A techno-economic analysis for an integrated solar PV/T system with thermal and electrical storage – case study

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***Abstract*— A hybrid photovoltaic/thermal (PV/T) system is having the capability to convert solar energy to both electricity and thermal energy simultaneously and these systems can use to accomplish the energy demand of buildings. Performance analysis of such systems becomes essential to design PV/T systems matching with the operating conditions. It is essential to extend the energy flow analysis used in this regard considering economic limitations especially for urban applications. In this study a practical method to accomplish the energy demand of a building from a PV/T system is proposed and evaluated through a thermo-economic model. The performance of the PV/T collector is analyzed under different operating conditions in Sri Lanka. The responses of energy storage and local grid according to demand variations of the building are evaluated considering the economic aspects. Life cycle cost of the PV/T system is computed to assess the economic viability of harnessing energy from solar energy. Furthermore, the capability of deploying PVT technique and the potential to harvest solar energy in Sri Lanka is evaluated through conducting case studies for different locations.**

Keywords — solar PV/T system, multi energy storage, techno-economic analysis

I. Introduction

The rapid growth of energy demand has resulted in a notable increase in usage of fossil fuels. Therefore there is an urge to move towards more eco-friendly energy sources and conversion technologies to minimize emission levels of obnoxious gasses and global warming. Solar energy is a primary energy source which can be utilized in many ways including solar photovoltaic (PV) panels and solar thermal collectors. The hybrid photovoltaic/thermal (PV/T) system converts solar energy to both electricity and thermal energy simultaneously. Thus energy demand of buildings, in terms of electrical and thermal energy can be accomplished by energy extracted from PV/T systems, which makes it an area of interest for a large community of researchers [1] [2] [3]. A significant amount of research on PV/T systems has been carried out over past few years. The recent literature on PV/T can be mainly classified into two classes [3] [4].Developing mathematical models for PVT systems and experimentally validating these models can be taken as the prime concern [5] [6] [7].The second is evaluating the feasibility of PVT technology through case studies [8] [9] [10]. Most of the recent literature on the latter is based on different climatic conditions and demand profiles of buildings to assess the practical aspects of utilizing solar energy for building applications. The effect of important operating conditions such as ambient temperature and solar irradiance on the performance of the PV/T collector has been evaluated in summer and winter [11]. The performance with respect to the variation of geographical region and the area of the collector has also been examined [12]. Different types of PV/T collector configurations have been analyzed for building applications under various climatic conditions [8] [10].

Substantial amount of research on PV/T systems has been carried out based on theoretical models which were subsequently validated using experimental setups. F.Sarhaddi et al. [13] carried out a performance evaluation of a PV/T air collector with glass to tedlar PV module. A detailed thermal and electrical model was developed to calculate the thermal and electrical parameters of a typical PV/T air collector. The two configuration of air collector with glass to glass PV module, Case I (air flow above the absorber plate) and Case II (air flow below the absorber plate) are analyzed by S. Dubey et al. [14] for five different cities of India. G.N. Tiwari et al. [15] has showed that PV/T air collector with glass to glass type PV module gives higher efficiency than the glass to tedlar type PV module by using an analytical expression and has experimentally validated the results. F. Sobhamayan et al. [6] tried to optimize the exergy efficiency of a PV/T water collector through a similar analytical module coupled with an exergetic analysis. These studies clearly portray the technical feasibility of PVT technology which needs to be further evaluated as a part of an integrated system.

The possibility of energy storage to provide a continuous energy supply to the building and economic aspects have been considered in research. The responses of storage mediums according to demand variations and their effect on the cost of the system are studied [8]. S. Bhattarai et al. [16] carried out a comparative study of PV/T systems with different storage capacities and exercised a performance evaluation with an economic analysis. A. Ganguly et al. [17] presented modelling and analysis of a stand-alone integrated power system consisting of solar PV system, electrolyzer bank and Polymer Electrolyte Membrane (PEM) fuel cell. Optimal management of an integrated power system consisting solar PV system and fuel cell is carried out by N. M. Buker [18] performed a Life Cycle Cost (LCC) based techno-economic analysis for building integrated PV/T air collector. However, a practical method to accomplish energy demand of different building applications from converted solar energy through a PV/T system has not been proposed. Further, the major weakness of these studies is the opportunity of PV/T systems to be a part of an integrated energy system with future modifications of the grid such as smart metering is not evaluated.

This study presents results of few case studies conducted to evaluate the role of PV/T systems in integrated building energy systems with multiple energy storages and smart metering. The practical aspects to extract energy from PV/T systems and to respond demand variations of both residential and industrial applications are considered in this study. Consequently, case studies are conducted for different climatic conditions and demand profiles of buildings to evaluate the system performance and to evaluate the viability of harnessing solar energy through PV/T systems in Sri Lanka. A concise description about the mathematical model developed to analyze energy flow through system components and cash-flow is presented in Section 2. Section 3 presents the energy economic dispatch developed. Finally Section 4 presents the results obtained through the case studies with a detailed discussion.

II. Mathematical Model for PV/T System

A techno-economic model is developed to evaluate the sensitivity of operating and climatic parameters for a hybrid PV/T system. Five main configurations of the PV/T system are considered based on the heat transfer fluid and the arrangements of glass and tedlar layers of PV/T collector. The mathematical model of PV/T system is combined with storage models using the energy economic dispatch to match the energy requirement of a building. Proton Exchange Membrane (PEM) fuel cell and Phase Change Materials (PCM) are selected as electrical and thermal energy storage mediums respectively. A summary of the developed model is shown in Fig. 1. Hourly solar irradiation, wind speed and ambient temperature are taken using TMY2 climate file as the input for the model. Subsequently, energy model is simulated considering the demand and limitations in grid interactions as discussed in Section 3. A cost model is used to evaluate the case flow of the system.

A. Energy flow model

The energy analysis of the PV/T system is carried out to develop the mathematical model. A concise description about the mathematical model is presented in this study. Analytical expressions for thermal energy production and thermal efficiency of PV/T collector are obtained by writing energy balance equations for each component i.e. PV module, absorber plate and heat transfer fluid flowing through the duct [19] [20]. An expression for the fluid outlet temperature ($T_{f,out}$) is derived using the energy balance equations. The rate of useful thermal energy for a heat transfer fluid having a specific heat capacity C_f flowing at a mass flow rate of is calculated. $T_{f,in}$ is the fluid inlet temperature and G is the solar irradiance which are input parameters. The thermal efficiency of the PV/T collector with length L and width W is obtained as Eq. 1;

$$\eta_{th}=\frac{\text{Rate of useful thermal energy}}{\text{Rate of solar energy incident on the panel surface}}=\frac{\dot{m}C_f\left(T_{f,out}-T_{f,in}\right)}{WLG} \tag{1}$$

The electrical efficiency of the PV/T collector is derived using Five-parameter photovoltaic model [21]. A set of nonlinear equations that can be solved with numerical methods are derived to plot the I–V characteristic curve. The values of maximum power point voltage and maximum power point current (V_{mp}, I_{mp}) are obtained from solved I–V characteristic curve. The electrical efficiency of the PV/T collector is obtained as Eq.2;

$$\eta_{el}=\frac{\text{Actual electrical output power}}{\text{Rate of solar energy incident on the panel surface}}=\frac{V_{mp}I_{mp}}{WLG} \tag{2}$$

The energy analysis of the PEM fuel cell [22] and PCM [23] are performed on hourly basis. The efficiency and the thermal to electrical ratio of the fuel cell are determined considering the conversion efficiency drop due to part-load performances [24].

B. Cost model

The economic viability of PV/T system is analyzed for the energy demand of a building through sensitivity analysis using a Life-Cycle Cost (LCC) computation [25]. The purpose of LCC is to provide an effective cost estimation of a designed system. It takes into account of investment, operation and maintenance costs, discount rates and inflation rates. Difficulties in using LCC are data unavailability and unpredictable economic changes and cost changes [26]. The complete range of costs and time equivalent of the cash flows are considered in calculating the LCC as Eq.3;

$$LCC=C_{In}+C_{O,pv}+C_{M,pv} \tag{3}$$

In the cost model 20 year time horizon for the PV/T collector and 10 year time span for energy storage components is used to analyze the economic viability. The initial capital investment (C_{In}) is the sum of the investments of each part of the PV/T system, i.e. PV array, DC/AC converter, fuel cell, electrolyzer, PCM, transportation and installation, etc. In the energy economic dispatch different energy sources are incorporated. Most cost effective energy source is selected in the hourly simulation considering the price variations of the energy sources, these are included in the present value of operating cost ($C_{O,pv}$).The present value of maintenance cost ($C_{M,pv}$) includes the costs involved in maintaining the PV/T system at standard conditions.

III. Simulation

The proposed mathematical model is consisted of different energy sources namely the PV/T collector, PEM fuel cell, PCM storage and local grid. Therefore, there are multiple options to be considered when providing the demand of the building. Energy-economic dispatch strategy can be used in this regard select the best option. Energy economic dispatch strategies have been implemented for number of cases such as stand-alone hybrid energy systems [27]–[32], solar thermal power generation, V2G [23] etc. Nonetheless, a detailed dispatch strategy for PVT systems has not been carried out so far.

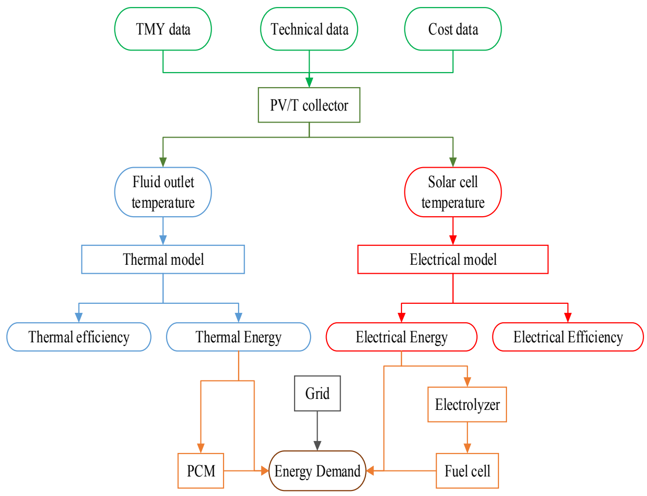

Fig1: Overview of the mathematical model

The responses of those energy sources are changed according to the demand variations. The demand profile is presented in Fig.5.The energy-economic dispatch for electrical model and thermal model can be shown in Fig. 2 and Fig. 3 respectively. The cost and income of each condition are calculated at the end of the path. The operating cost/income of the system is computed to the life cycle cost of the system.

IV. Results and Discussion

The simulated results for the five configurations of PV/T collectors indicate that PV/T water collector with glass to tedlar PV module provides the highest efficiency values. Therefore, water collector with glass to tedlar PV module is used for the detailed analyze of the system PV/T. The input parameters for the mathematical model are presented in Table 1. To analyze the sensitivity of seasonal changes on performance characteristics of PV/T collectors, hourly variation of PV/T collectors is presented for four months in Fig. 4 (a) and Fig. 4 (b). The results obtained for efficiency values were within the range of previous researches done [6] [7] [13] [14] [15] [25] [32].The details on the locations selected for case study are included in Table 2.

TABLE 1: Input parameters

Parameter	**Value**
PV module	BP 3225T, polycrystalline silicon 22.5kW
Energy model parameters	
mass flow rate	0.0113kg/s
L	16.7m
W	9m
C_f	
C_w	4190kJ/mol kg
C_a	1005kJ/mol kg
V_{mp}	29.1V
I_{mp}	7.70A
Cost model parameters	
C_{in} (11 solar panels)	$425,955
Maintenance cost	10% of C_{in}
Inflation rate	8%
Discounting rate	10%

The highest solar radiation intensity is reported in March and the lowest in December. The wind speed for these two months is relatively low compared to other two months. In March the thermal efficiency is the highest, however the electrical efficiency is the lowest due to very high solar irradiance and lower wind speeds. The lowest thermal and electrical efficiencies are reported in December due to lower solar radiation and wind speed. These figures clearly present that the electrical efficiency drops with increase of solar irradiance even though the thermal efficiency increases.

During June and September the wind speed increases where the solar irradiance in mid ranges. This results to enhance the electrical efficiency while diminishing the thermal efficiency as shown in Fig 4 (b). The increase of wind speed increases overall heat loss coefficient, therefore solar cell temperature decreases and in consequence, the thermal efficiency decrease and the electrical efficiency increases. The overall efficiencies in the months of March, June and September are in the same range reflecting the effect of thermal and electrical efficiency variations; however a significant drop in the overall efficiency is observed for the month of December. The changes in the performances and availability of renewable energy potential due to seasonal changes makes it essential to analyze the sensitivity of PV/T capacity on grid interactions and life cycle cost.

Fig. 6 shows the variation of annual grid integration with respect to solar panel capacity for Anuradhapura on a typical date on March. The building energy demand data are taken from an apparel manufacturing plant and electrical and thermal energy storage are kept constant.

The graph generally shows a decrease in grid interaction as the solar panel capacity increase, since the solar energy that can be converted into electrical and thermal energy increases.

When solar panel capacity is low, large portion of the energy demand of the building is accomplished from the local grid. At these levels most of the energy that is converted is used to accomplish the demand and less energy is stored in H2 and thermal storage. When the solar capacity is average levels, there is a reduction in grid interaction as the most of the energy demand of the building can be provided from the solar system, i.e. energy converted from solar and excess energy stored in fuel cell and thermal storage unit. As the solar capacity increases the grid interaction lowers further and contribution from fuel cell and thermal storage becomes high.

The responses of other energy supply units with respect to solar panel capacity can be expressed as following.

TABLE 2: Details on the locations selected for case study

Place	**Geographical location**	**Average Temperature (^{0}C)**	**Average Wind Speed (m/s)**	**Average Solar irradiance (W/m^2)**
Anurdhapura	08°22'N 80°28'E	28.3	1.37	366.17
Hambantota	06°10'N 81°10'E	28.0	6.80	426.87
Trincomalee	8°38'N 81°15'E	29.9	4.16	399.75
Puttalam	08°01'N 79°55'E	27.8	3.84	370.86
Ratmalana	06°45'N 79°55'E	28.2	2.81	345.86

Fig. 2: Electrical Dispatch [27]-[32]

Electrical energy produced by the solar panels is not supplied to the local grid at any level of solar capacity. When the thermal energy produced exceeds the energy requirement and storage capacity and excess can be supplied to the grid, hence a saving can be gained. This happens at the level of solar capacity is at an average. Detailed analysis of the variations shows that the thermal storage unit contributes more energy to the building application at high levels of solar capacity. The decision to fulfill the electrical energy demand of the building basically depends on the grid cost of the local grid. The electrical energy that can be taken from the fuel-cell mainly depends on the maximum conversion capacity of the fuel cell.

Fig. 7 shows the variation of NPV (Net Present Value) with respect to solar panel capacity for 5 different locations in Sri Lanka. It is observed that, as the solar panel capacity increases the rise of NPV decease for all 5 locations. This happens due to the decrease of initial investment cost as the number of solar panels increases and the decrease of total operating cost of the system because of capacity the solar panels can convert solar energy to useful energy increases.

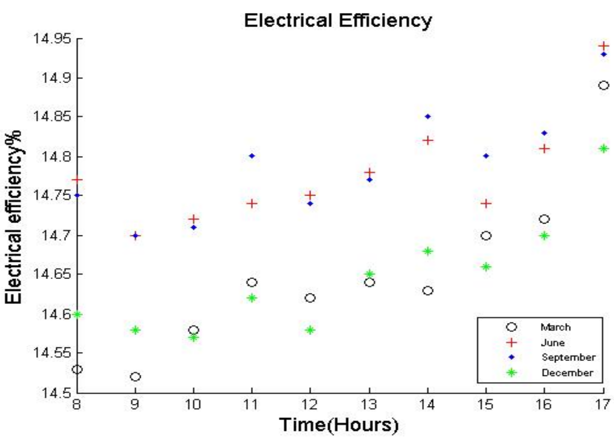

Fig 4(a): Seasonal variation of electrical efficiency

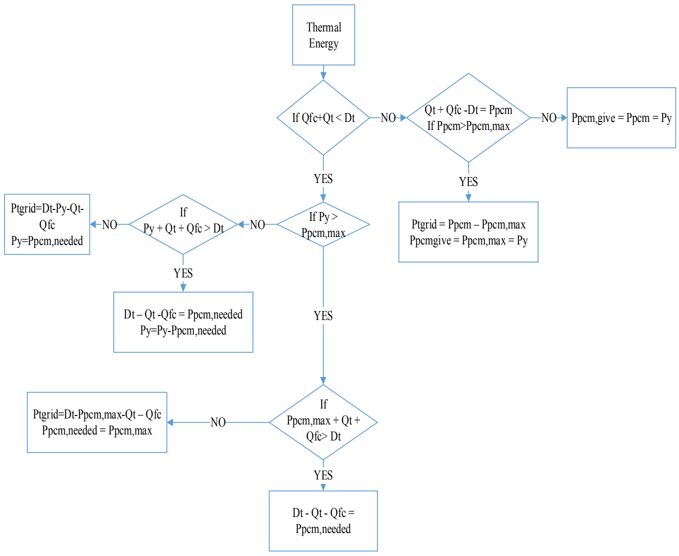

Fig. 3: Thermal Dispatch

V. CONCLUSIONS

In this paper, the changes in the performances of PV/T collector due to seasonal variations and the sensitivity of PV/T capacity on grid interactions and life cycle cost were analyzed. Following conclusions have been made on the basis of present study.

PV/T water collector with glass to tedlar PV module provides the highest efficiency values. The sensitivity analysis of seasonal changes on performance characteristics of PV/T collector indicates that higher solar radiation intensity enhances the thermal efficiency while increasing wind speed adversely affect the thermal efficiency. The electrical efficiency variation was the inverse of the above mentioned relations.

Case studies show that the increase in solar panel capacity results a decrease in grid interaction and life cycle cost of the system because the solar energy that can be converted into electrical and thermal energy increases. It is observed from the present results that the PV/T system with the electrical and thermal storage is suitable to supply energy demand of buildings both technologically and economically and deploying PV/T system in Sri Lanka is practical for the places considered here.

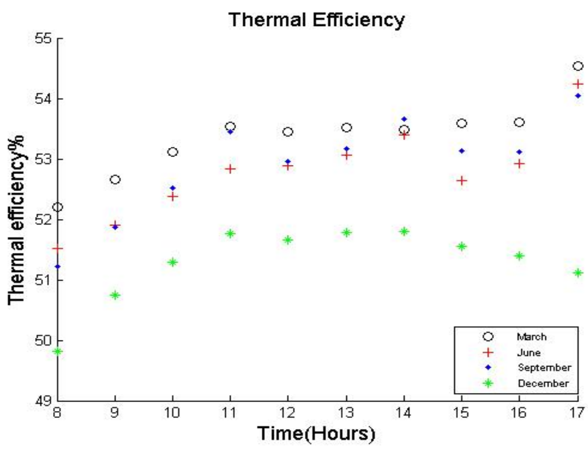

Fig 4(b): Seasonal variation of thermal efficiency

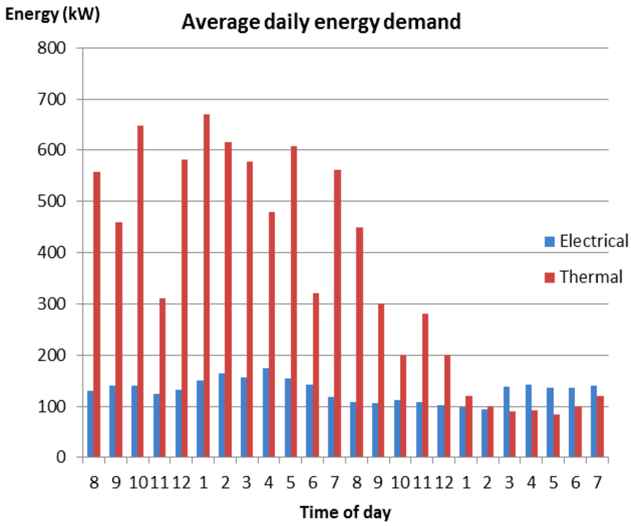

Fig 5: Average daily energy demand

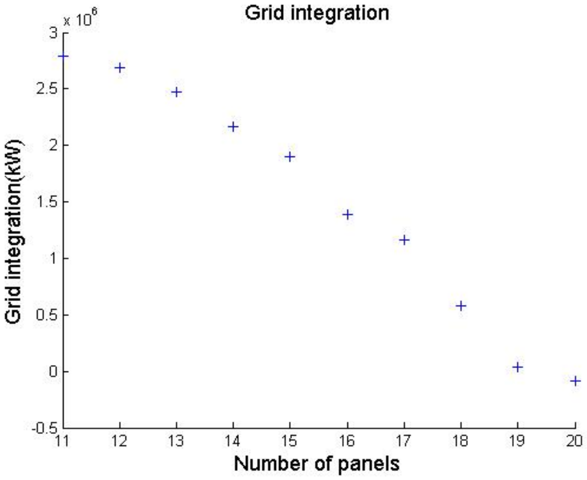

Fig 6: Variation of annual grid interaction with number of panels

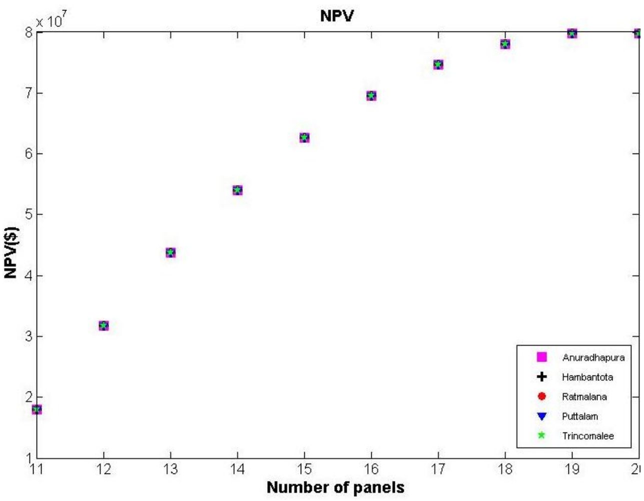

Fig 7: Variation NPV with number of panels

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