done to reduce the surface temperature, the desired temperature difference between inlet and outlet points of the water pipes and water mass flow in kilograms per second. It has been assumed that each decision making process will be carried out for 600 seconds. 600 seconds operation is the basis of selecting mass flow rate. Figure 17 gives a perspective on how water mass flow varies with the temperature differences and required work done to ensure surface temperature falls under a threshold.

Modifying the decision tree required further assumptions such as prioritization. The prioritization addresses electricity and heat requirement by classifying the requirement into two states. Table-2 describes the states of the priority set before decision making.

Table 2. Priority Table

Priority-1	Importance to electricity generation
Priority-2	Importance to heat generation

When the system is in priority-1, electricity demand is high and when the system is in priority-2 electricity demand is low thus heat generation can be focused. At priority-1 the system is run with minimum thermal efficiency. And during priority-2 thermal efficiency is selected based on heat demand. Finally with the data mentioned above a decision tree is constructed where target attribute or the bottom layer is the fluid flow rate in kilograms/second. The fluid flow has been calculated from the irradiance, surface temperature, dimensions of pipes, temperature difference between pipe ends, specific heat of water and silicon etc. Figure 18 shows the resultant decision tree with randomly chosen one hundred data points from the experiment.

LIMITATIONS

We encountered some limitations when performing this research work.

- For proper experimentation, the weather condition is important. It is obvious that the solar radiation is not always constant. So, even without cloud cover, within a day and between days, solar radiation incident on the PV module will change randomly. Wind velocity is an important factor in case the air heat extraction is taken into consideration. It is also obvious that it is not always sufficient to facilitate air heat extraction.
- As an experimental setup, the aperture area is limited. But in case of building integrations the aperture area can be increased to provide further increase of the efficiency.
- Due to recirculation of water in the same reservoir the temperature difference between the input and output water will gradually decrease and thereby the η_{th} will also decrease. In real situations the output water will be utilized from time to time. So, there is always some temperature difference expected.
- In the simulation, temperature dissipation has been considered linear in nature, which in practice is not observed with the physical system. The physical system exhibits some degree of non-linearity.
- Mass flow rate of cooling water in the simulation has been assumed higher than that of the experimental value. This is due to the assumption that the cooling water will absorb all the excessive heat rejected by the PV module.

CONCLUSIONS

Investigations that contribute to PV/T system improvements at Islamic University of Technology were briefly analyzed with the design improvements by considering dual PV/T type collector combining water and air heat extraction methods, though the analysis had been kept limited to the water heat extraction method only. A water heat exchanger at PV rear surface inside the air channel was tested for the best results from the combined water and air heat extraction. For air heat extraction from the system, a modification was done placing a TMS sheet in the air channel just below the water tubes and using three different shapes of corrugated ribs—sinusoidal, triangular and rectangular.

The system is applicable either by water and/or air as the heat extraction method from the PV module, which will depend on the thermal needs of the application and the efficient operation of system regarding the weather conditions in the desired location. In this paper, the decision based approach was conducted considering the system is only applicable for water heating application. It has been shown that the mass flow rate of the water should be related to temperature control within certain range of the PV module, so that the efficiency can be optimized. If air heating is needed, then further analysis could be made to control the air flow rate in the system.

From the simulation results, the water mass flow rate has been assumed much higher than that of the experimental data. So, the practical model should be implemented with modification in such a way that there will be larger provision for the water flow. Larger tube diameter will allow a higher mass flow rate. In another way, the water can be pressurized to increase the mass flow rate, but the maximum safe and sustainable pressure of the system is a limitation. Moreover, it has been considered in the simulation that there will be no water flow until the temperature of the PV module reaches to the optimal temperature for the maximum efficiency. Thus, the practical model should be designed to meet this requirement to develop such decision based arrangements. Automation of such control events is in order.

PV/T systems are practical devices for combined water heating and electricity generation utilizing the solar radiation, but they are not cost effective for commercial applications. Researchers have suggested several models for heat extraction by water and air circulation, but the design with water circulation through pipes in contact with a flat sheet placed in thermal contact with the PV module rear surface is more practical.

Further investigation should be done to develop devices with lower cost, more overall efficiency and lower environmental impact. Tracking system for the modified PV/T system could be one good option to have a higher efficiency, but the cost and complexity would also be higher due to the additional components and mechanism in the setup.

The PV/T systems with improved modifications can be extensively used in residences, offices, hospitals, agriculture sectors, and also in the industries in order to provide electricity and heat to the working fluid at the same time. This system is suitable for building integration or providing hot water/air depending on the thermal needs of the buildings due to its simplicity. It can be suitable for space heating, natural ventilation etc. considering air for the heat extraction.

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