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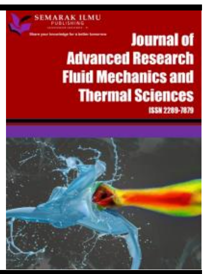

Fabricated of Photovoltaic Thermal System with Phase Change Material

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ABSTRACT

At present, solar energy is widely recognized as one of the primary sources of renewable energy. Nonetheless, conventional solar photovoltaic (PV) panels suffer a significant decrease in efficiency when exposed to extreme temperatures, making them unsuitable for long-term operation. To address these limitations, hybrid photovoltaic thermal (PVT) systems with phase change materials (PCM) have emerged as sophisticated solutions, leveraging thermal energy for water heating and PCM for thermal energy storage. This work aims to evaluate key economic parameters of fabricated PVT system (with and without PCM) against commercial solar water heaters and electric heaters, using metrics such as payback period and annual worth. The calculations are carried out using Microsoft Excel spreadsheets. The results reveal that the payback period for PVT systems, both with and without PCM, exceeds 25 years, primarily due to the high initial costs associated with PVT technology. In contrast, solar water heaters and electric water heaters offer shorter payback periods. Specifically, after 25 years, the annual worth for the fabricated PVT system is MYR 923.12. Essentially, the economic analysis suggests that the PVT system has a longer operational lifetime than solar water heaters and electric heaters, despite the extended payback period. This economic analysis has the potential to encourage the large-scale fabrication and installation of efficient PVT-PCM systems. It provides consumers with a viable alternative to consider installing PVT and PVT-PCM systems instead of PV and solar thermal systems separately. Additionally, this study contributes to reducing carbon emissions and advancing the Sustainable Development Goals (SDGs).

1. Introduction

The United Nations (UN) has established 17 Sustainable Development Goals (SDGs) to address global challenges, and one of them is Goal 7, which focuses on affordable and clean energy. Transitioning to new sources of energy that are clean, renewable, and sustainable is crucial to ensuring its continuous generation. Therefore, implementing various applications of harvested solar energy is considered a significant step toward achieving this goal. Solar energy fulfills the criteria as it is abundant and renewable, and the technologies used are becoming cheaper by the day. It can be

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harnessed to generate both electricity and heat energy, which play a vital role in maintaining human well-being. Photovoltaic (PV) systems are the most prevalent solar technology used to generate electricity, while hybrid photovoltaic with thermal (PVT) systems have emerged as a new technology capable of simultaneously producing electricity and thermal energy for applications such as water heating. Over the years, it has been observed that the simultaneous generation of electricity and thermal energy by PVT systems could be further enhanced. Numerous factors, including geographical conditions, solar irradiation, and system components, continue to influence their performance. Furthermore, while PVT systems outperform single PV and solar thermal collector systems, there is a growing demand for cleaner and more reliable methods of energy generation. To meet this demand, a more efficient PVT system has been introduced, incorporating phase change materials (PCMs). PCMs are materials that undergo phase transitions, such as from solid to liquid, when they release or absorb heat or thermal energy [1]. Therefore, many researchers perceive them as suitable materials for use in heat transfer within solar energy harvesting systems. Since PV modules in PVT systems operate more efficiently at lower temperatures, the integration of PCMs in these systems is observed to address this concern, as they absorb excess heat and facilitate the cooling process of the systems [2,3].

At present, many studies have explored on the technical potential and benefit of Photovoltaic Thermal with Phase Change Material (PVT-PCM) system [4-6]. Nevertheless, only scarce work conducted economic analysis related to the PVT and PVT-PCM technology. For instance, Mustapha *et al.,* [7] delved into the techno-economic performance of a PVT system combined with a heat pump system, catering to the supply of electricity and hot water to a terraced house in the chilly Belfast climate of the United Kingdom. They employed indicators such as cumulative cost (CC), net present value (NPV) and discounted payback period (DPP) which gauges the aggregated cost of the system across its operational span. Their findings ascertain a payback period of 14 years for the system, which remains below the average 25-year lifespan of the PVT system and the 20-year lifespan of the heat pump. However, this outcome is attainable only with a government-set electricity generation incentive rate of 5 p/kWh (MYR0.29/kWh) and a heat generation incentive rate of 21 p/kWh (MYR1.22/kWh). Excluding these incentives, the payback period exceeds 20 years, rendering it economically unfeasible. In the case of the PVT-PCM system, the payback period fluctuates based on weather conditions and the specific type of PCM. Nima *et al.*, [8] conduct a comprehensive exploration of the techno-economic attributed of the PVT-PCM system across four distinct climate conditions in Iran. They utilized a varied mixture of stearic acid and water as the PCM and employ Computational Fluid Dynamics (CFD) simulation to evaluate technical performance. Their study ascertained that the PVT-PCM system is most efficient in hot and humid climates, boosting the PV electrical efficiency by up to 3.11%. However, employing the NPV method for economic assessment, it becomes evident that the payback period for the system fails to be met within the initial two decades due to the substantial initial cost of the PCM, rendering it economically unjustified. Nevertheless, the analysis of cash flow trends revealed a noteworthy insight, where the PCM cooling effectively prolongs the service life of PV panels beyond the standard 20 years to a substantial span of over 40 years. Table 1 summarizes the literatures related to the economic analysis of PV, PVT and PVT-PCM systems. While many studies have explored the technical analysis of commercial PVT systems, both with and without phase change materials (PCM), there has been limited research on the economic analysis of these PVT systems in comparison with commercial solar water heating and electric water heaters. Thus, this work aims to fill the gap by evaluating key economic parameters of fabricated PVT system (with and without PCM).

Table 1
Economic analysis of PV, PVT and PVT-PCM systems

Type of system	Economic analysis method	Payback period	Remarks	Ref.
PV-PCM	LCOE	-	PCM can control the rapid temperature rise of PV panel. In current condition, PV-PCM is not cost-effective due to low electricity cost and no subsidies and incentives from government.	[9]
PV-PCM	LCOE	2.6 years	Ireland: Cost saving from the PV-PCM (MYR363.41) lesser than cost to produce 65 W_p PV-PCM system (MYR494.65). Pakistan: Cost saving is higher than cost to mass produce the system; (MYR817.68 >MYR312.94).	[10]
PVT-PCM	LCC, PBP	5-6 years	The use of PCM mitigate the fluctuations in PV panel temperature due to change of solar irradiations level.	[11]
PVT-PCM	Annual worth	6 years for PV panel	Electrical efficiency of PVT-PCM is 4.72% higher than a conventional PV system and more economical than PV and PVT due to longer lifespan.	[12]

LCOE: Levelized cost of electricity; LCC: Life cycle cost; PBP: Payback period

2. Methodology
2.1 Fabricated PVT and PVT-PCM System

The PVT and PVT-PCM system in this study was fabricated based on the commercial size of a PV panel available in the market as illustrated in Figure 1. For PVT, the system consists of 2 parts; a commercial 72-cell monocrystalline PV module and custom-made copper pipe as the heat exchanger (thermal system). In this work, monocrystalline PV was used because it provides higher electrical efficiency than polycrystalline PV in low temperature areas [13]. The detailed specification of the PV module is described in Table 2. For PVT-PCM system, the same fabricated PVT system was used, with the PCM was placed between the spaces of the copper pipe (as shown by the arrow in Figure 1). In this work, lauric acid was used as the PCM due its properties as a non-toxic and exhibiting high latent heat [14].

Table 2
Specification of PV module

Eagle PERC 72 (Jinko Solar) - JKM340M-72	
Length (mm)	1956
Width (mm)	992
Short circuit current (I_{sc}) [A]	9.24
Open circuit voltage (V_{oc}) [V]	47.1
Voltage at P_{max} [V]	38.7
Current at P_{max} [A]	8.79

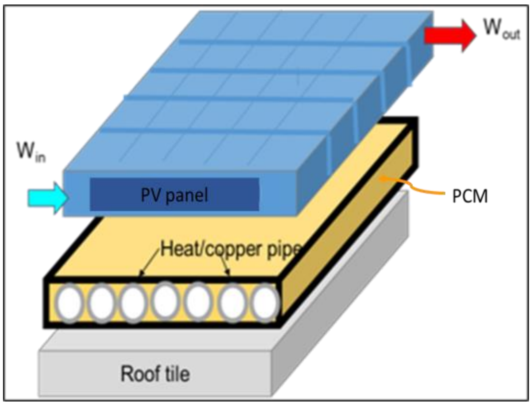


Fig. 1. Fabricated PVT/ PVT-PCM system

2.2 Economic Analysis

The objective of economic analysis is to evaluate key economic parameters of fabricated PVT system (with and without PCM) against commercial solar water heaters and electric heaters. The criteria are annual worth (AW) and payback period. The analysis was conducted in the Microsoft Excel spreadsheet by producing an equivalent uniform cash flow.

AW is determined by calculating the difference between the annual revenue and annual cost, as delineated in Eq. (1).

$$AW = B_A - C_A \quad (1)$$

To facilitate a comparative economic analysis encompassing the fabricated PVT and PVT-PCM systems, as well as solar water heaters and electric water heaters, the cash flow were performed using Eq. (2) and Eq. (3). This calculation approach was adopted from the study conducted by Hossain *et al.,* [15].

$$(AW)_{PVT} = -(I_c + I_{lc})(A/P\,,i,N) - A_{rc} - (C_{afic})(A/F\,,i,N) \quad (2)$$

$$(AW)_{El.heater} = -(I_c + I_{lc})(A/P\,,i,N) - A_{rc} - (H_{erc})(A/F\,,i,N) \quad (3)$$

The lump-sum payments or benefits were converted into equivalent uniform periodic time using the capital recovery factors (*A/P,i,N*) and (*A/F,i,N*) as shown in the Eq. (4) and Eq. (5).

$$\mathrm{A/P} = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (4)$$

$$A/F = \frac{i}{(1+i)^N - 1} \quad (5)$$

2.2.1 Estimation cost of fabricated PVT and PVT-PCM

Estimation cost of the fabricated PVT and PVT-PCM are tabulated in Table 3. The fabrication cost includes flowmeter, pump and fitting system, as the system is also used for water heating on top of generating the electricity. PCM was purchased from LGC Scientific Sdn. Bhd. while cost of commercial solar water heater and electric water heater were adopted from the study conducted by Ong *et al.,* [16] and Hossain *et al.*, [12,17] as summarized in Table 4.

Table 3
Breakdown cost of PVT and PVT-PCM System

Component	Description	Retail price (MYR)
Solar PV module	72 cells-Mono 340 W	700
Thermal collector	Absorber aluminium frame (5mm) Aluminium plate (4 x 2mm) Stainless steel back cover Copper pipe (DN25 & DN50)	5000
Water flow meter	0.4 – 40 m3/h	520
Water pump	Wilo RS15-6	650
Inlet, outlet pipe	Pipe fittings (PVC, steel)	1300
Installation cost	-	200
Salvage value	-	0
Total retail cost		8370
PCM	Lauric acid, 6 kg	900

Table 4
Cost of typical solar water heating system and electric water heating systems in Kuala Lumpur

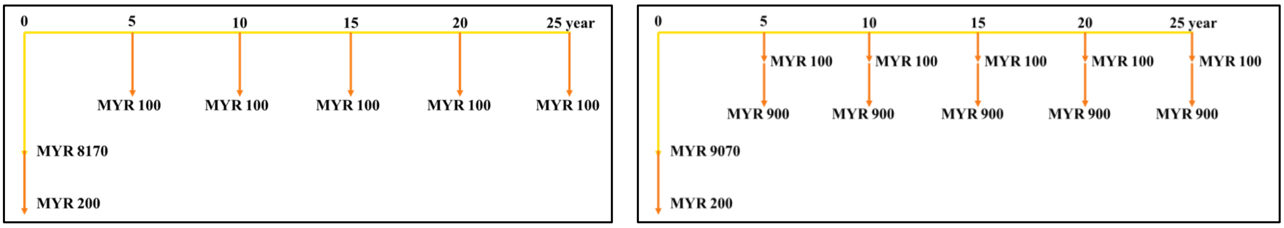
Component	Description	Retail Price (MYR)
Solar collector	Collector surface, 4m^2 Collector efficiency, 50% Tank volume, 250 L	4150
Installation cost	-	100
Annual running cost	-	124.50
Total retail cost		4250
Electric heater	Electric water heater (DSK-55), 5500 W	386.16
Heating element	Copper	200
Installation cost	-	100
Running cost	-	431.46
Total retail cost	-	686.16

3. Results

The economic analysis focuses on the AW and payback period for solar technologies (fabricated PVT, fabricated PVT-PCM, solar water heater) and commercial electric water heater. The cash flow and total cost over 25 years for all system are calculated at a fixed annual interest rate of 10%.

The initial cost of PVT system that includes PV module, thermal collector and all related accessories is MYR8170, including MYR200 as an installation cost with zero annual operating costs. A replacement fee of MYR100 is assumed for maintenance cost every five years. For PVT-PCM system, the initial cost year is MYR9070 (PVT + PCM) including installation cost. A replacement fee of MYR100 and RM900 were assumed for maintenance and PCM replacement every five years. Figure 2 shows the cash flow diagram of PVT and PVT-PCM system.

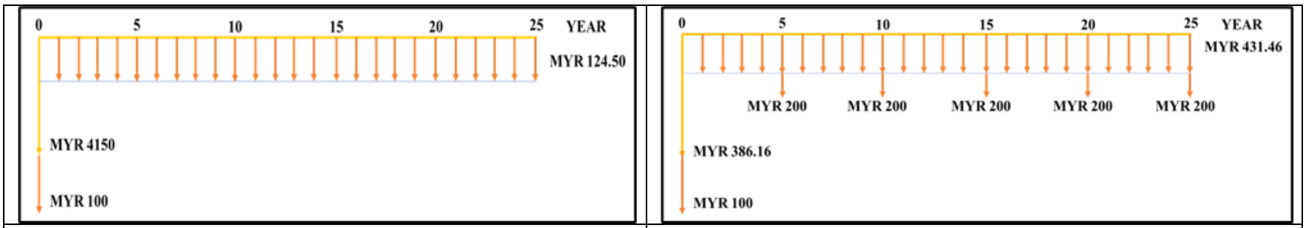
In addition, for cost benefit calculation, the average PVT system power for 8-hour data has been taken from the experiment which resulted in a monthly and annual energy of 46.72 kWh/month and 568.38 kWh/year, respectively. In this case, the Feed in Tariff (FiT) is not applicable, and the economic analysis used cost of electricity for the first 200 kWh at MYR0.218/ kWh [19]. Therefore, the annual benefit for the system is MYR123.91. Using formula in Eq. (1), it took more than 25 years for the PVT system to achieve a break-even. From the annual cost, the payback period for PVT and PVT-PCM were forecasted of taking more than 25 years for both systems to achieve a break-even.



(a) (b)

Fig. 2. Cash flow diagram (a) PVT (b) PVT-PCM system

On the other hand, the cost of a typical solar water heater in Kuala Lumpur is MYR4250 including installation cost. In addition, the annual maintenance cost of solar water heater is 3% of an initial installation cost (MYR124.50), with an annual electricity cost saving of MYR708 [16]. The cost of an electric water heater including heater element is MYR586.13 with MYR100 installation cost. The annual running cost of an electric water heater is MYR431.46 [17]. A heater element replacement fee of MYR200 is assumed for every 5 years. Figure 3 shows the cash flow diagram of commercial solar water heating system and electric water heater. It was revealed that the payback period for a solar water heater is 14 years and electric water heater is 6 years as the annual benefit outweighs the annual running cost.



(a) (b)

Fig. 3. Cash flow diagram for (a) Solar water heating system (b) Electric heater

It can be observed that the payback period for the PVT and PVT-PCM are longer than solar water heater and electric water heater, due to its higher initial cost. However, high AW reflect that the lifetime of PVT/PVT-PCM can be increased, allowing it to be used longer than electric heater with life expectancy only between 8 to 10 years [18]. Similar to the PVT system, the payback period for the PVT-PCM system exceeded 25 years. Nevertheless, the cost-benefit analysis indicates that the PVT-PCM system offers a 5% higher return on investment compared to the PVT system. This finding demonstrates that the incorporation of PCM has extended the lifespan of the PVT system and has the potential to promote the large-scale production and installation of efficient PVT-PCM systems. It presents consumers with a practical alternative to consider installing PVT and PVT-PCM systems instead of separate PV and solar thermal systems, primarily due to their longer lifespan. Based on the economic analysis, under current conditions, the PVT system may not be economically viable for commercial purposes. However, it's important to note that in this preliminary analysis, we only considered the electrical energy generation without offsetting the electrical energy used for thermal purposes. Additionally, the utilization of clean solar energy in this study contributes significantly to achieving the targets of Goal 7 in the Sustainable Development Goals (SDGs). Table 5 and 6 tabulate the AW and key economic criteria for all evaluated systems.

Table 5
Annual worth (AW) of solar technologies and electric heater system for 25 years

Year	PVT	PVT-PCM	Solar water heater	Electric water heater
5	MYR-2224.36	MYR-2609.20	MYR 1245.64	MYR592.47
10	MYR-1368.45	MYR-1571.40	MYR 816.17	MYR 523.13
15	MYR-1103.08	MYR-1250.24	MYR 683.26	MYR 501.67
20	MYR-984.88	MYR-1106.31	MYR 623.70	MYR 492.06
25	MYR-923.12	MYR-1031.43	MYR 592.71	MYR 487.05

Table 6
Economic analysis for solar systems and electric heater

	PVT	PVT-PCM	Solar water heater	Electric water heater
Initial cost (MYR)	8370	9270	4250	686.16
Annual operating cost (MYR)	0	0	124.50	431.46
Annual benefit (MYR)	123.91	130.72	708	-
Payback period (Year)	> 25	> 25	14	6

4. Conclusions

The objectives of this study are centered around contrasting the economic viability of the recently developed PVT system, both with and without the inclusion of PCM, within the context of typical Malaysian weather conditions. Furthermore, beyond its abilities in electricity generation and heating, this PVT system could potentially provide a foundation for cooling technologies, such as solar-driven absorption chillers [20]. A preliminary examination reveals that while the fabricated PVT system boasts an extended lifespan, its current economic feasibility is hampered by a significant initial cost and modest annual gains compared to solar water heaters and electric water heaters. This observation aligns with the findings of the study conducted by Samsudin et al. [21], which indicate that the implementation of renewable energy in Malaysia faces obstacles due to substantial financial demands.

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