Photovoltaic-Thermal (PVT) Systems in Malaysia: Technologies, Performance, Tropical Climate Adaptation, Applications, Economics and Future Prospects

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ABSTRACT

Photovoltaic-thermal (PVT) technology offers an integrated approach to solar energy conversion by simultaneously generating electricity and recovering useful thermal energy from photovoltaic modules. This combined energy conversion pathway is particularly relevant to Malaysia, where high solar irradiance and elevated ambient temperatures create favourable conditions for solar energy utilization but also contribute to increased photovoltaic cell operating temperatures and reduced electrical efficiency. This paper presents a comprehensive review of PVT systems with particular emphasis on their suitability, performance, applications, and deployment prospects under Malaysian conditions. The review examines major PVT configurations, photovoltaic technologies, thermal management approaches, cooling and heat-recovery techniques, and system integration strategies. Particular attention is given to the effects of tropical climatic conditions, including solar irradiance, ambient temperature, humidity, and operating conditions, on the electrical, thermal, overall energy, and exergy performance of PVT systems. The potential applications of PVT technology in residential, commercial, industrial, building-integrated, agricultural, and other energy-demand sectors are also discussed. In addition, the paper evaluates techno-economic, environmental, energy-security, policy, market, and commercialization considerations relevant to PVT deployment in Malaysia. The review identifies the principal technical and non-technical challenges limiting wider adoption and highlights opportunities for improved system design, thermal management, energy storage, intelligent control, system integration, and technology commercialization. An integrated framework is proposed to link Malaysia's climatic and solar-resource characteristics with PVT configuration, thermal management, system performance, application suitability, economic and environmental outcomes, and policy support. The review demonstrates the potential of PVT systems to contribute to Malaysia's renewable-energy transition while identifying areas requiring further experimental, numerical, techno-economic, and policy-oriented research.

Keywords: Photovoltaic-thermal; PVT; Malaysia; tropical climate; solar energy; thermal management

INTRODUCTION

The transition towards sustainable and low-carbon energy systems has become an increasingly important priority for countries seeking to balance economic development, energy security, environmental protection and growing energy demand. Solar energy is particularly relevant within this transition because it is widely available, modular and suitable for both centralized and distributed energy applications. Malaysia, located within the equatorial region, receives substantial solar radiation throughout the year and therefore has considerable potential for solar-energy utilization. The country's tropical climate, however, is also characterized by relatively high ambient temperatures, humidity, cloud variability and other environmental conditions that can influence the performance of solar photovoltaic (PV) systems. Recent studies of PV systems operating under Malaysian conditions have demonstrated the technical feasibility of solar electricity generation while also identifying thermal and environmental losses as important contributors to reductions in system performance [7, 35, 46, 53].

Conventional photovoltaic systems convert only a portion of incident solar radiation into electricity, while a substantial fraction of the absorbed solar energy is converted into heat. The accumulation of heat within photovoltaic modules increases cell operating temperature and generally reduces electrical conversion efficiency. This issue is particularly relevant in tropical climates, where elevated ambient temperatures can increase module operating temperatures. Consequently, improving the utilization of the thermal component of incident solar radiation while simultaneously controlling PV temperature has become an important area of solar-energy research [14, 34, 49, 51]. Photovoltaic-thermal (PVT) technology has emerged as one approach to address this issue by integrating photovoltaic electricity generation with thermal-energy recovery within a single solar-energy system.

1.1 Background of Solar Energy Development in Malaysia

Malaysia has progressively increased its interest in renewable energy as part of its broader energy-transition objectives. Solar PV has become an important renewable-energy technology because of the country's favourable solar resource and the flexibility of PV deployment across residential, commercial and utility-scale applications. Studies examining Malaysian PV installations and simulations indicate that grid-connected PV systems can provide significant electricity generation under local climatic conditions, although thermal, collection, environmental and other system losses influence the final energy yield [7, 35, 46]. The continuing development of PV systems has consequently created opportunities to investigate technologies that can increase the overall utilization of solar radiation.

The development of PVT technology can be viewed within this broader solar-energy transition. Rather than treating the heat generated by a PV module solely as a source of efficiency loss, PVT systems recover a portion of this thermal energy for useful applications. This provides the possibility of producing electricity and useful heat from the same collector area. Such integration can be particularly attractive where electrical and thermal energy demands occur simultaneously, including buildings, hotels, institutions, industrial facilities and other applications requiring hot water or low-temperature thermal energy [20, 25, 37].

1.2 Solar Resource and Tropical Climatic Conditions in Malaysia

Malaysia's geographical position provides relatively high solar availability throughout the year. Nevertheless, solar-energy performance is not determined by irradiance alone. Ambient temperature, wind speed, humidity, rainfall, cloud cover, module orientation, tilt angle, surface condition and operating temperature can influence the actual energy output of solar systems. Research conducted under Malaysian climatic conditions has specifically demonstrated the importance of collector tilt angle and mass flow rate in determining PVT thermal performance [1]. Other Malaysian PV studies have similarly shown that thermal and environmental losses can have a significant effect on annual energy yield [7, 35, 46].

The tropical environment therefore presents both an opportunity and a challenge for PVT deployment. High solar irradiation provides an abundant energy input, while high ambient and module temperatures increase the importance of effective thermal management. In a conventional PV system, the thermal energy generated within the module is generally not recovered for useful purposes. In a PVT system, however, this thermal energy can be extracted through an appropriate heat-transfer mechanism. The resulting reduction in module temperature may improve electrical performance while simultaneously producing useful thermal output.

The importance of climatic conditions is also demonstrated by research from other tropical and hot-climate regions. Experimental investigation in Ghana, for example, compared conventional PV and water-based PVT under a hot and humid tropical climate and demonstrated that PVT can provide substantial combined electrical and thermal energy output [6]. Studies from India and other tropical or warm-climate regions have similarly investigated the effects of cooling, wind conditions, building integration and climate-sensitive design on PV and PVT performance [5, 23, 41, 58, 66]. These studies provide useful comparative evidence for understanding the technical requirements of PVT systems operating in Malaysia.

1.3 Limitations of Conventional Photovoltaic Systems in Hot Climates

Although PV technology offers an effective means of converting solar radiation into electricity, its performance is sensitive to operating temperature. As module temperature increases, the electrical characteristics of photovoltaic cells generally deteriorate. Consequently, the high-temperature conditions frequently encountered in tropical environments can create a significant performance challenge. Cooling technologies have therefore received considerable attention in solar-energy research, with water, air, heat sinks, nanofluids, phase change materials (PCM), thermoelectric systems and other passive or active approaches investigated for temperature control [14, 22, 29, 34, 43, 49, 64].

The challenge is not simply to reduce PV temperature, but to determine whether the recovered heat can be used productively. Conventional cooling systems may remove heat from PV modules without recovering it for a useful purpose. PVT systems instead seek to transfer the recovered heat to a working fluid, such as water or air, so that the thermal energy can be utilized. This distinction changes the objective from temperature reduction alone to combined energy recovery and system optimization.

For Malaysia, this distinction is particularly important because cooling requirements and thermal-energy demands may occur simultaneously. For example, a building may require electricity for lighting and appliances while also requiring hot water or low-temperature heat. A properly designed PVT system can potentially address both demands using the same solar collection area.

1.4 Concept and Development of Photovoltaic-Thermal Systems

A photovoltaic-thermal system combines a photovoltaic module with a thermal collector or heat-extraction mechanism. Solar radiation incident on the collector is divided among reflected radiation, electricity generation and thermal energy. The thermal component is extracted from the PV module through a heat-transfer medium, commonly water or air. The extracted heat can subsequently be used directly or integrated with thermal storage, heat pumps, cooling systems or other energy-conversion technologies.

PVT systems can be classified according to their working fluid, collector configuration, degree of glazing, building integration and method of thermal management. Water-based systems are widely studied because water has favourable heat-transfer characteristics and can be directly associated with domestic hot-water applications. Air-based PVT systems are particularly relevant to building applications where heated air can be used for ventilation or space-heating purposes. Building-integrated photovoltaic-thermal (BIPVT) systems incorporate the collector into building roofs or façades, allowing solar-energy conversion to be considered as part of the building envelope [3, 9, 36, 58, 59, 69].

Research has also expanded toward more advanced PVT configurations, including bifacial systems, concentrating PVT (CPVT), phase-change-material-assisted systems, nanofluid cooling and hybrid photovoltaic-thermal systems [11, 20, 28, 31, 43, 65, 67]. These developments demonstrate that PVT is not a single technology but rather a broad family of integrated solar-energy systems whose performance depends strongly on configuration and operating conditions.

1.5 Advantages of PVT over Conventional PV and Separate Solar-Thermal Systems

The primary advantage of PVT technology is the simultaneous production of electricity and useful thermal energy. By recovering thermal energy that would otherwise contribute primarily to module heating, PVT systems can increase the total useful energy obtained from a given solar-collector area. Studies evaluating PVT systems using energy, exergy and environmental indicators have demonstrated the importance of considering both electrical and thermal outputs when assessing system performance [10, 37].

PVT can therefore be advantageous in applications with simultaneous electrical and thermal energy requirements. A building equipped with a PVT system, for example, may use electricity generated by the PV

component while utilizing recovered heat for domestic hot water or other low-temperature applications. More advanced configurations can combine PVT collectors with thermal storage, adsorption cooling, heat pumps or trigeneration systems [18, 25, 45].

However, higher total energy recovery does not automatically mean that every PVT system is economically or technically superior to conventional PV. PVT systems generally involve additional components, heat-transfer circuits, pumps, controls, storage and maintenance requirements. Their suitability therefore depends on the value of the recovered heat, the thermal demand profile, available collector area, climate, system configuration and economic conditions. A systematic comparison of electrical, thermal, economic and environmental performance is consequently required.

1.6 Relevance of PVT to Malaysia

The Malaysian context provides several reasons for investigating PVT technology. First, the country's tropical climate provides substantial solar-energy availability throughout the year. Second, elevated ambient temperatures create a strong need for effective PV thermal management. Third, many Malaysian buildings and industries have simultaneous electricity and thermal-energy requirements. Finally, the integration of PVT with buildings, thermal storage, cooling systems and smart energy-management technologies may provide opportunities to improve the utilization of limited roof and façade areas.

Recent Malaysian research has begun to address these opportunities directly. Experimental investigation of a flat-plate PVT collector under Malaysian weather conditions found that collector tilt angle and mass flow rate significantly affected thermal efficiency, with a 10° tilt producing a reported thermal efficiency of 63% at a mass flow rate of 0.0028 kg/s [1]. Another study specifically evaluated PVT feasibility in Malaysia, highlighting the importance of assessing the technology within local technical and application conditions [17]. Experimental work on back-flow cooling of tempered-glass PVT systems under the Malaysian Peninsula climate further demonstrates the growing interest in locally validated thermal-management approaches [44].

These studies are important because PVT performance cannot be transferred directly from one geographical region to another. Collector design, tilt angle, fluid flow rate, cooling strategy and system operation must respond to local climatic conditions. Consequently, Malaysian experimental evidence should be considered alongside international research from comparable tropical and subtropical climates.

1.7 Research Problem and Knowledge Gap

Despite increasing research activity, the Malaysian PVT literature remains relatively fragmented. Existing studies address individual aspects of PVT systems, including collector performance, tilt angle, flow rate, cooling methods, building integration, thermal storage, modelling and feasibility. International literature has additionally examined advanced cooling methods, PCM, nanofluids, artificial intelligence, optimization and BIPVT systems [2, 15, 21, 28, 40, 43, 49, 51, 67]. However, these research areas are often considered separately.

A broader systems perspective is therefore required. The technical performance of a PVT collector is connected to thermal management; thermal management affects electrical efficiency and useful heat recovery; these outputs determine the suitability of a system for applications; and application suitability influences economic and environmental performance. Similarly, building integration introduces additional considerations related to orientation, façade or roof configuration, indoor thermal conditions and building energy demand [9, 27, 37, 59, 69].

Another important gap concerns the transition from laboratory-scale PVT research to practical deployment. Recent reviews identify automated control, hybrid cooling and artificial-intelligence-based optimization as promising approaches, but also emphasize the need for additional field validation, long-term stability assessment, scalability and cost-effectiveness [2, 21]. These issues are particularly relevant to Malaysia, where PVT systems must operate under real tropical conditions rather than under controlled laboratory environments.

Against this background, the present paper provides a structured review of photovoltaic-thermal systems with particular emphasis on their relevance to Malaysia. The review synthesizes the selected literature around the interconnected dimensions of PVT technology, tropical-climate performance, thermal management, applications, energy performance, economics, environmental considerations and deployment conditions.

PVT TECHNOLOGIES AND SYSTEM CONFIGURATIONS

2.1 Overview of PVT Systems

Photovoltaic-thermal (PVT) systems combine photovoltaic electricity generation with the recovery of useful thermal energy from the same solar collector. The fundamental purpose of this configuration is to increase the overall utilization of incident solar radiation while controlling the temperature of the photovoltaic cells. In conventional PV modules, a substantial fraction of absorbed solar radiation is converted into heat, which increases module temperature and can reduce electrical conversion performance. PVT systems introduce a thermal collector or heat-transfer mechanism behind or around the PV module to remove and utilize a portion of this heat [1, 14, 17, 20].

The selected literature demonstrates that PVT technology encompasses a wide range of configurations rather than a single standardized design. Differences occur in the photovoltaic material, collector geometry, working fluid, thermal-management mechanism, glazing arrangement, building integration and operating strategy [2, 3, 9, 20, 31]. These design differences are important because they determine the relative electrical and thermal outputs, operating temperature, system complexity and suitability for particular applications.

For Malaysia, PVT configuration is particularly important because the system must operate under relatively high solar irradiation and tropical ambient conditions. A suitable design therefore needs to achieve effective heat removal without introducing excessive pumping requirements, installation costs or maintenance requirements. Malaysian experimental research has already demonstrated that operating parameters such as collector tilt angle and mass flow rate can substantially affect PVT thermal performance [1].

2.2 Fundamental Operating Principle

A PVT collector receives solar radiation at the upper surface of the photovoltaic module. A portion of the radiation is converted directly into electricity, while another portion is transformed into heat. The thermal energy raises the temperature of the PV cells and surrounding components. A thermal collector positioned in contact with the rear surface of the PV module transfers part of this heat to a working fluid.

The extracted heat can subsequently be used for domestic hot water, space heating, drying, industrial processes or other low- and medium-temperature applications, depending on the collector design and operating temperature. At the same time, removing heat from the PV module can reduce its operating temperature and potentially improve electrical output. The system therefore has two interconnected outputs: electrical energy and thermal energy.

This interaction makes PVT performance more complex than conventional PV performance. Increasing heat extraction may improve PV electrical performance and thermal output, but excessive fluid flow can increase pumping power and auxiliary energy consumption. Similarly, a collector optimized for high thermal efficiency may not necessarily provide the highest economic value if the recovered heat has limited practical demand. PVT design must therefore consider electrical output, thermal output and the requirements of the final application simultaneously [10, 20, 37].

2.3 Classification of PVT Systems

PVT systems can broadly be classified according to the working fluid and thermal-collector arrangement.

The most common configurations include liquid-based PVT, air-based PVT, glazed and unglazed collectors, building-integrated PVT and concentrating PVT systems.

Liquid-based systems generally circulate water or another liquid through channels attached to the rear of the PV module. Because water has relatively high heat-transfer capacity, water-based systems can achieve effective heat extraction and are particularly suitable for hot-water applications. Experimental research under Malaysian conditions has investigated flat-plate PVT collectors using water as the working fluid and demonstrated the influence of flow rate and collector inclination on thermal efficiency [1].

Air-based PVT systems use air as the heat-transfer medium. They can be integrated with ventilation systems and may be suitable where heated air is directly useful. Their configuration can be relatively simple, although the lower heat capacity of air compared with water may require larger heat-transfer surfaces or higher air-flow rates.

Glazed PVT collectors incorporate a transparent cover above the collector, while unglazed configurations expose the PV surface more directly to the environment. Glazing can increase thermal retention but may also influence PV operating temperature and optical losses. Consequently, the appropriate configuration depends on the desired balance between electrical and thermal performance.

2.4 Photovoltaic Technologies Used in PVT Systems

The photovoltaic component is a central determinant of PVT performance. The selected literature includes research involving different PV technologies and configurations, including conventional silicon-based modules and more advanced photovoltaic arrangements [11, 20, 31, 65].

Monocrystalline and polycrystalline silicon technologies are particularly relevant because of their established commercial availability. Their integration with thermal collectors provides a relatively mature pathway for PVT development. However, the electrical temperature coefficient of the photovoltaic material remains an important consideration because the operating temperature of the module changes as heat is absorbed and removed.

Emerging photovoltaic technologies may provide additional opportunities for PVT applications where flexibility, lower weight, optical characteristics or improved temperature behaviour are desirable. Nevertheless, technology selection must be considered together with availability, durability, cost and compatibility with the thermal collector.

For Malaysia, commercially available PV technologies may offer an advantage because their supply chains and installation expertise are already established through the wider solar-PV industry. PVT development can therefore potentially build upon existing PV manufacturing, installation and maintenance capabilities.

2.5 PVT Collector Configurations

Collector geometry strongly influences heat transfer between the photovoltaic module and the working fluid. Common designs include flat-plate arrangements with channels, tubes or ducts attached to the rear of the PV module. The geometry determines the available heat-transfer area, fluid velocity, pressure drop and temperature distribution.

In water-based collectors, thermal channels may be arranged in parallel or serpentine patterns. The design affects flow distribution and local temperature differences. In air-based collectors, duct geometry and air-flow paths influence heat transfer and pressure losses.

The selected Malaysian experimental literature demonstrates that collector operating conditions can have a significant influence on performance. In particular, collector inclination and mass flow rate affect thermal efficiency, indicating that collector geometry cannot be considered independently from operating conditions [1].

Advanced collector configurations have also been investigated internationally. These include bifacial photovoltaic-thermal systems, concentrating PVT and hybrid collector arrangements [11, 20, 65]. Such systems may increase energy collection but generally introduce additional design complexity.

2.6 Building-Integrated Photovoltaic-Thermal Systems

Building-integrated photovoltaic-thermal (BIPVT) systems incorporate PVT collectors directly into building roofs, façades or other elements of the building envelope. This approach allows the same building surface to provide energy generation while also contributing to thermal management.

BIPVT systems are particularly relevant to Malaysia because buildings represent important electricity consumers and many commercial and institutional buildings have substantial roof and façade areas. Integration can reduce the need for additional land and may provide a direct relationship between solar generation and building energy demand.

The selected literature includes research on building-integrated PVT and BIPVT applications, including systems incorporating thermal storage and building-energy considerations [3, 9, 36, 37, 58, 59, 69]. These studies indicate that the performance of integrated systems depends not only on collector efficiency but also on building orientation, envelope characteristics, thermal demand and system control.

For Malaysian buildings, BIPVT may be particularly useful where roof area is limited relative to energy demand. However, the design must account for tropical cooling requirements. Unlike colder climates, where recovered heat may be required for space heating, Malaysian buildings generally have greater demand for cooling and hot water. Consequently, BIPVT design should prioritize useful thermal applications compatible with local building-energy profiles.

2.7 Building-Applied Photovoltaic-Thermal Systems

Building-applied photovoltaic-thermal (BAPVT) systems are installed on or attached to existing building surfaces rather than being fully incorporated into the architectural structure. Roof-mounted PVT collectors represent one of the most straightforward configurations.

Roof-mounted systems can be positioned to optimize solar exposure and may provide relatively easy access for maintenance. They are also compatible with existing PV installation practices. In Malaysia, where rooftop PV deployment is already established, BAPVT provides a potential pathway for introducing thermal recovery without fundamentally changing building construction.

The principal design challenge is matching thermal production with demand. If hot water or other thermal loads are available during periods of high solar radiation, recovered heat can be utilized effectively. Where thermal demand is intermittent, storage may be necessary to prevent useful heat from being rejected.

2.8 Hybrid PVT Configurations

Hybrid PVT systems combine photovoltaic-thermal collectors with additional technologies to improve energy utilization or extend the range of applications. Examples include PVT combined with heat pumps, thermal storage, phase change materials, adsorption cooling and other energy-conversion technologies [18, 25, 28, 43, 45].

The integration of a heat pump can be particularly useful because PVT provides a relatively low-temperature heat source while the heat pump upgrades this energy to a temperature suitable for domestic hot water or other applications. This configuration can increase the utilization of recovered heat but introduces additional capital and electrical requirements.

Similarly, PVT combined with cooling or trigeneration systems can potentially provide electricity, useful heat and cooling from a common solar resource. Such systems are especially relevant to commercial and institutional buildings where electrical and cooling loads occur simultaneously.

2.9 PVT with Thermal Energy Storage

Thermal energy storage can improve PVT system utilization by separating the timing of heat generation from the timing of thermal demand. Without storage, thermal energy generated during periods of strong solar radiation must either be used immediately or rejected.

Water tanks provide one relatively simple form of thermal storage. More advanced systems use phase change materials to increase storage density and regulate temperature. The selected literature includes studies examining PVT systems with thermal storage and PCM-based approaches [18, 28, 43, 45].

Thermal storage may be particularly relevant to Malaysia because solar radiation is strongest during daytime while domestic and commercial hot-water demand can occur at different times. Storage can therefore increase the useful fraction of recovered heat.

However, storage systems introduce additional capital cost, heat losses, space requirements and control complexity. Their economic justification consequently depends on the thermal-demand profile and the value of displaced conventional energy.

2.10 PVT with Phase Change Materials

Phase change materials (PCM) have been investigated as a means of regulating photovoltaic temperature and storing thermal energy. During a phase transition, a PCM can absorb a relatively large quantity of latent heat while maintaining an approximately stable temperature.

When integrated with a PVT collector, PCM can temporarily absorb excess heat and reduce temperature fluctuations. The stored heat can subsequently be released when conditions change or when useful thermal demand is present. Studies of PCM-assisted PV and PVT systems have explored the potential for improving thermal regulation and overall energy performance [28, 43].

For Malaysia, PCM integration is potentially attractive because high solar irradiance can produce significant thermal loads during daytime. Nevertheless, PCM selection must be matched to the desired operating temperature, climate, thermal load and long-term cycling requirements.

2.11 PVT with Nanofluids and Advanced Heat-Transfer Fluids

Nanofluids have been investigated as advanced working fluids because the addition of nanoparticles can modify thermal properties and potentially improve heat-transfer performance. Research has examined nanofluid-based PV and PVT cooling under different operating conditions [22, 31, 40].

Improved heat transfer can potentially reduce PV temperature and increase thermal-energy recovery. However, the benefits must be evaluated against additional costs, pumping requirements, fluid stability, corrosion, nanoparticle handling and long-term system reliability.

Consequently, nanofluids should not be evaluated solely according to instantaneous thermal efficiency. For practical Malaysian deployment, long-term stability, environmental implications, maintenance requirements and economic performance must also be considered.

2.12 PVT with Heat Pumps and Other Hybrid Systems

The relatively low-temperature heat produced by many PVT collectors can be integrated with heat pumps to increase its usefulness. A PVT-assisted heat-pump system can use recovered solar heat as a source for producing domestic hot water or other useful thermal outputs.

Research on PVT-based hybrid systems has demonstrated the potential for combining solar electricity and thermal energy with heat pumps, storage and cooling technologies [18, 25, 45]. These configurations are particularly relevant where electricity and thermal demand are coupled.

In Malaysia, such systems may be appropriate for hotels, hospitals, universities, commercial buildings and industrial facilities with substantial hot-water requirements. The feasibility of these systems, however, depends strongly on system sizing and demand matching. Oversizing the thermal component can result in unused heat, while undersizing may limit the ability to satisfy the thermal load.

2.13 Important PVT Design and Operating Parameters

PVT performance is influenced by a combination of design and operating parameters. The most important variables identified in the selected literature include:

- solar irradiance;
- ambient and PV-cell temperature;
- collector tilt angle;
- collector orientation;
- working-fluid type;
- mass-flow rate;
- channel and absorber geometry;
- heat-transfer area;
- PV technology;
- glazing configuration;
- wind conditions;
- thermal-storage characteristics; and
- control strategy [1, 2, 14, 20, 34, 37, 43].

These parameters are strongly interdependent. For example, increasing mass flow rate may improve heat extraction but also increase pumping power. Increasing thermal contact between the PV module and collector can improve heat transfer but may increase manufacturing complexity. Similarly, increasing thermal storage capacity may improve heat utilization but increase system cost.

The selected literature therefore supports the view that PVT design should be optimized according to the intended application rather than according to a single performance indicator. Electrical efficiency, thermal efficiency, overall energy efficiency, exergy efficiency, economic return and environmental performance can provide different conclusions about the same system [10, 20, 37].

2.14 Summary

PVT technology represents a broad class of integrated solar-energy systems capable of producing electricity and useful thermal energy from a common collector. The selected literature demonstrates substantial diversity in collector configuration, working fluid, thermal-management method, building integration and hybridization. Water- and air-based systems provide established pathways, while BIPVT, thermal storage, PCM, nanofluids, heat pumps and advanced control strategies provide opportunities for improving system performance and application flexibility.

For Malaysia, the selection of an appropriate PVT configuration must account for tropical climatic conditions, high solar availability, elevated operating temperatures and the characteristics of local thermal-energy demand. Malaysian experimental evidence indicates that operating parameters such as collector inclination and mass flow rate can significantly influence performance [1]. International research provides additional evidence concerning advanced cooling, building integration, thermal storage and hybrid systems [2, 3, 18, 28, 43, 58, 69].

PERFORMANCE OF PVT SYSTEMS UNDER MALAYSIAN AND TROPICAL CONDITIONS

3.1 Introduction

The performance of photovoltaic-thermal (PVT) systems is strongly influenced by the interaction between solar irradiance, ambient conditions, photovoltaic operating temperature, thermal-fluid behaviour, and system configuration. These interactions are particularly important in Malaysia because PVT systems operate under tropical conditions characterized by high solar availability, relatively high ambient temperatures, humidity, and variations in solar radiation associated with cloud cover and rainfall. Consequently, assessment of PVT performance in Malaysia requires consideration of both electrical and thermal energy conversion rather than electrical generation alone [1,14,17,20].

Table 1. Summary of PVT technology options and design parameters relevant to Malaysia.

PV / collector type	Working fluid	Flow rate	Tilt angle	Electrical gain
Crystalline-Si flat-plate PVT [1]	Water	0.0028 kg/s	10°	Not stated in manuscript
Air PVT / BIPVT [3,9,36,58,59,69]	Air	Study-specific	Roof/site-dependent	Not consistently reported
Glazed liquid PVT	Water / water-glycol	Study-specific	Site-dependent	Trade-off possible due to higher thermal retention
Unglazed liquid PVT	Water	Study-specific	Site-dependent	Depends on inlet temperature and flow
PCM-assisted PVT [28,43]	Water/air + PCM	Control-dependent	Study-specific	No generalized numerical gain
Nanofluid PVT [22,31,40]	Nanofluid	Study-specific; pressure drop matters	Study-specific	Study-specific

The performance of a PVT system can be evaluated using several complementary indicators, including electrical efficiency, thermal efficiency, overall energy efficiency, exergy efficiency, useful heat gain, electrical power output, and temperature reduction. The relative importance of these indicators depends on the intended application and the configuration of the PVT system. Studies covering different PVT configurations demonstrate that thermal management is a central factor in determining the balance between electrical and thermal performance [2,3,9,20].

3.2 Solar Irradiance and Ambient Temperature

Solar irradiance is one of the principal factors controlling the output of both the photovoltaic and thermal components of a PVT collector. An increase in incident solar radiation generally increases the available energy for conversion, resulting in higher electrical generation and greater thermal energy recovery. However, increased irradiance can also increase the operating temperature of the photovoltaic cells when heat is not removed sufficiently [1,14,20].

Ambient temperature is particularly significant under Malaysian and other tropical conditions. Higher ambient temperatures reduce the temperature difference available for certain heat-rejection processes and can contribute to increased PV-cell temperature. Therefore, a PVT system must be assessed as a coupled solar-energy conversion system in which increased solar input can simultaneously increase energy availability and thermal stress on the photovoltaic component [3,9,36].

3.3 Effect of High Ambient Temperature on PV Performance

Photovoltaic electrical efficiency generally decreases as cell temperature increases. This relationship is important in Malaysia because the combination of strong solar radiation and elevated ambient temperature can result in relatively high module operating temperatures. In a conventional PV system, this additional heat is generally treated as a loss, whereas a PVT collector provides an opportunity to recover part of this energy as useful heat [1,14,17].

Thermal management is therefore one of the principal advantages of PVT technology. By removing heat from the rear or surface of the PV module, the collector can reduce the operating temperature of the photovoltaic cells while simultaneously producing useful thermal energy. The effectiveness of this approach depends on the collector configuration, heat-transfer medium, mass-flow rate, operating conditions, and thermal boundary conditions [2,3,20,34].

3.4 Thermal Behaviour of PVT Collectors

The thermal behaviour of a PVT collector is determined by the transfer of absorbed solar energy through the photovoltaic layer, absorber structure, heat-transfer medium, and surrounding environment. Part of the absorbed energy is converted into electricity, while the remaining energy appears primarily as heat. The objective of thermal management is to recover an appropriate fraction of this heat without causing excessive thermal losses or compromising electrical performance [9,20,31].

In liquid-based PVT systems, heat is transferred from the collector to a circulating fluid. The resulting temperature increase of the fluid represents useful thermal energy that can subsequently be supplied to domestic hot-water systems, building services, industrial processes, or other thermal loads. Air-based systems operate according to a similar principle, although the heat-transfer characteristics and achievable outlet temperatures differ [18,25,28].

3.5 Electrical Performance

Electrical performance is commonly expressed in terms of electrical power output and electrical efficiency. Because photovoltaic conversion is temperature-sensitive, the electrical component of a PVT system is closely linked to its thermal behaviour. Effective heat removal can reduce PV operating temperature and consequently help maintain electrical output under high-temperature conditions [1,14,17].

The electrical performance of PVT systems must therefore be evaluated together with the energy required for thermal-fluid circulation. In actively cooled systems, pumps or fans consume auxiliary electricity. A system that achieves substantial thermal cooling but requires excessive auxiliary power may not provide the expected net energy benefit. This consideration is particularly relevant when comparing different flow rates and active cooling configurations [2,20,34].

3.6 Thermal Performance

Thermal efficiency represents the proportion of incident solar energy converted into useful thermal energy. It depends on the collector design, heat-transfer medium, inlet temperature, mass-flow rate, absorber characteristics, thermal losses, and environmental conditions.

Water-based PVT systems can provide effective heat removal because of the favourable heat-transfer characteristics of water. Air-based systems, meanwhile, may offer advantages where hot air is directly required or where concerns associated with water use, leakage, corrosion, and water quality are important. The appropriate choice therefore depends on the required thermal output and the application environment [18,25,43].

3.7 Overall Energy Efficiency

One of the principal benefits of PVT technology is the simultaneous production of electrical and thermal energy. Consequently, evaluation based only on electrical efficiency does not fully represent the energy contribution of

the system. Overall energy efficiency combines the useful electrical and thermal outputs and can therefore provide a broader measure of system performance [1,14,20].

The distinction between electrical efficiency and total energy efficiency is particularly important when comparing PVT systems with conventional PV systems. A conventional PV system may achieve a similar or higher electrical conversion efficiency under certain conditions, but the thermal energy contained in the module is not normally recovered as a useful output. PVT technology seeks to utilize this otherwise rejected heat, thereby increasing the total useful energy obtained from the available solar resource [3,9,20].

3.8 Exergy Performance

Energy analysis alone does not account for the quality or usefulness of different forms of energy. Electrical energy represents a high-quality energy form, whereas low-temperature thermal energy has lower exergy content. Exergy analysis can therefore provide additional insight into the performance of PVT systems by evaluating the quality of the energy produced rather than only its quantity [20,31].

Exergy performance is particularly useful when comparing different operating temperatures, thermal applications, collector configurations, and heat-recovery strategies. A system producing a large quantity of low-temperature heat may have high thermal-energy efficiency but relatively lower exergy efficiency. This distinction should be considered when selecting PVT configurations for applications with specific temperature requirements.

3.9 Effect of Mass-Flow Rate

Mass-flow rate is an important operating parameter for liquid- and air-based PVT systems. Increasing the flow rate generally improves heat removal from the collector and can reduce PV operating temperature. At the same time, higher flow rates can reduce the temperature rise of the circulating fluid and increase pumping or fan requirements [2,3,34].

Consequently, an optimum operating range may exist in which the benefits of improved cooling are balanced against the reduction in fluid temperature rise and the increase in auxiliary energy consumption. The optimum value is application-dependent and should therefore be determined from the combined electrical, thermal, and system-level performance rather than from thermal efficiency alone.

3.10 Effect of Tilt Angle

Collector inclination influences incident solar radiation, fluid behaviour, heat transfer, and the overall operating conditions of a PVT system. In Malaysia, the selection of tilt angle must consider the geographical location, solar-resource characteristics, seasonal variation, and application requirements.

The effect of tilt angle is therefore not limited to maximizing incident solar radiation. For an integrated PVT system, the optimum inclination should ideally be evaluated in relation to electrical generation, thermal recovery, and the practical requirements of installation and maintenance [3,9,36].

3.11 Orientation

Collector orientation affects the amount and temporal distribution of solar radiation received by the PVT system. Orientation is consequently an important design variable for both building-mounted and ground-mounted installations. In building-integrated applications, however, orientation may be constrained by the existing building geometry, roof arrangement, façade direction, or architectural requirements [36,37,58,59].

This constraint emphasizes the importance of assessing PVT systems under realistic installation conditions rather than relying exclusively on idealized orientations. Building-integrated PVT designs should consider the interaction between architectural configuration, available solar radiation, thermal performance, and electrical output.

3.12 Influence of Wind Speed and Humidity

Wind speed affects the convective heat transfer between the collector surface and the surrounding environment. Increased air movement can enhance heat dissipation from exposed surfaces, influencing both the thermal balance of the collector and its photovoltaic operating temperature.

Humidity is another characteristic feature of tropical climates. Although its direct influence on PVT performance may vary according to collector configuration, humidity forms part of the environmental conditions under which Malaysian systems operate. Long-term PVT assessment should therefore consider not only instantaneous solar irradiance and temperature but also the environmental conditions associated with tropical operation.

3.13 Water Cooling

Water cooling is among the most widely considered thermal-management approaches for PVT systems. Water can circulate behind or through a thermal collector structure, absorbing heat from the PV module and transporting it to a useful thermal load or storage system [18,25,28].

The principal advantage of water cooling is that the recovered heat can have direct practical value. In Malaysia, potential applications include domestic water heating, commercial hot-water demand, and selected industrial processes. However, water-based systems also require consideration of pumping energy, piping, leakage, corrosion, maintenance, water availability, and operating temperature.

3.14 Air Cooling

Air-based PVT systems use air as the heat-transfer medium. These systems can be attractive for applications where heated air is useful, including space heating, drying, ventilation-related applications, and selected agricultural processes. Their configuration can also avoid some issues associated with liquid circulation.

However, the relatively different thermal characteristics of air compared with water influence heat-transfer performance and collector design. Air-channel geometry, flow resistance, fan power, and heat-transfer area therefore become important design parameters. The selection between air and liquid cooling should ultimately be based on the required thermal service and system boundary conditions [18,25,43].

3.15 Nanofluid Cooling

Nanofluids have been investigated as advanced heat-transfer fluids for improving thermal performance. The addition of nanoparticles to a base fluid can modify its thermal and transport properties, potentially enhancing heat transfer within the collector [22,31,40].

For PVT applications, the potential benefit of enhanced heat transfer must be evaluated against practical considerations such as fluid stability, pressure drop, pumping requirements, material compatibility, cost, and long-term operation. Therefore, nanofluids should be assessed not only according to instantaneous thermal enhancement but also according to their overall system and economic implications.

3.16 PCM-Based Thermal Management

Phase-change materials (PCMs) provide another approach to thermal management by absorbing heat during a phase transition. In PVT systems, PCM integration can help moderate temperature fluctuations and store part of the thermal energy generated during periods of high solar radiation [28,43].

The use of PCM is particularly relevant where thermal storage and temperature regulation are both required. Nevertheless, PCM selection must consider melting temperature, thermal conductivity, latent-heat capacity, cycling stability, containment, and compatibility with the PVT collector. These factors influence whether PCM integration can provide a meaningful improvement at system level.

3.17 Passive versus Active Cooling

PVT cooling approaches can broadly be divided into passive and active methods. Passive approaches rely on natural convection, conduction, thermal storage, or collector design without continuous mechanical circulation. Active systems employ pumps, fans, or other mechanisms to control the movement of a heat-transfer medium [2,20].

Passive systems can offer simplicity and lower auxiliary energy requirements, whereas active systems generally provide greater control over heat removal. The appropriate strategy depends on the required thermal output, electrical performance, system complexity, maintenance requirements, and application. A hybrid approach may also be appropriate where passive thermal management is combined with controlled active operation.

3.18 Automated Control and Optimization

Because PVT performance varies with solar irradiance, ambient temperature, fluid temperature, and thermal demand, operating conditions may need to be adjusted dynamically. Automated control can regulate flow rate, pump operation, fan operation, thermal storage, or other system components in response to changing conditions.

Optimization should consider the system as an integrated energy-conversion unit. Maximizing thermal output alone may result in unnecessary auxiliary consumption, while maximizing electrical output alone may underutilize the thermal component. Therefore, control strategies should consider the desired combination of electrical production, useful heat recovery, auxiliary consumption, and thermal demand [20,34].

3.19 AI-Based and Smart PVT Control

The increasing availability of sensors, computational methods, and data-driven techniques provides opportunities for intelligent PVT system management. Smart control approaches can potentially use measurements of solar radiation, temperature, flow conditions, electrical output, and thermal demand to determine appropriate operating conditions.

For Malaysian applications, such approaches may be particularly useful because solar conditions can vary rapidly due to cloud cover and tropical weather. However, the practical value of intelligent control depends on sensor reliability, data availability, computational requirements, control-system cost, and robustness under real operating conditions. Further validation under Malaysian conditions is therefore important before widespread deployment.

3.20 Experimental versus Numerical Investigations

PVT research commonly employs experimental testing, numerical modelling, analytical approaches, or combinations of these methods. Experimental investigations provide direct information about actual collector behaviour and are important for validating thermal, electrical, and system-level performance.

Numerical and analytical models provide opportunities to investigate a wider range of configurations and operating conditions without requiring full-scale experimental testing for every case. However, modelling assumptions regarding heat transfer, boundary conditions, weather data, material properties, and system operation can influence the results. Consequently, numerical investigations should ideally be supported by experimental validation where possible [2,3,9,20].

3.21 PVT versus Conventional PV

The principal distinction between PVT and conventional PV systems is the treatment of thermal energy. Conventional PV systems primarily convert solar radiation into electricity, with the remaining absorbed energy becoming heat. PVT systems seek to recover a portion of this heat while simultaneously maintaining or improving the electrical operating condition of the PV module [1,14,17,20].

The comparison should therefore be made using appropriate system boundaries. For applications with significant thermal demand, PVT can provide an advantage through combined electricity and useful heat production. Where thermal demand is limited, the additional complexity of the thermal subsystem may provide less benefit. Thus, the suitability of PVT depends strongly on the relationship between solar availability, electrical demand, thermal demand, installation conditions, and system economics.

3.22 Summary

PVT performance in Malaysia is governed by the interaction of solar irradiance, ambient temperature, PV operating temperature, thermal-fluid characteristics, collector configuration, and operating conditions. High solar availability provides an important energy resource, while high ambient temperatures make thermal management particularly significant. Effective cooling can simultaneously recover useful thermal energy and reduce photovoltaic operating temperature.

Water, air, nanofluids, and PCM-based approaches provide different pathways for thermal management, each involving specific technical and practical trade-offs. Similarly, parameters such as mass-flow rate, tilt angle, orientation, wind conditions, and control strategy influence the overall performance of the system. Consequently, PVT assessment should move beyond individual electrical or thermal indicators and consider overall energy, exergy, auxiliary consumption, application requirements, and system-level performance.

For Malaysia, the most appropriate PVT configuration is therefore unlikely to be universal. Instead, configuration and operating strategy should be selected according to local climatic conditions, the required electrical and thermal services, building or site characteristics, and economic feasibility. These considerations provide the basis for evaluating the practical applications and system-integration opportunities discussed in the following section.

PVT APPLICATIONS AND SYSTEM INTEGRATION IN MALAYSIA

4.1 Introduction

The practical value of photovoltaic-thermal (PVT) technology depends not only on collector performance but also on how effectively electricity and thermal energy can be integrated with existing energy-demand systems. Unlike conventional photovoltaic systems, PVT collectors provide two useful energy streams that can be matched with electrical and thermal loads. This characteristic creates opportunities for PVT deployment across residential, commercial, industrial, agricultural, and building-integrated applications.

Table 2. Quantitative performance evidence and comparability limits under Malaysian/tropical conditions.

Configuration	Fluid	Flow rate	Critical interpretation
Malaysia flat-plate PVT [1]	Water	0.0028 kg/s	Reported experimental point; not universal optimum
Ghana tropical comparison [6]	Water	Study-specific	Useful tropical comparator; avoid unverified numerical transfer
Warm-climate studies [5,23,41,58,66]	Varied	Varied	Climate, geometry and test protocols differ
PCM/nanofluid PVT [22,28,31,40,43]	Water/air + additives	Varied	Net benefit must include auxiliary power and durability

In Malaysia, the suitability of PVT applications is closely associated with the country's climatic conditions and energy-demand profile. The relatively high availability of solar radiation provides an opportunity for continuous solar-energy conversion, while the tropical climate creates significant requirements for hot-water production, cooling, ventilation, drying, and other thermal services. Consequently, PVT should be considered as an integrated energy technology rather than simply as an alternative PV collector [1,14,20].

4.2 Residential Applications

Residential buildings represent an important potential application for PVT because electricity and low- to medium-temperature thermal energy are commonly required within the same location. A residential PVT system can supply electricity while recovering heat for domestic hot-water production or other household thermal requirements.

The integration of PVT with domestic hot-water systems can increase the utilization of the available solar resource because both electrical and thermal outputs are obtained from the collector area. Water-based PVT configurations are particularly relevant where hot-water demand is sufficiently high to justify the additional thermal subsystem [18,25,28].

Residential application, however, requires consideration of installation area, system cost, maintenance, water circulation, storage requirements, household energy demand, and the availability of suitable roof space. These factors influence whether a combined PVT system provides sufficient benefit compared with separate PV and conventional water-heating technologies.

4.3 Commercial Buildings

Commercial buildings can provide favourable conditions for PVT deployment because they may have simultaneous electricity and thermal-energy requirements. Hotels, educational facilities, healthcare buildings, office complexes, and commercial premises can require electricity throughout the day together with hot water or other thermal services.

The relatively large roof areas available on some commercial buildings provide opportunities for PVT installation. Building-integrated configurations can further incorporate collectors into the building envelope while maintaining their energy-generation function [36,37,58,59].

For commercial applications, system sizing should be based on the relationship between the available solar resource and the building's electrical and thermal demand profiles. Excess thermal energy may otherwise reduce the effective utilization of the PVT system, particularly during periods when thermal demand is low.

4.4 Building-Integrated PVT

Building-integrated photovoltaic-thermal (BIPVT) systems combine PVT collectors with architectural building components. Integration can occur on roofs, façades, or other parts of the building envelope. This approach can improve the utilization of available building surfaces while providing electrical and thermal energy [36,37,58,59].

BIPVT is particularly relevant in Malaysia because a large proportion of solar-energy installations are associated with buildings. Integration with the building envelope can reduce the requirement for separate collector structures and potentially improve the use of otherwise underutilized surfaces.

Nevertheless, BIPVT design involves additional considerations compared with conventional roof-mounted collectors. Architectural appearance, structural requirements, ventilation, access for maintenance, orientation, shading, waterproofing, and thermal interaction with the building envelope must all be considered. Consequently, successful BIPVT deployment requires coordination between energy-system design and building design.

4.5 Building-Applied PVT

Building-applied PVT (BAPVT) systems are mounted onto existing building surfaces without necessarily becoming an integral part of the building structure. This approach can provide greater flexibility for retrofitting

existing buildings.

The distinction between building-integrated and building-applied systems is important when considering the Malaysian building stock. New buildings may provide opportunities for integrated design from the planning stage, whereas existing buildings may be more suitable for applied systems that can be installed with limited modification to the building structure.

Both approaches can provide electricity and thermal energy, but their performance and economic characteristics depend on available surface area, orientation, inclination, shading, thermal loads, and installation constraints.

4.6 Domestic Hot-Water Production

Domestic hot-water production is one of the most direct applications of the thermal output from PVT systems. The thermal energy recovered from the PV collector can be transferred to a storage tank and subsequently used to satisfy hot-water demand.

This application is attractive because the thermal requirement can coincide with the operating period of the solar collector, while storage allows some separation between solar-energy availability and hot-water consumption. The system can therefore provide a combined electrical and thermal service from a single collector area [18,25,28].

For Malaysia, the suitability of this application depends on the magnitude and timing of hot-water demand, storage requirements, and the performance of the selected PVT configuration.

4.7 Solar-Assisted Cooling

Malaysia's tropical climate creates substantial cooling requirements in buildings. This creates an opportunity for PVT systems to contribute indirectly to cooling services by supplying electricity to conventional cooling equipment or thermal energy to suitable solar-assisted cooling systems.

The use of PVT-generated electricity for cooling can improve the correspondence between solar-energy production and building cooling demand because both are strongly associated with daytime conditions. Thermal output may also be integrated into appropriate thermally driven cooling configurations where sufficient temperature levels can be achieved.

However, thermal integration for cooling generally requires greater system complexity than direct hot-water applications. The collector temperature, thermal storage, cooling technology, control strategy, and overall system efficiency must therefore be considered together.

4.8 Industrial Applications

Industrial facilities can offer significant opportunities for PVT deployment because many industrial processes require both electricity and low- or medium-temperature heat. PVT systems can potentially supply part of these requirements while reducing dependence on conventional energy sources.

The suitability of industrial applications depends strongly on the required process temperature. Low-temperature processes are generally more compatible with conventional PVT thermal output than applications requiring very high temperatures. System integration should therefore begin with characterization of the industrial energy demand before selecting the PVT configuration.

Industrial facilities may also provide larger installation areas than residential buildings, although available roof space, structural loading, process continuity, maintenance access, and integration with existing energy infrastructure must be considered.

4.9 Agricultural Applications

Agriculture represents another potential application of PVT technology. Thermal energy can be useful for crop drying, agricultural-product processing, water heating, and other low-temperature processes, while electricity can support pumps, ventilation, monitoring, and other electrical loads.

Air-based PVT systems may be particularly suitable for drying applications because the heated air can be delivered directly to the drying process. Liquid-based systems may instead be more suitable where hot water is required.

The integration of PVT with agricultural systems therefore provides an opportunity to utilize both energy outputs according to the specific requirements of the agricultural process.

4.10 Solar Drying

Solar drying requires controlled thermal energy and airflow to remove moisture from agricultural products. PVT systems can provide heated air while simultaneously producing electricity for fans, pumps, sensors, or control equipment.

An integrated PVT drying system can therefore reduce the need for separate electrical and thermal energy supplies. The effectiveness of such systems depends on collector temperature, airflow rate, product characteristics, drying requirements, and weather conditions.

For Malaysia, where agricultural products and high ambient humidity can influence drying processes, system design should consider both the thermal performance of the collector and the environmental conditions affecting moisture removal.

4.11 PVT with Thermal Energy Storage

Thermal energy storage can improve the utilization of PVT heat by allowing thermal energy collected during periods of high solar availability to be used later. Storage can therefore reduce the mismatch between solar-energy production and thermal demand [18,25,28,43].

Storage may take the form of sensible heat storage, latent heat storage using phase-change materials, or other thermal-storage approaches. The appropriate technology depends on the required temperature range, storage duration, system scale, cost, and application.

The integration of thermal storage is particularly relevant for PVT systems because thermal output can otherwise become underutilized when demand is lower than solar heat production.

4.12 PVT and Heat-Pump Systems

PVT collectors can also be integrated with heat-pump systems. In such arrangements, the PVT system can provide electricity for heat-pump operation while also serving as a source of low-grade thermal energy.

The combination can potentially improve the overall utilization of solar energy by linking photovoltaic electricity and recovered heat within the same energy system. The effectiveness of such configurations depends on the heat-pump operating conditions, source temperature, collector performance, electricity demand, and control strategy.

This type of integration demonstrates the importance of evaluating PVT as part of a wider energy system rather than as an isolated collector.

4.13 PVT in Microgrids and Distributed Energy Systems

The distributed nature of PVT technology makes it potentially suitable for integration into building-scale and community-scale energy systems. Electricity generated by PVT collectors can contribute to local electrical loads, while thermal output can be directed to local heating or hot-water requirements.

Where several energy technologies are connected, PVT can become one component of a distributed renewable-energy system that includes conventional PV, energy storage, heat pumps, electrical loads, and thermal storage.

Such integration requires appropriate energy-management strategies to determine how electricity and heat should be utilized at different times. The system objective should be to maximize useful energy utilization rather than simply maximizing instantaneous collector output.

4.14 PVT for Remote and Off-Grid Applications

PVT systems may also be considered for locations where access to conventional energy infrastructure is limited. In such settings, simultaneous electricity and thermal generation can be advantageous because one solar-energy system can address multiple energy requirements.

However, off-grid PVT applications require careful consideration of storage and system reliability. Electrical storage may be necessary when electricity demand occurs outside solar-generation periods, while thermal storage may be required to maintain useful heat availability.

The additional components required for autonomous operation can increase system complexity and cost. Consequently, the application should be evaluated using a complete system boundary that includes generation, storage, control, and end-use equipment.

4.15 PVT for Water-Related Applications

Water-related applications provide an additional opportunity for utilizing PVT thermal output. Heated water can support domestic or commercial hot-water demand and potentially contribute to selected water-treatment or water-management processes.

Where water is used as the heat-transfer medium, the thermal subsystem must account for water quality, corrosion, scaling, leakage, circulation, and maintenance. These factors become particularly important for long-term operation in tropical environments.

4.16 PVT Integration with Energy Storage

Electrical and thermal storage can be considered separately or jointly in PVT systems. Electrical storage can improve the utilization of generated electricity when production and demand do not coincide, while thermal storage serves a similar purpose for recovered heat.

Combined electrical and thermal storage creates an opportunity for more flexible energy management. However, the additional capital cost, control requirements, conversion losses, and maintenance requirements must be evaluated against the improvement in system utilization.

The most appropriate storage configuration is therefore dependent on the application rather than being universally applicable to all PVT installations.

4.17 Application Suitability under Malaysian Conditions

The suitability of PVT for a particular Malaysian application depends on several interconnected factors. These

include solar availability, electrical demand, thermal demand, available installation area, required thermal temperature, collector configuration, storage requirements, installation cost, and system maintenance.

A PVT system is particularly attractive where electrical and thermal loads occur within the same facility and where both outputs can be utilized effectively. Conversely, where there is little thermal demand, the additional thermal subsystem may not provide sufficient benefit relative to conventional PV.

This application-dependent characteristic indicates that PVT deployment should be based on energy-demand matching rather than on collector efficiency alone.

4.18 System Integration and Energy-Demand Matching

Energy-demand matching is one of the most important considerations for PVT deployment. The electrical and thermal outputs of the collector should ideally correspond to the energy requirements of the end user. A system that produces substantial thermal energy without a corresponding thermal load may experience significant energy losses or require additional storage.

Consequently, PVT system design should consider hourly or seasonal demand profiles where appropriate. Electrical load, hot-water demand, thermal storage, auxiliary equipment, and solar availability should be evaluated together.

This systems perspective can help identify applications where PVT provides a stronger advantage than conventional PV or separate solar-thermal technologies.

4.19 Integration Challenges

Despite its potential, PVT integration presents several challenges. The combined electrical and thermal subsystems increase design complexity compared with conventional PV. Additional pumps, fans, heat exchangers, storage tanks, controls, and piping may be required depending on the selected configuration.

Maintenance requirements may also increase because the system includes both electrical and thermal components. The economic value of the additional thermal output therefore depends on whether the recovered heat can be utilized consistently and whether the resulting energy savings justify the additional system complexity.

Building integration introduces additional challenges involving structural design, architectural requirements, waterproofing, shading, ventilation, and access. These factors should be addressed during system planning rather than after installation.

4.20 Summary

PVT technology provides opportunities for integrated electricity and thermal-energy generation across a range of Malaysian applications. Residential buildings, commercial facilities, industrial sites, agricultural operations, and building-integrated systems can all provide potential applications when sufficient electrical and thermal demand exists.

The principal advantage of PVT is the ability to utilize the available collector area for two energy-conversion pathways. However, effective deployment depends on matching the thermal and electrical outputs with actual energy demand. Thermal storage, electrical storage, heat pumps, cooling systems, and intelligent control can further expand the range of possible applications.

For Malaysia, PVT deployment should therefore be considered from a system-integration perspective. Collector selection, thermal management, building or site characteristics, energy demand, storage, control, economics, and

maintenance should be evaluated as interconnected components. This provides the foundation for the techno-economic, environmental, and energy-performance assessment presented in the next section.

ECONOMIC, ENVIRONMENTAL AND ENERGY-PERFORMANCE DIMENSIONS

5.1 Introduction

The technical performance of photovoltaic-thermal (PVT) systems is only one component of their overall suitability for deployment. The simultaneous production of electricity and thermal energy can provide significant benefits, but these benefits must be considered together with investment cost, operating requirements, environmental performance, energy savings, and the value of the recovered heat. A system with high technical efficiency may not necessarily provide the most favourable economic or environmental outcome if its additional components are costly or if its thermal output cannot be effectively utilized.

For Malaysia, assessment of PVT technology should therefore adopt an integrated perspective encompassing energy performance, economic feasibility, environmental impacts, and resource utilization. Such an approach is consistent with the broader objective of improving renewable-energy utilization while maintaining the reliability and affordability of energy services [1,14,20].

5.2 Energy Performance

The principal energy advantage of PVT systems arises from the simultaneous generation of electricity and useful heat. Conventional PV systems primarily utilize the electrical component of solar conversion, whereas PVT systems seek to recover part of the thermal energy that would otherwise remain as heat in the PV module and surrounding environment [1,14,17].

Energy performance can therefore be evaluated through electrical output, useful thermal output, total useful energy, and auxiliary energy consumption. The appropriate performance indicator depends on the system boundary and application. For example, a PVT system supplying hot water should account for useful thermal delivery, whereas a system primarily intended to maintain photovoltaic electrical performance may place greater emphasis on temperature reduction and net electrical output.

5.3 Primary Energy Savings

PVT systems can contribute to primary-energy savings by replacing electricity or conventional fuels that would otherwise be required to provide electrical and thermal services. The magnitude of these savings depends on the amount of useful energy produced and the energy source displaced.

The thermal output is particularly important in this context. If recovered heat replaces conventional electrically or fuel-driven water heating, the combined energy benefit may be substantially greater than that obtained by considering electrical generation alone. However, this benefit depends on actual thermal demand and the efficiency of the displaced conventional technology.

5.4 Electrical Energy Yield

Electrical yield is influenced by solar irradiance, module characteristics, cell temperature, collector design, orientation, inclination, and thermal-management strategy. The thermal component of PVT can influence electrical yield by removing heat from the photovoltaic layer.

Consequently, the value of active cooling should be assessed on the basis of net electrical benefit rather than temperature reduction alone. Pumping or fan requirements introduce auxiliary electricity consumption, and this consumption should be included when evaluating the overall system performance [2,20,34].

5.5 Thermal Energy Yield

The useful thermal yield of a PVT system depends on the temperature and flow characteristics of the heat-

transfer medium, collector design, solar radiation, and thermal losses. The value of thermal output also depends on whether the recovered heat can be delivered at a temperature suitable for the intended application.

Low-temperature heat can be valuable for domestic hot water, selected agricultural processes, and other applications, while higher-temperature requirements may require additional system components or alternative technologies. Therefore, thermal energy yield should be assessed together with the temperature level and timing of heat availability.

5.6 Combined Energy Utilization

One of the strongest arguments for PVT deployment is the ability to utilize a greater fraction of incident solar energy within the same collector area. This can be particularly beneficial where roof or land area is limited and where electrical and thermal loads are colocated.

The combined output can also improve the utilization of solar resources over the operating period. However, high theoretical combined efficiency does not automatically translate into high practical performance. The electrical and thermal outputs must both be utilized effectively for the combined-energy advantage to be realized.

5.7 Exergy Considerations

Exergy analysis provides a complementary perspective to conventional energy analysis. Electrical energy has relatively high exergy, whereas thermal energy at temperatures close to ambient has a lower capacity to perform useful work. Consequently, two PVT systems with similar total-energy efficiencies may have different exergy performances depending on their operating temperatures and thermal applications [20,31].

This distinction is important when evaluating PVT configurations for different applications. Where high-quality energy is required, electrical output may have greater value than low-temperature heat. Conversely, where a substantial low-temperature thermal demand exists, thermal-energy recovery can still provide significant practical value despite its lower exergy content.

5.8 Economic Evaluation

The economic feasibility of PVT systems depends on capital cost, operating and maintenance costs, energy savings, system lifetime, replacement requirements, and the value assigned to both electrical and thermal outputs.

Compared with conventional PV, PVT systems generally involve additional components and greater system complexity. Pumps, fans, heat exchangers, thermal storage, controls, piping, and supporting structures may increase initial investment. The additional cost must therefore be justified by the value of the recovered thermal energy and any improvement in electrical performance.

5.9 Initial Capital Cost

Initial capital cost is one of the principal barriers to wider PVT deployment. The cost of the collector itself is only one component; installation, thermal circulation equipment, storage, heat exchangers, controls, supporting structures, and electrical equipment may also contribute to the total investment.

System scale can influence the economic outcome. Larger systems may provide opportunities for improved utilization of equipment and thermal demand, whereas small systems may have relatively high costs per unit of useful output. Consequently, economic assessment should be conducted at the system level rather than based solely on collector cost.

5.10 Operation and Maintenance

PVT systems require maintenance of both electrical and thermal components. In liquid-based systems, maintenance may include inspection of pumps, pipes, valves, heat exchangers, fluid quality, and storage equipment. Air-based systems may require maintenance of fans, ducts, filters, and airflow pathways.

The tropical Malaysian environment may further influence maintenance requirements because of humidity, rainfall, biological growth, dust, and other environmental factors. Long-term performance therefore depends not only on initial system design but also on appropriate maintenance practices.

5.11 Payback and Life-Cycle Considerations

Economic indicators such as payback period, life-cycle cost, net present value, and levelized cost can be used to assess the financial performance of PVT systems. The appropriate indicator depends on the purpose and boundary of the assessment.

A short payback period may be attractive to users making investment decisions, whereas life-cycle analysis provides a broader assessment that accounts for operation, maintenance, component replacement, and long-term energy savings. For PVT systems, the value assigned to thermal output is particularly important because excluding useful heat can underestimate the economic benefit of the technology.

5.12 Value of Thermal Energy

The economic value of the thermal output is strongly dependent on the energy source it replaces. If PVT heat replaces electricity used for water heating, the avoided energy cost may be significant. If the recovered heat has little practical use, however, its economic value may be limited.

This highlights the importance of application matching. PVT systems should preferably be installed where a relatively stable thermal demand exists or where thermal storage can maintain a useful match between solar heat production and demand.

5.13 Environmental Benefits

PVT systems can contribute to environmental objectives by reducing dependence on conventional energy sources and increasing the utilization of renewable solar energy. The environmental benefit depends on the electricity and fuel sources displaced by the system and on the environmental impacts associated with manufacturing, installation, operation, and eventual disposal.

Because PVT generates electricity and thermal energy simultaneously, its environmental assessment should consider both displaced electrical generation and displaced thermal-energy production. A system with high thermal utilization may therefore provide a different environmental benefit from one in which most of the recovered heat is rejected.

5.14 Reduction in Greenhouse-Gas Emissions

The substitution of renewable electricity and solar-derived heat for conventional energy can reduce greenhouse-gas emissions. The magnitude of the reduction depends on the carbon intensity of the displaced energy and the actual useful energy produced by the PVT system.

For Malaysia, this consideration should be linked to the electricity-generation mix and the conventional technologies used to meet thermal demand. Therefore, environmental benefits should not be assumed solely from collector efficiency; they should be calculated using an appropriate system boundary and realistic operating conditions.

5.15 Life-Cycle Environmental Assessment

Although operational emissions from PVT systems are low, environmental impacts may arise during material extraction, manufacturing, transportation, installation, maintenance, and end-of-life processing. Photovoltaic modules, absorber materials, thermal components, pumps, storage systems, and supporting structures all contribute to the overall life-cycle footprint.

Life-cycle assessment can therefore provide a more complete evaluation than operational emissions alone. Such analysis can also identify components or materials that contribute disproportionately to environmental impacts and provide opportunities for future design improvement.

5.16 Resource Efficiency

PVT technology can improve solar-resource utilization by producing two useful energy outputs from a common collector area. This is particularly relevant where land or building-surface availability limits the installation of separate PV and solar-thermal systems.

However, resource efficiency should include more than collector-area utilization. Water consumption, materials, auxiliary electricity, thermal storage, and maintenance requirements should also be considered. A system that produces high thermal output but requires substantial additional resources may not necessarily provide the most efficient overall solution.

5.17 Land and Roof-Space Considerations

The dual-output nature of PVT can be advantageous in locations where available installation area is constrained. A single collector surface can provide electricity and thermal energy, potentially reducing the need for separate areas for PV and solar-thermal collectors.

This characteristic is particularly relevant to urban and building applications. However, roof structure, shading, orientation, accessibility, and architectural constraints remain important. The effective area available for PVT should therefore be determined from the actual building or site rather than from theoretical surface area.

5.18 Water Consumption and Management

Water-based PVT systems introduce specific resource considerations. Although water serves as an effective heat-transfer medium, the system may require water for initial filling, maintenance, cleaning, or other purposes depending on the configuration.

Water quality can also influence scaling, corrosion, and system lifetime. Closed-loop systems may reduce ongoing water requirements, but they require appropriate fluid management and system maintenance. These considerations should be included in environmental and economic assessments.

5.19 Environmental Conditions and Durability

The long-term environmental performance of a PVT system depends on its durability under actual operating conditions. Tropical environments can expose collectors and associated components to high temperature, humidity, rainfall, solar radiation, and potentially corrosive conditions.

Material selection and protective measures are therefore important for maintaining performance over the system lifetime. Degradation of thermal or electrical components can reduce the expected energy and economic benefits and should be considered in life-cycle assessments.

5.20 Social and Energy-Security Benefits

In addition to direct economic and environmental benefits, PVT deployment can contribute to broader energy-security objectives. Distributed generation can reduce dependence on centralized energy supplies, while local thermal generation can reduce demand for conventional fuels or electricity used for heating.

The decentralized nature of PVT can also support energy resilience in suitable applications. However, the extent of this benefit depends on system design, storage, grid interaction, and the ability of the system to continue supplying useful energy under varying operating conditions.

5.21 Integrated Techno-Economic Assessment

A meaningful assessment of PVT technology should combine technical, economic, and environmental indicators. Electrical efficiency alone cannot capture the full value of the technology, while thermal efficiency alone does not indicate whether the recovered heat is economically useful.

An integrated assessment should therefore consider electrical generation, useful thermal delivery, auxiliary energy consumption, investment cost, operating and maintenance cost, avoided conventional energy consumption, emissions reduction, system lifetime, and application-specific energy demand. This approach is particularly important when comparing PVT with conventional PV or separate PV and solar-thermal systems.

5.22 Comparison with Separate PV and Solar-Thermal Systems

PVT systems can be compared with two alternative arrangements: conventional PV alone and separate PV plus solar-thermal collectors. The first alternative may have lower system complexity but does not recover useful thermal energy. The second can provide both energy forms but may require greater surface area and separate infrastructure.

Table 3. Illustrative techno-economic comparison using tariff-value scenarios.

System	Value assumption	Gross annual value	CAPEX / O&M	Simple payback
PV-only (1 kWp)	RM0.30/kWh avoided import	RM450	RM3,500 / RM50/y	8.8 y
PVT (1 kWp-equivalent)	Electricity and useful heat each valued at RM0.30/kWh equivalent	RM1,170	RM6,000 / RM100/y	5.6 y
Separate PV + solar thermal	Same assumptions; heat counted only when used	RM1,050	RM6,000 / RM100/y	6.3 y

PVT therefore has a potential advantage where collector area is constrained and both electrical and thermal outputs are required. However, the additional complexity of PVT means that its economic advantage cannot be assumed in every application. Comparative analysis should use the same system boundary, energy services, lifetime, and operating assumptions.

5.23 Key Economic and Environmental Trade-Offs

The principal trade-off associated with PVT is between additional system complexity and increased energy utilization. Thermal recovery can improve overall energy output, but additional equipment increases capital cost and maintenance requirements. Similarly, advanced thermal-management approaches may improve performance while introducing additional material, pumping, or control requirements.

These trade-offs indicate that optimization should focus on the complete system rather than maximizing an individual performance parameter. The preferred PVT configuration should provide an appropriate balance between energy production, reliability, cost, environmental performance, and application requirements.

5.24 Summary

The economic, environmental, and energy-performance benefits of PVT systems are closely interconnected. The simultaneous production of electricity and useful thermal energy provides an opportunity to increase solar-resource utilization and reduce dependence on conventional energy sources. However, these benefits depend strongly on thermal-demand matching, system complexity, capital cost, auxiliary energy use, maintenance, and long-term performance.

For Malaysia, PVT evaluation should therefore incorporate electrical and thermal energy yield, exergy, economic indicators, greenhouse-gas reduction, resource utilization, durability, and life-cycle impacts. Particular attention should be given to the value of recovered thermal energy because this factor strongly influences both the economic and environmental performance of PVT.

The resulting assessment demonstrates that PVT deployment cannot be evaluated solely through collector efficiency. Its suitability must be determined through an integrated consideration of technical performance, energy demand, economics, environmental outcomes, and system lifetime. These considerations lead directly to the policy, market, and commercialization issues addressed in the following section.

MALAYSIAN POLICY, MARKET AND COMMERCIALIZATION PERSPECTIVES

6.1 Introduction

The wider deployment of photovoltaic-thermal (PVT) technology in Malaysia depends not only on technical performance but also on the policy, regulatory, financial, market, and institutional environment in which the technology is developed and adopted. PVT combines photovoltaic and thermal-energy functions and therefore does not always fit directly within policy and market structures designed separately for electricity generation or solar-thermal applications.

This creates both an opportunity and a challenge. On one hand, PVT can contribute simultaneously to renewable electricity generation and thermal-energy substitution. On the other hand, its combined nature requires appropriate recognition within renewable-energy planning, building-energy strategies, investment assessment, standards, and commercialization pathways. The deployment of PVT should therefore be considered within the broader Malaysian transition toward more efficient and diversified renewable-energy systems.

6.2 Renewable-Energy Policy Context

Malaysia's renewable-energy development provides an important context for evaluating the potential contribution of PVT systems. Solar energy represents a particularly relevant renewable resource because of the country's geographical and climatic conditions. Within this context, PVT can extend the utilization of solar energy beyond electricity generation by recovering useful thermal energy.

The policy relevance of PVT is therefore associated with its potential to support several objectives simultaneously, including renewable-energy utilization, energy efficiency, reduction of conventional energy consumption, and diversification of energy supply. However, the extent to which PVT can contribute to national targets depends on appropriate deployment mechanisms and recognition of both energy outputs.

6.3 Position of PVT within Solar-Energy Policy

Solar-energy policies have traditionally placed considerable emphasis on photovoltaic electricity generation. PVT introduces a broader energy-service perspective because the collector provides both electricity and heat.

A policy framework that evaluates solar technologies solely on electrical capacity may therefore undervalue PVT systems. The thermal output should also be recognized when assessing the contribution of a PVT installation to energy supply and fossil-fuel or conventional-electricity displacement.

This suggests that technology-neutral or energy-service-based assessment mechanisms may provide a more appropriate framework for comparing PVT with other renewable-energy technologies.

6.4 Regulatory Considerations

PVT systems combine electrical and thermal equipment and may consequently interact with different technical and regulatory requirements. Electrical components require appropriate safety and installation practices, while

thermal components introduce additional requirements associated with fluid circulation, pressure, storage, piping, and building integration.

Clear technical requirements can support market confidence by ensuring that systems are designed, installed, and maintained according to appropriate standards. At the same time, regulatory procedures should avoid unnecessary complexity that could discourage adoption of combined-energy technologies.

6.5 Building Regulations and Integration

Building-related regulations are particularly relevant to PVT because roofs and façades provide important installation surfaces. Building-integrated PVT systems require coordination between energy-system requirements and building design, including structural loading, fire safety, waterproofing, access, ventilation, and maintenance.

Integration at the design stage can reduce some of these challenges because collector orientation, structural support, thermal pathways, and service connections can be incorporated into the building from the beginning. Retrofitting existing buildings may require additional engineering assessment and installation measures.

6.6 Market Development

The Malaysian PVT market remains influenced by the relative maturity and visibility of conventional photovoltaic technology. PV systems have a more established market structure, supply chain, installer base, and customer awareness. PVT, by contrast, requires simultaneous understanding of electrical and thermal-system design.

This difference can create barriers to market development. Potential users may be familiar with PV electricity generation but less familiar with the value of recovering useful heat from the same collector. Market development therefore requires demonstration of practical applications and clear communication of the combined energy benefits.

6.7 Technology Awareness

Awareness among building owners, engineers, developers, installers, and energy managers is important for PVT commercialization. Because the technology combines two energy functions, stakeholders must understand not only collector performance but also system integration, thermal demand, storage, control, and maintenance.

Technical training and demonstration projects can help develop this knowledge base. Universities, research institutions, industry participants, and public agencies can play complementary roles in developing technical expertise and disseminating information about successful applications.

6.8 Financial Barriers

The higher initial complexity of PVT systems can create a financial barrier compared with conventional PV. Additional thermal components may increase the upfront investment, while the financial value of the thermal output may not be immediately recognized by conventional investment models.

Financial assessment should therefore consider both electricity savings or revenues and avoided expenditure for thermal energy. Where only electrical output is valued, the economic attractiveness of PVT may be underestimated.

6.9 Incentive Mechanisms

Appropriate financial incentives can potentially improve the attractiveness of PVT systems, particularly during

early market development. Incentives may be structured around renewable-energy generation, energy savings, thermal-energy substitution, capital investment, or building-energy performance.

The appropriate mechanism should reflect the dual-output nature of PVT. A framework that rewards only electrical generation may provide less support for PVT than a framework that recognizes the combined useful energy delivered by the system.

6.10 Financing and Investment Decisions

Commercial investment decisions require predictable returns and a clear understanding of system performance. PVT projects may face additional uncertainty because financial returns depend on both electrical and thermal utilization.

Investment models should therefore incorporate realistic thermal-demand profiles, collector degradation, maintenance requirements, auxiliary energy consumption, and the lifetime of major components. Where possible, performance guarantees and standardized assessment procedures could reduce uncertainty for investors.

6.11 Demonstration Projects

Demonstration projects can provide an important pathway for establishing confidence in PVT technology. Pilot installations in residential, commercial, institutional, agricultural, and industrial settings can generate practical data on performance, maintenance, reliability, and user acceptance.

Demonstration projects are particularly valuable in Malaysia because local operating conditions may differ from those represented in studies conducted in other climatic regions. Long-term local monitoring can therefore support the development of realistic performance expectations and techno-economic models.

6.12 Standardization and Performance Testing

Standardized testing is important for comparing PVT collectors and systems. Without consistent testing conditions and performance definitions, comparisons between different configurations may be difficult.

Performance standards should ideally account for both electrical and thermal outputs, including operating temperatures, flow rates, solar irradiance, ambient conditions, and auxiliary energy consumption. Standardization can support manufacturers, researchers, investors, and users by providing a common basis for technology comparison.

6.13 Certification and Quality Assurance

Certification and quality assurance can help reduce uncertainty associated with PVT system reliability. The combined electrical and thermal nature of PVT means that component quality must be considered across multiple subsystems.

Quality assurance can include collector manufacturing, thermal connections, electrical connections, fluid circuits, storage systems, controls, and installation procedures. Establishing confidence in system quality is particularly important for commercial deployment because poor installation or component failure can affect both energy outputs.

6.14 Supply-Chain Development

A reliable supply chain is necessary for large-scale PVT commercialization. This includes manufacturers, suppliers, installers, engineering firms, maintenance providers, monitoring specialists, and component

manufacturers.

The development of a local or regional supply chain can reduce dependence on imported components, improve service availability, and support local technical capabilities. However, the appropriate level of local manufacturing should be determined by market size, production economics, technology maturity, and supply-chain requirements.

6.15 Local Manufacturing Opportunities

PVT systems contain components that may offer opportunities for local manufacturing or assembly. Collector structures, mounting systems, thermal piping, storage components, heat exchangers, control systems, and supporting equipment may potentially be supplied through existing industrial capabilities.

Local production could contribute to technology adaptation for Malaysian conditions. Nevertheless, manufacturing decisions should be based on technical quality, cost competitiveness, reliability, and market demand rather than localization alone.

6.16 Research and Industry Collaboration

Continued collaboration between research institutions and industry is important for overcoming the gap between laboratory development and commercial deployment. Academic research can investigate new collector configurations, thermal-management techniques, materials, modelling approaches, and optimization strategies, while industry can provide practical information concerning manufacturing, installation, cost, maintenance, and customer requirements.

Collaborative research can therefore improve the relevance of PVT technologies to actual Malaysian applications and accelerate the transition from experimental systems to commercially viable products.

6.17 Human-Capital Development

PVT commercialization requires personnel with knowledge spanning photovoltaic systems, solar thermal systems, heat transfer, fluid mechanics, electrical engineering, building services, controls, and energy economics.
Training programmes and multidisciplinary engineering education can help develop the required capabilities. Installer and technician training is also important because system performance depends strongly on correct installation, commissioning, monitoring, and maintenance.

6.18 Market Segmentation

PVT commercialization should not necessarily target all energy users equally. Market segmentation can identify applications where combined electrical and thermal generation provides the greatest value.

Potential priority segments include buildings with significant hot-water demand, facilities with suitable roof area, industrial users requiring low-temperature heat, agricultural operations requiring thermal energy, and institutions where electricity and thermal loads occur simultaneously.

This approach can reduce the risk of deploying PVT in applications where the thermal output would remain largely unused.

6.19 Business Models

Different business models may support PVT deployment. These can include direct equipment ownership, third-party investment, energy-service arrangements, leasing, or performance-based contracts.

The appropriate model depends on system scale, customer investment capacity, energy prices, expected savings, and the ability to measure electrical and thermal outputs. Because PVT provides two forms of useful energy, contracts should clearly define how both outputs are valued and measured.

6.20 Monitoring and Verification

Monitoring is important for establishing the actual performance of PVT systems after installation. Measurements can include solar irradiance, electrical output, inlet and outlet fluid temperatures, flow rate, ambient conditions, thermal output, and auxiliary energy consumption.

Performance monitoring can provide evidence for financial evaluation, maintenance planning, and system optimization. It can also generate the local operational data needed to improve future PVT designs and techno-economic models.

6.21 Commercialization Barriers

Several interconnected barriers can restrict PVT commercialization. These include relatively high initial cost, limited market awareness, lack of standardized performance assessment, limited installer expertise, uncertain valuation of thermal output, system complexity, and competition from mature conventional PV technology.

These barriers are not exclusively technical. Addressing them requires coordinated action involving research, industry, policy, financing, standards, training, and market development.

6.22 Policy Opportunities for PVT Deployment

Several policy opportunities can be considered to support PVT deployment in Malaysia. First, PVT can be explicitly recognized as a combined renewable-electricity and solar-thermal technology. Second, assessment mechanisms can account for both electrical and useful thermal energy. Third, demonstration projects can establish local evidence of technical and economic performance.

Additional opportunities include support for research and development, technical training, performance standards, building integration, pilot projects, and financing mechanisms. Such measures could reduce the uncertainty currently associated with emerging PVT applications.

6.23 Commercialization Roadmap

A practical commercialization pathway can be considered in several stages. The first stage involves research, laboratory validation, and characterization of suitable PVT configurations. The second involves pilot and demonstration projects under Malaysian operating conditions. The third focuses on standardization, certification, installer training, and development of supply chains. The final stage involves broader commercial deployment in application segments where electrical and thermal demand can be effectively matched.

This staged approach can reduce technological and financial risks while allowing lessons from early installations to inform later deployment.

6.24 Policy and Market Integration

Policy support is most effective when it is connected to actual market requirements. Technology incentives without adequate technical standards may not ensure long-term performance, while technical standards without financial or market support may not generate sufficient adoption.

An integrated approach should therefore connect renewable-energy objectives with building policy, industrial energy efficiency, research and development, skills development, financing, standards, and commercialization.

Such coordination can help establish a more favourable environment for PVT deployment.

6.25 Summary

The commercialization of PVT technology in Malaysia requires more than improvements in collector efficiency. Policy recognition, financial mechanisms, standards, technical training, market awareness, supply-chain development, and demonstration projects are all relevant to establishing a sustainable PVT market.

The dual-output nature of PVT presents both an opportunity and a challenge. Its ability to provide electricity and useful heat can increase the value of solar-energy systems, but conventional assessment and incentive structures may not fully capture this benefit. Market development should therefore focus on applications where electrical and thermal demand can be matched effectively.

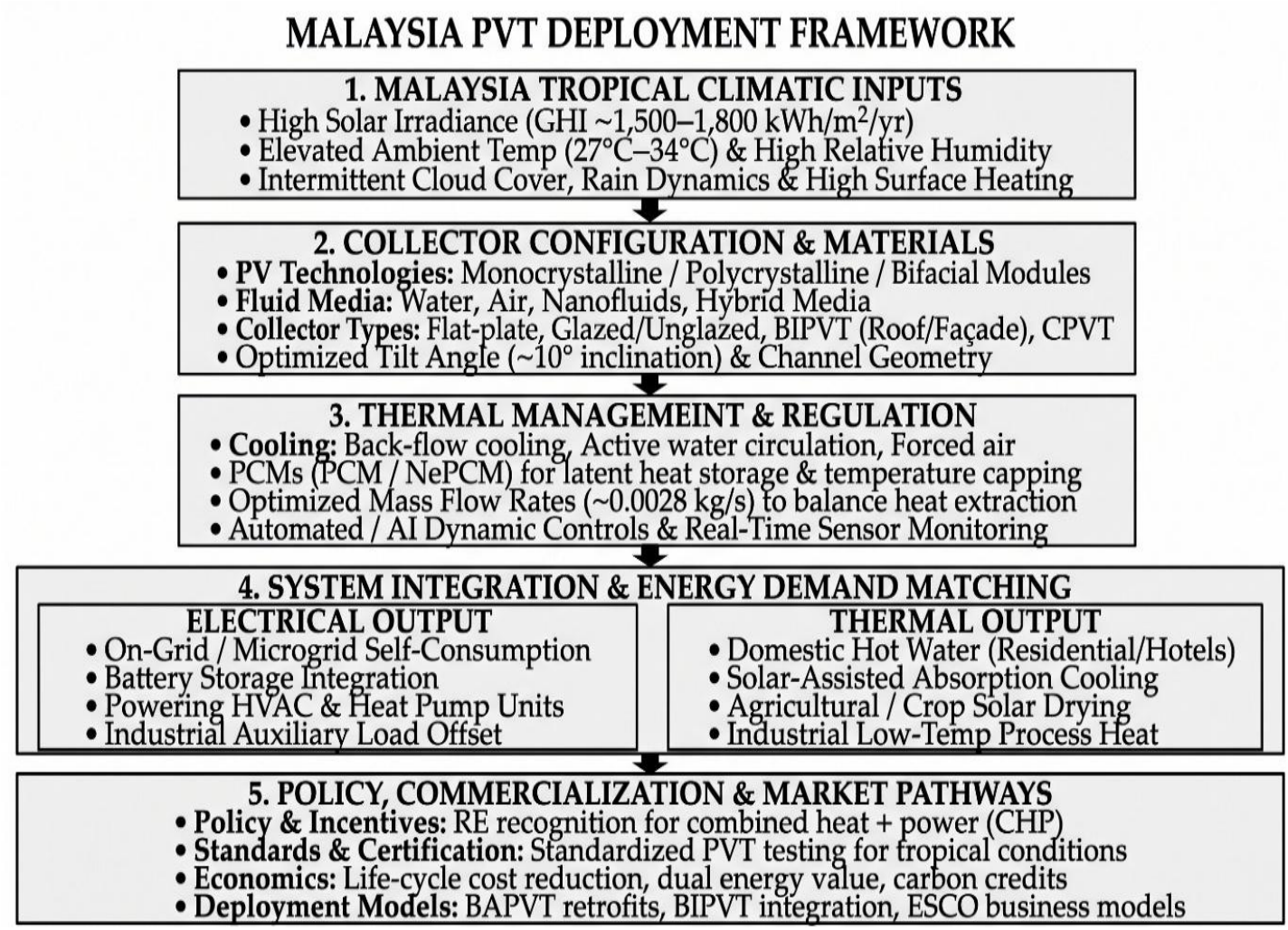


Figure 1. Proposed integrated deployment framework

A coordinated strategy involving government agencies, research institutions, manufacturers, engineering companies, building owners, and energy users can help reduce the technical and non-technical barriers to PVT deployment. The resulting policy and market framework provides the basis for developing an integrated deployment framework for PVT systems in Malaysia.

CONCLUSION

Photovoltaic-thermal (PVT) systems offer a promising approach for improving solar-energy utilization in Malaysia by simultaneously producing electricity and useful thermal energy. The country's high solar availability

and tropical climate provide suitable conditions for PVT deployment, while elevated operating temperatures highlight the importance of effective thermal management.

The review shows that PVT performance depends strongly on collector configuration, cooling method, operating conditions, thermal storage, and the matching of electrical and thermal outputs with actual energy demand. Water- and air-based systems, advanced cooling approaches, building-integrated configurations, and hybrid systems provide different opportunities depending on the intended application.

Beyond technical performance, successful PVT deployment requires consideration of economic feasibility, environmental benefits, maintenance, system complexity, market development, standards, and policy support. PVT is particularly attractive where electricity and thermal demand occur simultaneously and where available installation area is limited.

Overall, PVT technology has potential to contribute to Malaysia's renewable-energy transition and improve the utilization of solar resources. Further work should focus on long-term field validation under Malaysian conditions, system optimization, techno-economic assessment, thermal-energy utilization, intelligent control, and commercialization strategies.

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