Retrofit Design And Optimization Of PVT-ASHP Plant In Tropical Healthcare Facility.

M.AZLY AZIZ[a,*], SOHIF MAT[b], NM WAJID[a], MOHD KHAIRUL ANUAR SHARIF[a]

[a]Public Works Department of Malaysia.
Menara Kerja Raya,
Jalan Sultan Salahuddin,
50582 Kuala Lumpur,
MALAYSIA

[b]Solar Energy Research Institute
Universiti Kebangsaan Malaysia,
43600 Bangi, Selangor,
MALAYSIA

Abstract:- A proposed large scale PhotoVoltaic Thermal (PVT) system integrated with existing Air Source Heat Pump (ASHP) hot water plant in a healthcare facility located in tropical ambient has been simulated and optimized. Healthcare facility, which is characterized, by consistent thermal and energy demand, day and night has been selected due to its high economic potential for integration of PVT system with typical ASHP plant widely installed in Malaysia's healthcare facility. Make-up water is pre-heated by the PVT system before entering the ASHP's calorifer and thus reducing the energy input for ASHP as well as generating electricity for hospital consumption. This configuration is selected because it does not require any major modification and minimal disruption to the existing, operational ASHP system. In search of economically optimum system configuration, 3.87m^2/bed PVT collector area per bed ratio, 0.04 m^3/m^2 and eight numbers of PVT collector connected in series proved to be the most economically superior design at a total solar fraction of 198.2%, thermal solar fraction of 78% and an electrical solar fraction of 336%. The results signify the potential of integrating large scale PVT collector systems with existing ASHP plants, particularly in the healthcare facility.

Keywords: - Photovoltaic Thermal Collector, Renewable Energy, Hot Water, Air Source Heat Pump.

1 INTRODUCTION

Concerns for negative environmental impacts of conventional fossil fuels and rising energy costs have been the main drivers towards the transition to renewable energy technologies. Researches and policymakers all around the world are actively scouting for strategies to reduce greenhouse emissions and energy costs by promoting renewable energy integration and energy efficiency initiatives. Solar energy is the most promising source of renewable energy with its abundance in most parts of the world.

PVT collector has many advantages compared to independent collectors including but not limited to better PV performances, lower installation footprint, and a slower rate of cell degradation, resulting in maximization of the life span of photovoltaic modules and space-saving compared to having two separate systems [1]–[3].

In a PVT collector, a considerable amount of solar energy will be converted into thermal energy and absorbed by the flat plate collector underneath, simultaneously reducing the surface temperature of the photovoltaic cells and improving its efficiency. Every 1°C surface temperature rise of the PV module causes a reduction in efficiency from 0.2% to 0.5% depending on the type of PV collector [4], [5]. PVT generates higher useful energy output than the combination of PV and PT [6].

Many research focuses on improving PVT efficiency particularly on the effect of glazing [7]–[10], and collector tube configuration [1], [11]–[14]. Few types of research had been conducted on system-level integrating PVT collector with other thermal demand systems in an attempt to determine the effect of PVT array size, configuration, storage tank capacity, and geometry. Concerning PVT efficiency and output, increasing the collector area will increase PVT output up to a point where the performance becomes plateau [15]. Herrando et.al (2018) developed a methodology for modeling the energetic and economic performance of such PVT-based S-CHP (solar combined heat and power) systems, which is used to optimally size and operate systems for covering the energy demands of single-family reference households. The results demonstrate that optimized systems are capable of covering up to 65% of the annual household electricity demands in Athens, London and Zaragoza when employing 14.0m^2, 17.0m^2, and 12.4m^2 collector array areas respectively [16].

Researches also focused on the impact of PVT collector array configuration of PVT system performance. From the PVT collector perspective, adding a collector in a series connection reduces the thermal and electrical efficiency due to elevated PV surface temperature [17]. A study by Liang (2017) indicated that thermal efficiency decreases from 62% to 45% for six PVT collectors connected in series and the electrical efficiency decreases from 15.73% to 15.21%. However, in the context of collector-storage interaction, the thermal performance of a hot water system can be increased by maximizing the level of thermal stratification within the storage tank, which could lead to huge energy saving [17], [18]. Increasing the tank's height/diameter aspect ratio, decreasing inlet/outlet flow rates, and moving the inlet/outlet to the outer extremities of the tank all result in increasing levels of thermal stratification [19]. By connecting PVT collectors in series, the lower inlet flow rate can be achieved and enhance thermal stratification within storage tanks. Aste, Del Pero and Leonforte (2012) conducted PVT systems simulations of PVT systems for domestic application via TRNSYS carrying out subsequently a detailed energetic, and economic analysis. The study aims to determine the optimal value of solar fraction for hybrid PVT systems, under the energetic end economic point of view. The optimum value of the PVT systems solar fraction was found to be between 40-60% depending on the analyzed case using fixed capacity storage. PVT system design is strongly influenced by the thermal load profile of a particular installation or building category. On economic terms, Kalogirou and Tripanagnostopoulos (2006) conducted PVT system simulation via TRNSYS coupled with domestic hot water applications. Analysis of Life Cycle Cost (LCC) revealed that without price subsidy, the LCC obtained are negative, with a payback period greater than 20 years, which is considered as the life of the systems. Hazi et.al (2014)] conducted a technical and economical assessment of the opportunity to use PVT systems for water heating in the industry. The numerical analysis revealed the influence of solar irradiance, air temperature, and water supply temperature on the energy parameters and economic indicators. The conclusion is that using a PVT system for water heating in the industry is economically attractive, in the climatic conditions of Romania, and the payback period is lower than its lifetime.[22]. The cost of PVT still remains high relative to PV, it is important to consider how to promote this technology [16]. Many studies also focused on PVT system-level design and optimization [15], [20], [21], [23], [24]. Thermal demand understudy is typically for household or small office demand [21], [23].

So far, comprehensive literature by the author has yet to find any study focusing on the integration of large scale PVT systems on existing ASHP plants serving the thermal demand of healthcare facilities under tropical conditions. Malaysia has great potential to utilize solar energy as a renewable source of energy due to its equatorial location and high solar energy potential with the daily average solar radiation of 4000–5000Wh/m^2 with average sunshine duration in the range of 4–8 h/day [25]. Typically, for a healthcare facility in Malaysia, ASHP is employed to generate hot water at 60^{o}C. In line with Malaysia's national aspiration to promote sustainability, an increasing number of healthcare facilities had been retrofitted with renewable energy technologies exclusively STC and PV technologies due to their demand for both types of energy. Up to 2017, there are a total of 144 existing healthcare institutions in Malaysia with 41,995 beds comprising of hospitals and Special Institution [26]. Total hot water plant thermal and electricity demand is estimated at 264,729 MJ/year and 69,666 MJ/year respectively with an approximate energy cost of RM 7,000,000 /year. There is great potential for retrofitting the current ASHP plant with the PVT system.

It is the interest of the study to identify the optimal main design parameters of the integrated PVT-ASHP that will maximize the net present value (NPV) of the investment. The main design parameters selected for the study are PVT collector area to bed ratio, storage volume per PVT collector area, and the number of PVT series connection.

2 DESCRIPTION OF SERDANG HOSPITAL HOT WATER PLANT

A 129,000 square meters, Serdang Hospital is located in Serdang, Selangor provides medical services to approximately 570,000 residents in Serdang, Putrajaya, Kajang and Bangi areas. Serdang Hospital is a government hospital that operates as a reference hospital with 620 beds equipped with a variety of up-to-date facilities. The hospital provides medical services and treatments according to current needs for internal and external patients while serving as a teaching hospital for Universiti Putra Malaysia (UPM) medical students. Current hot water demand is served from 168 kW_{th} Centralized Air Source Heat Pump (ASHP) plant (see Appendix 1 for plant schematic). A total of four units of ASHP are installed with a capacity of 42kW each providing hot water at 60°C to all hot water fittings distributed throughout the hospital. Four (4) number of 5,000-liter calorifier complete with auxiliary heater are provided for storage purposes. Make-up water is fed from the domestic water roof tank directly into the calorifier via a feed pump. Water in the calorifier is heated by ASHP via the primary water pump. The hot water temperature in the calorifier is set at 60°C. A secondary water pump will then distribute the hot water in the calorifier to all fittings throughout the hospital. All final fittings are connected in a closed-loop distribution system.

3 METHODOLOGY

The research has been conducted in phases starting with existing ASHP Plant field data measurements, ASHP plant modeling and calibration in TRNSYS, integrated PVT-ASHP plant modeling in TRNSYS, and finally economic optimization of the integrated PVT-ASHP plant.

3.1 ASHP plant field data measurements

Thermal energy demand data and the associated electricity input to the ASHP plant were measured for one (1) week which is deemed sufficient given the fairly consistent weekly hot water demand for the hospital [27]. Measuring equipment used is shown in Table 1. Energy meter for thermal energy input measurement to domestic hot water was attached to incoming feed water pipe from the roof storage tank to the calorifier. Water temperature in the feed pipe as well as the outgoing hot water temperature in the distribution pipe was measured at an interval of 10 minutes. Power logger was attached to an incoming power supply to ASHP and record power and energy consumption of heat pump Thermal energy input to domestic hot water was calculated according to;

$$Q_t = \dot{m}C_p(T_{dhw} - T_{fw}) \qquad (1)$$

Where Q_t is the thermal energy input, $\dot{m}$ is the mass flow rate, Specific heat capacity, C_p of water is taken at an average temperature of feed water, and domestic hot water setpoint temperature. The temperature rise of the heated water is taken as the difference between outgoing hot water temperature, $T_{dhw,}$ and feed water temperature, T_{fw}.

3.2 ASHP Plant modeling and calibration

Field data collected were used and conditioned as a performance data file for ASHP and hot water demand. This model was then calibrated by comparing to previously measured data, enabling the replication of the actual operating condition of the ASHP plant. This model is used as the baseline model for ASHP and provides baseline energy data before integration with the PVT system.

Table 1 Measuring equipment specification

Legend	Equipment	Brand	Accuracy	Measured Variable
FM	Ultrasonic Flowmeter	GE Panametrics	± 1.0 %	Water flowrate
PL	Power Logger	Chauvinarnoux PEL 103	± 0.7 %	Electrical power measurements
T	Temperature logger	KIMO	±0.4°C from -20 to 70°C	Water temperature

A good agreement was observed between the simulation and field data measurements. The correlation coefficient (r) and root mean square percent deviation (e) have been evaluated by using the following expressions. The result of the validation is shown in Table 2.

$$r = \frac{N\sum X_iY_i - (\sum X_i)(\sum Y_i)}{\sqrt{N\sum X_i^2 - (\sum X_i)^2}\sqrt{N\sum Y_i^2 - (\sum Y_i)^2}} \qquad (2)$$

$$e = \sqrt{\frac{\sum\left(\left(\frac{X_i - Y_i}{X_i}\right)\times 100\right)^2}{N}} \qquad (3)$$

3.3 Integrated PVT System and ASHP Plant Modelling

The calibrated model of ASHP plant in TRNSYS is then integrated with a subsystem of PVT collectors which consists of a combination of series and parallel PVT collectors and feedwater storage tanks enabling the in-depth study of the effect of PVT collectors on ASHP plant performance. The Integrated PVT-ASHP plant model in TRNSYS is shown in Appendix 2. PVT collector array is connected to the ASHP plant in series, by pre-heating the incoming feed water to calorifier.

a. PVT Collector

The geometry and performance data of the PV cells and absorber plate is based on commercially available PVT collectors, ECOMESH by Endef Engineering SL [28] PVT collector specification is shown in Table 3.

Table 2 Result of validation

Parameter	Average value		(r)	(e) (%)
	Field Data	Simulation		
ASHP Thermal Output (kW)	126.4	128.1	0.75	4.3
ASHP Electrical Input (kW)	31.8	32.3	0.88	5.0

Table 3 PVT Collector data [29]

Item	Parameter
General	
Manufacturer	ENDEF Engineering SL
Model	Ecomesh V230/00
Cell size (mm x mm x qty)	156 x 156 x 60
Dimensions	1945 x 978 x 93
Gross area	1.64 m2
Orientation	North
Inclination angle	10°
PV specifications	
Nominal power	255 Wp
Nominal voltage	31.65 V
Nominal current	8.06 A
Short circuit current (Isc)	9.06 A
Open circuit voltage (Voc)	38.58 V
Power temperature coefficient	0.47%/K
PV efficiency at reference condition	15.98%
Thermal absorber specifications	
Absorber material	Copper
Absorber tube	Copper
Optical performnce (ηo)	0.51
Heat loss coefficient (a1)	4.93 W/m2.K
Heat loss coefficient (a2)	0.021 W/m2.K2
Water temperature loss	0.04 bar

b. PVT array area, configuration and storage volume

To study the effect of PVT collector area, configuration, and storage volume on PVT energy outputs and economics, various combinations of PVT collector area, configurations (series and parallel), and storage tank capacities are simulated as shown in Table 4. The maximum number of PVT collectors connected in series is limited to 8 and the number of rows, depending on the number of PVT panel selected. Determination of the number of row for a given number of panel and number of PVT connected in series is given by;

$$|N_r| = \frac{A_c}{N_s} \tag{4}$$

Since N_r computed from the above relationship may be non-integer, N_r is rounded up to the nearest integer and the actual collector area and the simulation result will be normalized back to the nominal collector area. The optimal water flow rate is set at 118kg/hr in which the performance data is based on. Storage tank capacity is limited to 150m^3 and 4.0m height due to site constraints and practicality.

Table 4 Simulation variables and variants

Variables	Variants	Quantity of variants
Nominal collector area (A_c)	80 to 3280 m^2 (increment of 50 panels)	41
Storage Volume (m^3) (V_{st})	5 to 150 m^3 (increment of 5 m^3)	30
No of PVT collector connected in series (N_s)	1 to 8	8

c. PVT collector efficiency and solar fraction

PVT collector overall efficiency consists of both thermal and photovoltaic components as described below;

$$\zeta_{pvt} = \zeta_{th} + \frac{\zeta_{pv}}{\zeta_p} \tag{5}$$

PVT thermal and electrical efficiency is given by;

$$\zeta_{th} = \frac{E_{th,pvt}}{A_{pvt} I_T} \tag{6}$$

$$\zeta_e = \zeta_{ref}\left[1-\beta_{pv}\left(T_{pv}-T_{ref}\right)\right] \quad (7)$$

Where A_{pvt} is the PVT collector area in m^2, I_T is the incidence solar radiation in kJ/hr.m^2 based on Kuala Lumpur, Malaysia solar radiation data. ζ_{ref} is the PV efficiency at reference conditions, β_{pv} is the temperature coefficient in %/K, T_{pv} is PV cell temperature in Celcius (^oC) and T_{ref} is reference PV cell temperature.

The term ζpv/ζp represents the PV efficiency normalized by the typical efficiency of power plant efficiency (ζp) in Malaysia. This efficiency term represents the energy output of the PV cell in terms of primary energy enabling us to make a fair comparison with the thermal energy output of the PVT collector. The efficiency of the power plant (ζp) in Malaysia is taken as 38% as reported in Malaysia's National Energy Balance 2015.

In this paper, the annual thermal and electrical solar fraction is used as one of the performance indicators of the PVT system output. Annual thermal solar fraction (SF_{th}) is defined as the ratio of the annual useful thermal energy output of PVT collector ($E_{th,pvt}$) transferred to feed water (load) and annual thermal energy demand of the hot water system ($E_{th,dhw}$). Annual electrical solar fraction (SF_e) is defined as the ratio of annual PVT electrical energy output ($E_{e,pvt}$) minus energy required for PVT collector array circulating pump ($E_{e,wp}$) and ASHP plant electrical energy demand ($E_{e,dhw}$).

$$SF_{th} = \frac{E_{th,pvt}}{E_{th,dhw}} \quad (8)$$

$$SF_e = \frac{E_{e,pvt}-E_{e,wp}}{E_{e,dhw}} \quad (9)$$

The total annual solar fraction is then defined as;

$$SF_T = \frac{E_{th,pvt}+\frac{E_{e,pvt}-E_{e,wp}}{\zeta_p}}{E_{th,dhw}} \quad (10)$$

$E_{th,dhw}$ and $E_{e,dhw}$ is based on annual hot water thermal demand and annual electricity consumption of the PVT-ASHP plant. PVT collector circulating pump annual energy ($E_{e,wp}$) is given by:

$$E_{e,wp} = \int_0^T \frac{\dot{m}_{pvt,t}\Delta P_{pvt,t}}{\rho_w \zeta_m \zeta_p} \quad (11)$$

Where $\dot{m}_{pvt,t}$, $\Delta P_{pvt,t}$ and ρ_w are total mass flow rate, total pressure drop, and density of water through PVT collector array in kg/s, Pa, and kg/m^3. Motor efficiency (ζ_m) and pump efficiency (ζ_p) are taken as 0.9 and 0.6 respectively. T is the annual simulation time taken as 8760 hours/year. $\dot{m}_{pvt,t}$ *and* $\Delta P_{pvt,t}$ area dictated by PVT configuration given by;

$$\dot{m}_{pvt,t} = \dot{m}_{pvt,p}N_r \quad (12)$$

$$\Delta P_{pvt,t} = \Delta P_{pvt,p}N_s \quad (13)$$

where PVT collector mass flowrate ($\dot{m}_{pvt,p}$) and associated pressure drop ($\Delta P_{pvt,p}$) selected are 0.03 kg/s and 153 Pa respectively based on PVT collector test flowrate [28].

3.4 Integrated PVT and ASHP plant simulation and optimization

a. Energetic Optimization

Simulations were carried out with a different set of variables as mentioned previously to minimize the total net plant energy consumption of PVT-ASHP plant (NPEC) given by;

$$E_{t,pl} = E_{hp} - E_{e,pvt} + E_{e,wp} \quad (14)$$

Where $E_{t,pl}$ is total net energy of PVT-ASHP plant, $E_{e,pv}$ is the annual electrical energy produced by PVT collector (MJ/yr), E_{hp} is the annual electrical energy input to ASHP (MJ/yr) and E_{wp} is the electrical energy input to circulating pump (MJ/yr). As the PVT collector area increases, PVT collector's electrical energy and thermal output increases while reducing ASHP plant electrical input.

b. Economic Optimization

Net Present Value (NPV) of PVT-ASHP plant is selected as economic appraisal criteria and given by;

$$NPV = \sum_{n=0}^{N} \frac{F_n}{(1+d)^n} \quad (15)$$

N is the economic life of PVT collector taken as 25 years, F_n is the annual cash flows in year n. and d is the annual discount rate taken as 3.25% [30]. The

Solar PV degradation rate is taken as 1% per annum [31]. Solar PV energy output cost is as per Malaysia's Sustainable Energy Development Authority (SEDA) [32]. Other electricity input energy costs for the rest of the PVT-ASHP plant use Tenaga Nasional Berhad (TNB) rate for a commercial building, Tariff C2 at RM 0.365/kWh. A maximum demand charge is not considered in the economic analysis.

The estimated capital cost of the PVT installation is shown in Table 5. PVT module cost is inclusive of the inverter and balance of system (BOS) cost at the ratio proposed by EPIA [33].

Table 5 Estimated PVT module and ancillary cost

Component	Cost
PVT module (RM/m^2)	1,660
Pipework (RM/m^2)	100
Storage tank (RM/m^3)	2,000

4 RESULTS AND DISCUSSION

4.1 Existing ASHP Plant hot water demand and energy input

Measured hot water consumption for a week resulted in a total average daily consumption of 80,000 lpd, corresponding to 132 lpd/bed as shown in Fig.1. This is in line with other findings from 80 to 130 lpd/bed in Europe and, 100 to 150 lpd/bed in the USA and 90 to 120 lpd/bed in Greek (cited in [34]).

TRNSYS simulation of the calibrated ASHP plant model was then run to obtain the annual energy baseline of ASHP plant energy as shown in Fig.2. The annual heat demand and electricity demand of the ASHP plant are 3,327,021MJ$_{th}$/year, 864,626MJ$_e$/year with an annual energy cost of RM87,664/year.

4.2 Effect of PVT collector storage volume and array configuration on Solar Fraction (SF) , Net Plant Electricity Consumption (NPEC)

Storage tank capacities for all series connections influence the total solar fraction and net plant electricity consumption (NPEC) of the PVT system as shown in Figure 3 (only result for 1120m^2 PVT collector area is presented). As the storage volume increases, the heat storage capacity of the storage tank reduces the water temperature inlet to the PVT array and improves its solar fraction until it becomes plateaued. This is in line with other studies on the effect of a storage volume on PVT output [16], [35]. As solar fraction increases, the useful energy transferred to Air Source Heat Pump (ASHP) calorifier increases followed by a corresponding drop in ASHP electrical energy input. Total solar fraction for all parallel PVT connections (N_s=1) for 1120 m^2 PVT collector area, rose from 73.5% to 93.0 % upon reaching storage tank capacity of 150m^3 or at 0.13m^3/m^2 and for N_s=8, total solar fraction rose from 83.8% to 108.1% at storage tank capacity of 125m^3 or 0.11m^3/m^2.

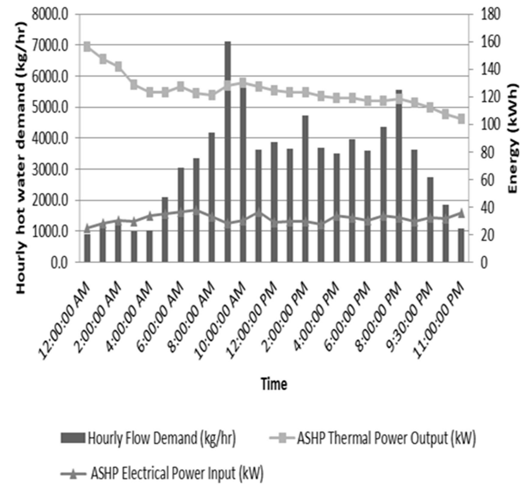


Fig. 1 Daily average daily hot water flow demand (kg/hr)

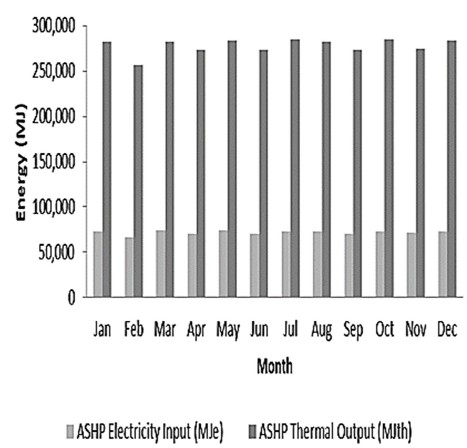


Fig.2 Monthly ASHP Plant electricity input and thermal output

As the number of series connection (N_s) increases, inlet flowrate to the storage tank is reduced with higher temperature and thus enhancing thermal stratification within the storage tank. The reduction of collector flowrate not only increases tank outlet temperature but also results in an overall reduction of system cost with lower pump capacity and smaller pipe size. However, there is a limit in adding PVT collectors in a series configuration. As water temperature rises across the PVT collector, collector heat loss to the ambient increases and reaches a balance point where there are no further heat gains to the PVT collector. There are no significant changes in the total solar fraction from N_s=3 to N_s=8. The highest total solar fraction value is achieved with N_s=6 with a total solar fraction value of 108.6% at a storage volume of 115 m^3 or 0.1 m^3/m^2 as shown in Fig. 4. Conversely, for all other numbers of series connection, there exists an optimum storage capacity that further increments beyond that prove no additional benefit on PVT output. Optimum storage volume that will result in the highest total solar fraction for all series connection ranges from 0.08 to 0.13 m^3/m^2. Studies on optimum storage volume for solar collectors serving residential hot water demand showed quite similar results between 0.05-0.18 m^3/m^2 of the PVT area [36].

In terms of energetic performance, adding a storage tank improves total solar fraction but its monetary benefits are offset by additional cost due to a higher capacity storage tank. Economic appraisal using the Net Present Value (NPV) method is conducted to economically determine the most optimum storage tank capacity that will result in the highest NPV. The result of the NPV analysis for the 1120 m^2 collector area is presented in Fig.5. Positive NPV values indicate profitable investment except for N_s=1 at low storage volume below 10.0 m^3. As storage volume increases, NPV increases until it reaches optimum storage volume at 80m^3 with an NPV value of RM 284,785. Further increment of storage volume proves no further benefit as the additional storage cost outweighs the benefits of additional performance of PVT collector. Economically optimized storage volume is 0.07 m^3/m^2 for 1,120m^2 PVT collector area.

4.3 Net Zero Energy Plant (NZEP)

Numbers of simulations have been conducted to determine the optimum PVT collector area required to achieve NZEP. All parallel configuration (N_s=1) was initially simulated as a baseline case to determine NPEC and associated NPV. In each simulation, storage volumes were varied from 5m^3 to 150 $m^{3,}$ and only results with optimized storage volume for each PVT collector area is presented in Fig.6.

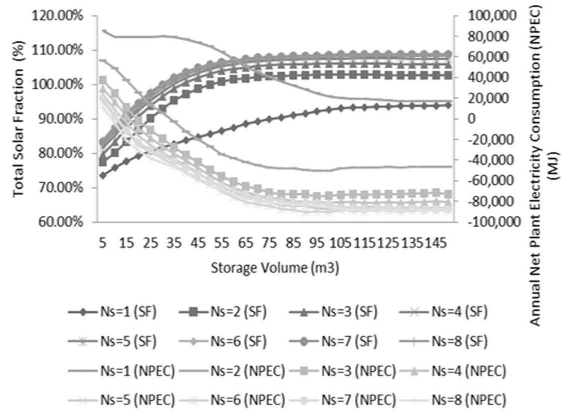


Fig. 3 Effect of a storage volume on total solar fraction and NPEC for 1120 m^2 PVT collector area.

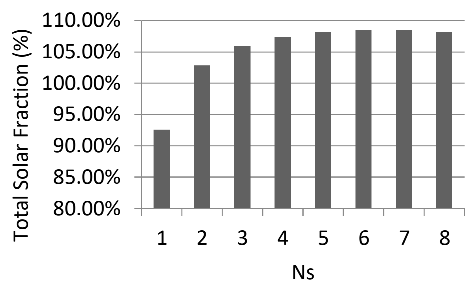


Fig.4 Effect of N_s on total solar fraction for 1120 m^2 PVT collector area.

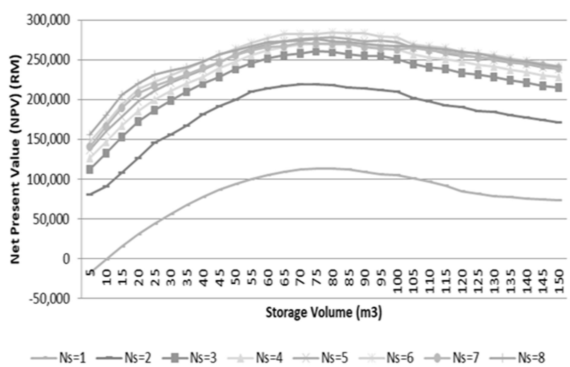


Fig. 5 Effect of a storage volume on Net Present Value for 1120 m2 PVT collector area.

As the PVT collector area increases, annual net plant electricity consumption ($E_{e,pvt}$) and solar fraction increases and offset the electrical energy consumption of the ASHP plant (E_{hp}). Negative NPEC indicates that annual net PVT electricity output has exceeded the electrical energy input to ASHP. Net Zero Energy Plant (NZEP) is achieved when all the energy input to the ASHP plant is fully satisfied by the PVT system. Thus, for all parallel

PVT array, NZEP or 100% electrical SF_e is achieved at approximately $1.80m^2$/bed PVT collector area to bed ratio and storage volume of 0.13 m^3/m^2.

Further analysis was carried out with the number of series connections varied between N_s=1 to N_s=8. The objective is to determine the effect of series connection on the PVT collector area required to achieve NZEP. The result of the simulation is presented in Fig.7. PVT collector area with an optimized number of series connection and storage volume has a linear relationship with NPEC. Data regression between PVT collector area and a solar fraction (electricity) indicates that NZEP is achieved at 1,020 m^2 PVT collector area ($1.65m^2$/bed), 100 m^3 storage tank capacity, or 0.10 m^3/m^2 of PVT collector area and N_s=6.

By series connection of PVT collector, PVT collectors area required to achieve NZEP decreases from 1.80m2/bed for all parallel array (Ns=1) to 1.65m2/bed, a 9% reduction in PVT collector area required.

4.4 Economic Optimization

Economic analysis of all PVT collector area with optimized array and storage volume is presented in Fig.8. For all PVT collector area range under study, optimum Ns ranges from 6 to 8 and the ratio of the storage volume to the PVT collector area from 0.01 to 0.13 m3/m2.

PVT collector area range understudy is extended from 2400 m^2 to 3280 m^2 to determine the optimum PVT collector area where NPV flattens and adding PVT collector area beyond that point evidence no benefits. NPV value increases linearly with PVT collector areas until it reaches an optimum point except at a low PVT collector area (80-160m^2).

From the simulation, under the Malaysia FiT tariff scheme, the optimized configuration that maximise the NPV for all PVT areas under this study is $3.87m^2$/bed PVT collector area to bed ratio, storage volume to PVT collector area ratio of $0.04m^3/m^2$ and number of series connection of N_s=8. NPV and payback period attained with such configuration is RM455,990 with associated capital expenditure of RM 2,713,270 and total solar fraction of 198.2%, thermal solar fraction of 78% and an electrical solar fraction of 336%.

The application of FiT distorts NPV due to its stratified structure. The FiT tariff is relatively high at low capacity PVT array below 24kWp electrical output.

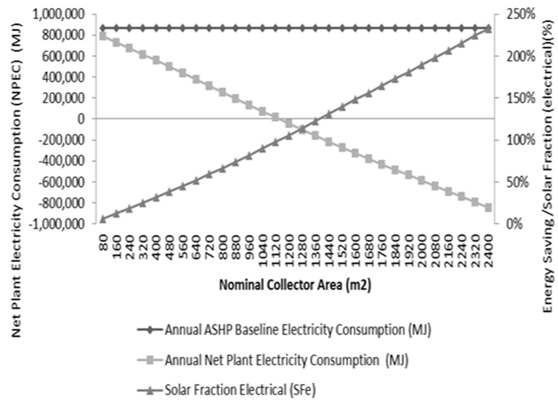


Fig.6 Effect of PVT collector area with optimized storage volume on electrical solar fraction and NPEC [All parallel (Ns=1)]

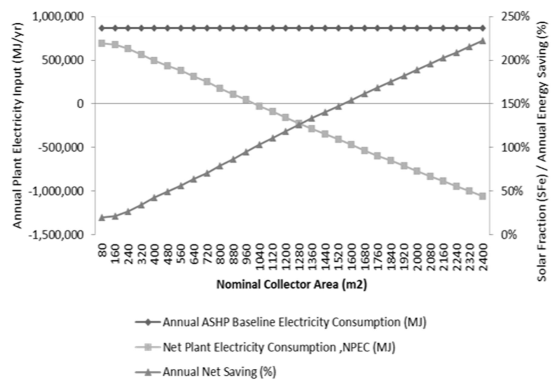


Fig.7 Effect of PVT collector area and Net Plant Electricity Consumption (NPEC) (MJ/yr) in optimized PVT collector array and storage volume.

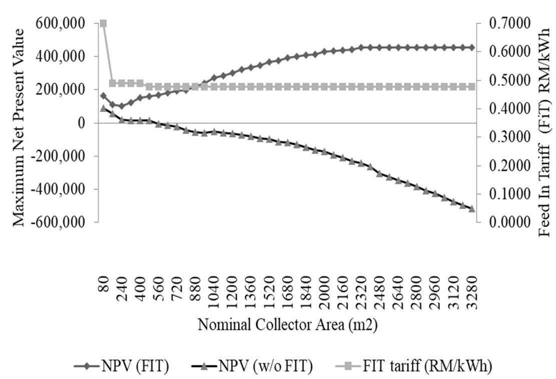


Fig.8 Net Present Value for each collector area with Fit tariff rate, optimized storage tank capacity and PVT collector connected in series

Lower capacity PVT system enjoys a higher FiT rate making it more attractive to invest in smaller-scale PVT installation. NPV for 80 m^2 PVT collector area is RM164,827, higher than 480m^2 PVT collector area with NPV of RM159,461. For investment without the benefit of FiT and under current cost structure, only the PVT collector area below 560 m^2 (0.90 m^2/bed) has an NPV value greater than zero and thus viable for investment.

5 CONCLUSIONS

Energetic and economic optimization of the proposed large scale PVT collector system retrofitted into existing ASHP plant serving healthcare facilities had been presented that will result in the highest NPV of the investment. From the study, it can be concluded that with the benefits of FiT, the proposed system integration between the PVT system and ASHP plant serving healthcare facilities has economic potential and should be further explored. Without the benefit of FiT, additional fiscal incentives shall be in place to promote the nationwide application of the integrated PVT-ASHP system.

.

REFERENCES

[1] H. A. Zondag, D. W. de Vries, W. G. J. van Helden, R. J. C. van Zolingen, and A. A. van Steenhoven, "The yield of different combined PV-thermal collector designs," *Sol. Energy*, vol. 74, no. 3, pp. 253–269, 2003.

[2] W. G. J. van Helden, R. J. C. van Zolingen, and H. A. Zondag, "PV thermal systems: PV panels supplying renewable electricity and heat," *Prog. Photovoltaics Res. Appl.*, vol. 12, no. 6, pp. 415–426, 2004.

[3] G. Fraisse, C. Ménézo, and K. Johannes, "Energy performance of water hybrid PV/T collectors applied to combisystems of Direct Solar Floor type," *Sol. Energy*, vol. 81, no. 11, pp. 1426–1438, 2007.

[4] N. Aste, C. del Pero, and F. Leonforte, "ScienceDirect Water flat plate PV – thermal collectors : A review," *Sol. Energy*, vol. 102, pp. 98–115, 2014.

[5] P. Mahtani, N. P. Kherani, and S. Zukotynski, "The use of amorphous silicon in fabricating a photovoltaic-thermal system," 2007.

[6] T. Matuska, "Performance and economic analysis of hybrid PVT collectors in solar DHW system," *Energy Procedia*, vol. 48, pp. 150–156, 2014.

[7] J.-H. Kim and J.-T. Kim, "The experimental performance of an unglazed PVT collector with two different absorber types," *Int. J. Photoenergy*, vol. 2012, 2012.

[8] I. Guarracino, A. Mellor, N. J. Ekins-Daukes, and C. N. Markides, "Dynamic coupled thermal-and-electrical modelling of sheet-and-tube hybrid photovoltaic/thermal (PVT) collectors," *Appl. Therm. Eng.*, vol. 101, pp. 778–795, 2016.

[9] R. Santbergen, C. C. M. Rindt, H. A. Zondag, and R. J. C. Van Zolingen, "Detailed analysis of the energy yield of systems with covered sheet-and-tube PVT collectors," *Sol. Energy*, vol. 84, no. 5, pp. 867–878, 2010.

[10] P. Dupeyrat, C. Ménézo, M. Rommel, and H.-M. Henning, "Efficient single glazed flat plate photovoltaic–thermal hybrid collector for domestic hot water system," *Sol. Energy*, vol. 85, no. 7, pp. 1457–1468, 2011.

[11] B. J. Huang, T. H. Lin, W. C. Hung, and F. S. Sun, "Performance evaluation of solar photovoltaic/thermal systems," *Sol. energy*, vol. 70, no. 5, pp. 443–448, 2001.

[12] Y. Tripanagnostopoulos, "Aspects and improvements of hybrid photovoltaic/thermal solar energy systems," *Sol. energy*, vol. 81, no. 9, pp. 1117–1131, 2007.

[13] P. Ooshaksaraei *et al.*, "Large scale solar hot water heating systems for green hospital," in *Proceedings of the 2010 American conference on Applied mathematics*, 2010, pp. 504–509.

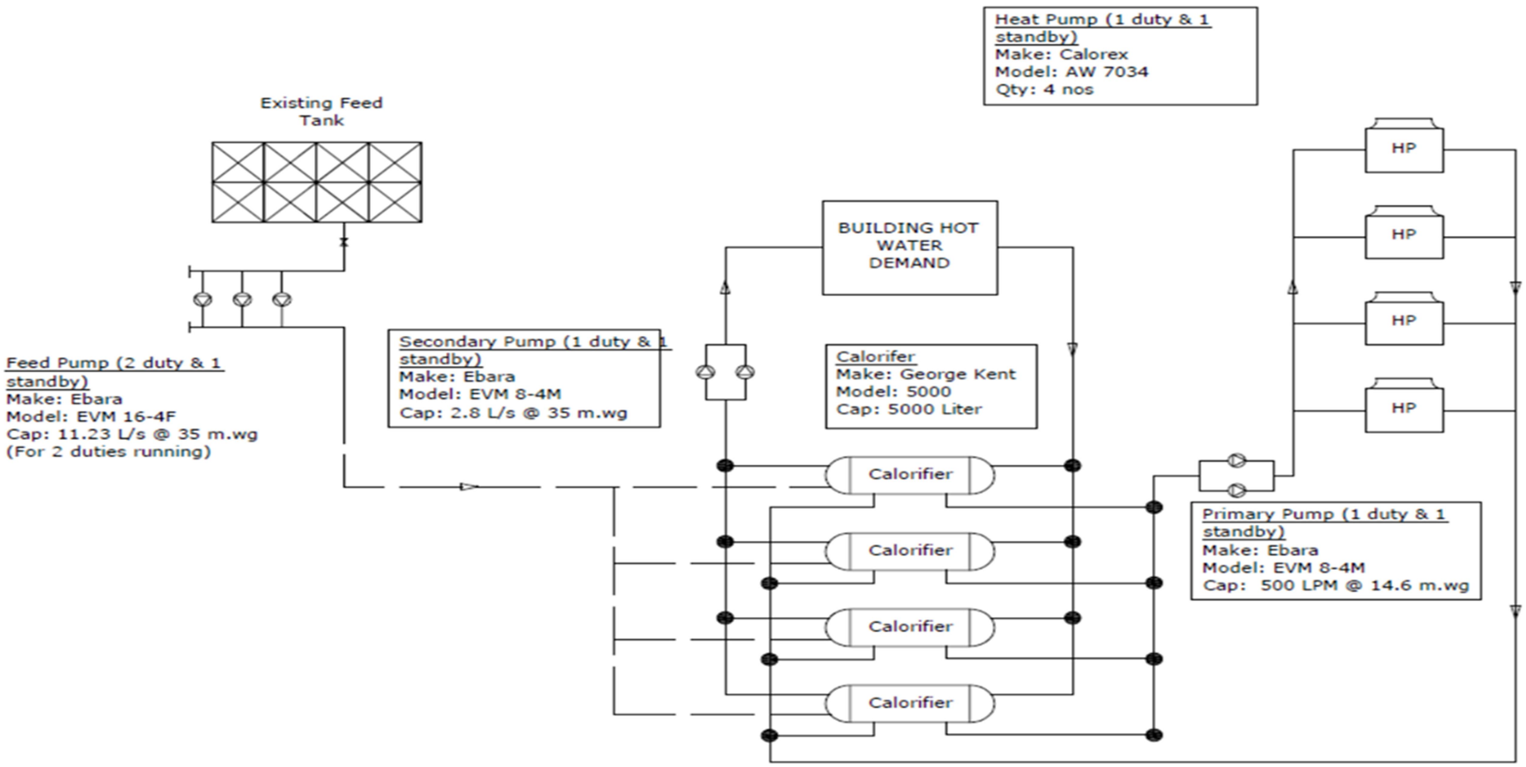
[14] A. Ibrahim *et al.*, "Performance of photovoltaic thermal collector (PVT) with different absorbers design," *WSEAS Trans. Environ. Dev.*, vol. 5, no. 3, pp. 321–330, 2009.

[15] R. Daghigh, M. H. Ruslan, A. Zaharim, and K. Sopian, "Monthly performance of a photovoltaic thermal (PV/T) water heating system," 2011.

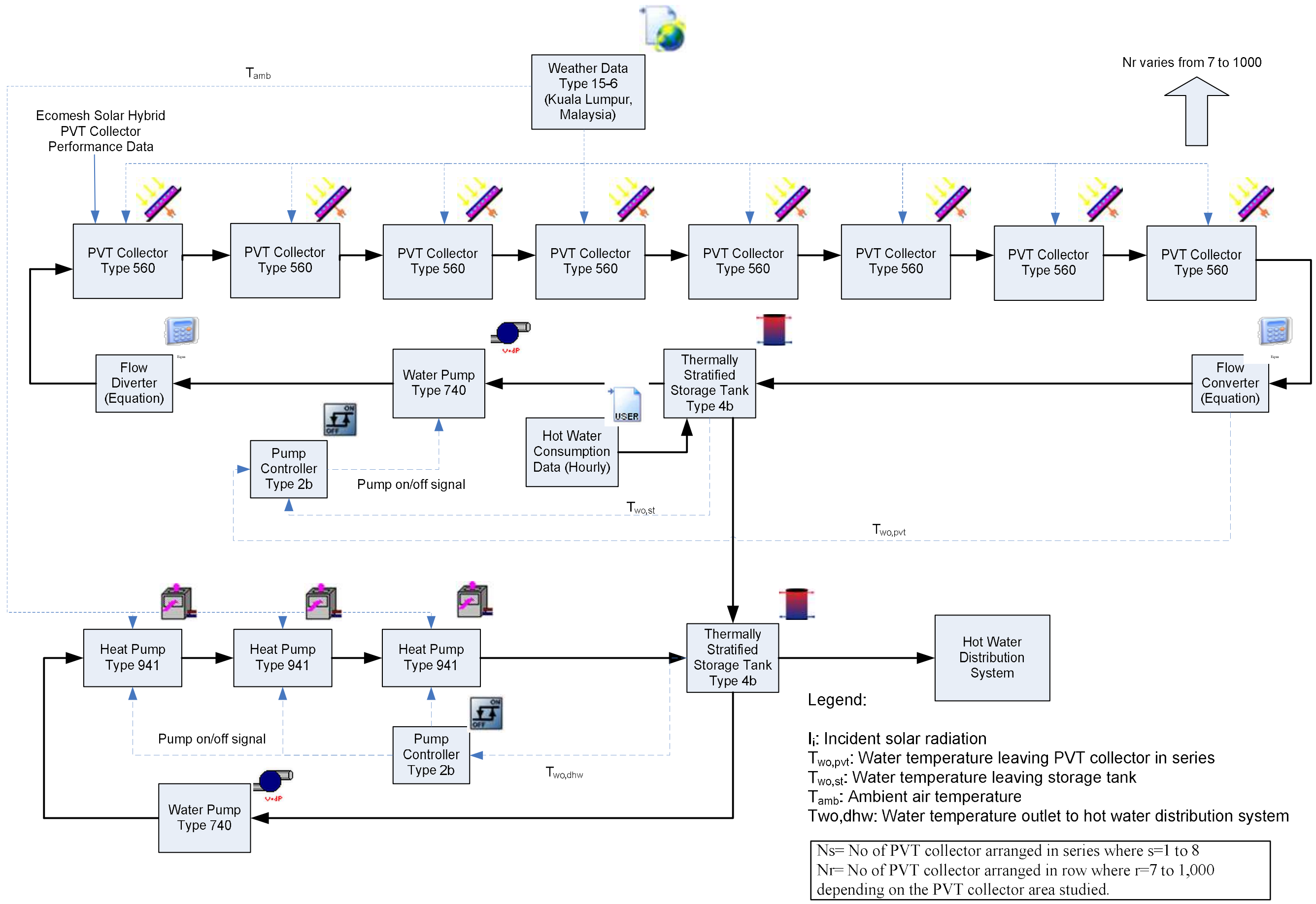
[16] M. Herrando, A. Ramos, J. Freeman, I. Zabalza, and C. N. Markides, "Technoeconomic modelling and optimisation of solar combined heat and power systems based on flat-box PVT collectors for domestic applications," *Energy Convers. Manag.*, vol. 175, pp. 67–

85, 2018.
[17] R. Liang, C. Zhou, Q. Pan, and J. Zhang, "Performance evaluation of sheet-and-tube hybrid photovoltaic/thermal (PVT) collectors connected in series," *Procedia Eng.*, vol. 205, pp. 461–468, 2017.
[18] C. Cristofari, G. Notton, and J. L. Canaletti, "Thermal behavior of a copolymer PV/Th solar system in low flow rate conditions," *Sol. Energy*, vol. 83, no. 8, pp. 1123–1138, 2009.
[19] S. Ievers and W. Lin, "Numerical simulation of three-dimensional flow dynamics in a hot water storage tank," *Appl. Energy*, vol. 86, no. 12, pp. 2604–2614, 2009.
[20] N. Aste, C. Del Pero, and F. Leonforte, "Optimization of Solar Thermal Fraction in PVT Systems," *Energy Procedia*, vol. 30, pp. 8–18, 2012.
[21] S. A. Kalogirou and Y. Tripanagnostopoulos, "Hybrid PV/T solar systems for domestic hot water and electricity production," *Energy Convers. Manag.*, vol. 47, no. 18, pp. 3368–3382, 2006.
[22] A. Hazi, G. Hazi, R. Grigore, and S. Vernica, "Opportunity to use PVT systems for water heating in industry," *Appl. Therm. Eng.*, vol. 63, no. 1, pp. 151–157, 2014.
[23] G. Vokas, N. Christandonis, and F. Skittides, "Hybrid photovoltaic–thermal systems for domestic heating and cooling—a theoretical approach," *Sol. energy*, vol. 80, no. 5, pp. 607–615, 2006.
[24] T. T. Chow, G. Pei, K. F. Fong, Z. Lin, A. L. S. Chan, and J. Ji, "Energy and exergy analysis of photovoltaic–thermal collector with and without glass cover," *Appl. Energy*, vol. 86, no. 3, pp. 310–316, 2009.
[25] S. Mekhilef, A. Safari, W. E. S. Mustaffa, R. Saidur, R. Omar, and M. A. A. Younis, "Solar energy in Malaysia: Current state and prospects," *Renew. Sustain. Energy Rev.*, vol. 16, no. 1, pp. 386–396, 2012, doi: https://doi.org/10.1016/j.rser.2011.08.003.
[26] Kementerian Kesihatan Malaysia, "Petunjuk Kesihatan 2017," 2017.
[27] JKR, "Personal Communication on type of hot water plant for goverment's hospital in Malaysia." 2017.
[28] CENER, "ECOMESH Solar Hybrid Collector Performance Test report," 2015.
[29] Endef, "Ecomesh Hybrid Solar Panel Catalogue." 2017.
[30] BNM, "ECONOMIC AND FINANCIAL DATA FOR MALAYSIA," 2019.
[31] D. C. Jordan and S. R. Kurtz, "Photovoltaic degradation rates—an analytical review," *Prog. photovoltaics Res. Appl.*, vol. 21, no. 1, pp. 12–29, 2013.
[32] SEDA, "Feed In Tariff Rates," 2019. .
[33] E. P. I. A. and Greenpeace, "Solar Generation." 2011.
[34] J. Bujak, "Heat consumption for preparing domestic hot water in hospitals," *Energy Build.*, vol. 42, no. 7, pp. 1047–1055, 2010.
[35] M. del C. Rodríguez-Hidalgo, P. A. Rodríguez-Aumente, A. Lecuona, M. Legrand, and R. Ventas, "Domestic hot water consumption vs. solar thermal energy storage: The optimum size of the storage tank," *Appl. Energy*, vol. 97, pp. 897–906, 2012.
[36] C. T. de la Edificación, "Documento Básico he Ahorro de energía," *CTE, DB-HE*, 2013.

APPENDICES



Appendix 1 Existing ASHP Plant schematic



Appendix 2 PVT-ASHP simulation model schematic in TRNSYS