Flat-Plate Solar Collectors: Development Methods and Challenges

A.A. Saad[1], M.H. Khaleel[2,*], A.M. Abdulwahaab[2], S.E. Kaska[1]

[1] Northern Technical University, Oil and Gas Engineering Techniques College, Iraq
[2] Northern Technical University, Kirkuk Technical Institute, Iraq

***Abstract* — One of the key technologies in the field of solar energy is the flat plate solar collector, recognized for its extensive applications. It is effective in meeting residential needs for heating and water, as well as the needs of various industrial processes. There are innovative solutions, such as the use of coatings and nanofluids, to enhance the efficiency of flat plate solar collectors. However, as advanced solutions arise, manufacturing and operational expenses, space availability, and material degradation continue to hinder their adoption. This study focuses on future research to enhance the thermal performance of flat plate solar collectors while addressing the challenges facing the global shift towards clean and sustainable energies**

***Index Terms* — Flat-plate solar collectors, development methods, challenges, thermal energy systems.**

I. Introduction

One of the prominent techniques in solar energy that shines the spotlight on the transition from conventional energy systems to sustainable and clean energy systems is solar collectors, specifically flat plate solar collectors. Their prominence is due to their diverse applications in water heating systems in home appliances, heating systems in conditioned places, and their industrial use, where solar energy is converted to thermal energy. Flat plate solar collectors are characterized by their simple design, durable structure, handy configuration, and affordable cost in comparison to other solar energy applications. Still, challenges and obstacles are present, such as overall system efficiency, initial and operational expenses, and maintenance. Environmental challenges, public preferences, and the availability of space on buildings should also be taken into account when utilizing flat plate solar collectors. This study puts a significant emphasis on developing innovative systems that align with the concept of sustainability [1].The necessity of employing sustainable energy, especially solar energy, has arisen due to the concerns over depleting fossil fuels. This sparked a worldwide shift towards the emerging renewable energy because of its abundancy and compatibility with climate change initiatives despite the rise of other competing renewable energy technologies [2]. Flat plate solar collectors (FPCs) are considered the major techniques for saving and supplying thermal energy in a wide range of home applications for hot water consumption and space heating systems and industrial applications with lower thermal energy requirements [3].FPCs are a widely preferred solution because they perform well in changing climates and offer low operational and maintenance costs. Moreover, they are suitable for broader use and on an international scale, which sets them apart from other developed systems such as concentrated photovoltaics. Yet, the presence of challenges and barriers underscores the need to improve their performance by using innovative materials and advanced production systems [4]. The primary challenges facing the conversion and storage of thermal energy from solar energy in FPCs are the heat loss from the solar collectors, which can be caused by components themselves, or environmental heat loss that occurs at night. Other problems are related to material corrosion in piping and performance degradation in harsh environments, alongside environmental cost issues. To address these issues and come up with sustainable solutions, a novel approach for designing solar collectors

* Corresponding author.
E-mail: mahmood.aboretag.husain@gmail.com

DOI:10.25729/esr.2025.03.0009

Received April 22, 2025. Revised August 20, 2025. Accepted September 2, 2025. Available online November 28, 2025.

should be provided [5].There can be new ideas in designing the external shape of solar collectors, such as the rhombus shape, or enhancing the efficiency that may reach 59% in March [6], or considering another design and operation analysis of an Integrated Collector Storage (ICS) solar water heater. The heater consists of an asymmetric compound parabolic concentrating reflector trough and two concentric cylinders. The environmental footprint is analyzed through Life Cycle Assessment (LCA) to evaluate environmentally friendly and cost-effective devices with improved thermal performance and offer new perspectives on ICS solar water heater design. Methods used to evaluate thermal energy, environmental impacts, and economic results of the ICS solar water heater include a multi-criteria optimization algorithm and Life Cycle Assessment (LCA), utilizing different configuration parameters [7].The dish-Stirling configuration is commonly used in small-scale concentrated solar power plants, but its high maintenance costs and reliability issues limit its market appeal. Micro gas turbines, which are cheap, reliable, and widely available, are a promising solution. A plant simulator is crucial for predicting performance and optimizing plant operations under different conditions. This method is employed to develop a simulation tool for solar dish-micro gas turbine applications and model the solar concentrator, receiver/absorber, micro gas turbine, high-speed generator, and power electronic systems. The simulator uses quadratic programming technique and performs steady-state simulations to predict performance and ensure safe and reliable power plant operation. The results show a nominal peak efficiency of about 10% for a net generated power of about 6 kW [8]. Concentrating the solar radiation falling on the system, focusing on a specific point to collect solar radiation is considered one of the methods that concern enhancing the performance, where the part that receives the rays is fixed at a distance of 3 meters and the performance is noticeably activated for an amount of solar radiation falling with a value of 700 W/m^2 and above [9]. Another avenue to develop the solar collector system is to add inter-heat exchangers that use different fluids, in which the performance efficiency of the solar collector may reach 64% at a 1 L/min flow rate over a working period of 15 hours [10].To handle the issues facing these systems, a profound awareness and understanding is required, which can be achieved through a thorough study of the factors affecting the performance of FPCs [11]. This research analyzes the techniques that can enhance the thermal performance of solar collectors, providing valuable insights into potential solutions to overcome the obstacles [12]. This work focuses on solar collectors being an essential component of the transition to renewable energy by delivering an engineering assessment of challenges, drawbacks, and advantages.

A. Scope and Review Contributions

This paper provides an overall review of recent technologies applied in flat plate solar collectors, focusing on smart materials, environmentally friendly designs, and AI technologies. Although numerous previous studies overview these critical points, this review presents a comprehensive approach that links the developments in materials, such as nanofluids and coatings. It also addresses design improvements, such as optimal angles and improved flow pathways, alongside their integration with hybrid PV-T collectors.

The areas highlighted in this paper are as follows:

- Design adaptability, especially in regions with low solar irradiation.
- Important aspects of employing AI technologies in improving the data analysis and operations of flat plate solar collectors.
- Directions for the future research provided with overall review of nanomaterials and affordable sustainable designs.
- Critical analysis of PV-T bifacial systems, clarifying their advantages compared to conventional systems.

Thus, this review provides an important roadmap in enhancing the efficiency of thermal solar systems in the context of the transition to sustainable energies.

II. Flat-Plate Solar Collectors: Development Strategies

A. Improvement in Components and Materials

To improve the solar radiation absorption and reduce heat losses and material resistance, it is crucial to consider the components and material structure for constructing flat-plate solar collectors.

Choosing the right material for absorber plate enhances the overall efficiency. The high heat conductivity of aluminum and copper make them common in manufacturing absorber plates. This is because higher conductivity means faster heat transfer from the absorber plate to the working fluid, thus increasing the efficiency. Modern developments mostly concentrate on selective surfaces and nanocoating to reduce heat loss and improve absorption. Methods like black chrome, titanium nitride oxide, and new multilayer coatings lower emissivity and increase absorptivity. Selective coatings are shown to increase thermal efficiency by up to 10%. Clear covering that protects the absorber plate while reducing heat loss depends critically on transparency of the glass and polymer used [13]. Transparent covers in flat-plate solar collectors are of great importance in minimizing heat losses. Low-iron glass and anti-reflective coatings to improve transmittance are among recent advances. Furthermore, double or triple glazing reduces convective heat loss.

Materials for insulation, such as polyurethane foam, fiberglass, and vacuum insulation panels, are among the upgraded insulating materials used to lower heat losses from the back and sides of collectors. These materials guarantee that the system keeps more heat inside, thus improving general efficiency.

Development of improved heat transfer fluids, including nanofluids with increased thermal conductivity and stability, is the main emphasis of research here. The findings reveal that adding nanoparticles, such as $TiO_2$and Al_2O_3, to base fluids greatly increases heat transfer capability [14, 15]. The hybrid solar systems may include a porous cushion and a spiral tube designed for use with a $CuFe_2O_4$/water nanofluid motor. Experimental and numerical modeling for the system demonstrates a 22% improvement in thermal transfer (Nusselt) and nearly a 20% increase in heat flux compared to water [16].

B. Design Improvement

The efficiency of flat-plate collectors is largely influenced by their geometric arrangement. Recent research has identified ideal proportions and layouts for reducing heat losses and optimizing solar absorption through the use of computational fluid dynamics (CFD) simulations. Varied tilt angles coupled with adjusted seasonal sun angles show better energy collection in many different climatic settings. The FPC performance is evaluated using CFD analysis based on the model proposed for predicting the energy yield of south and east-west facing bifacial PV system compared with south facing monofacial system [17]. The study shows that the accuracy in the model is highest when predicting the energy yield of south facing inclined bifacial PV system. Such models can guide the deployment of bifacial PV systems.

Enhanced flow patterns like meandering and bifurcation channels are replacing conventional flow designs like serpentine and parallel flow to improve heat transfer rates and guarantee homogeneous fluid temperature distribution. Incorporating turbulators or vortex generators into flow channels leads to an increase in thermal efficiency, as convective heat transfer rises without an appreciable increase in pressure drop.

Combining flat-plate collectors with phase-change material (PCM) thermal energy storage provides constant output independent of changing solar irradiation. Together, these help reduce reliance on supplemental heating systems [18]. For example, a numerical model using ANSYS was employed to simulate a flat collector incorporating a nano-coated octadecane PCM behind the absorber plate. Results indicated better performance at a 5% nano concentration, which improved morning heat output but did not fully dissolve at night, demonstrating a mixed effect on performance [19].

Embedded storage units in modular designs allow residential and commercial applications to have better scalability and flexibility. Enhancement of optical designs and reflections by adding exterior or internal reflectors such as Compound Parabolic Concentrators (CPCs), markedly improves solar energy collection, particularly in low-sunlight hours. Improvements in anti-reflective and self-cleaning coatings help to further increase light transmission through transparent coverings, hence lowering maintenance needs.

Hybrid PVT systems, combining flat-plate collectors with photovoltaic panels simultaneously generate thermal and electrical energy [20]. This two-fold utilization maximizes land use and increases general energy output. Real-time performance monitoring and adaptive operation offered by hybrid systems coupled with IoT-enabled sensors and smart controllers facilitate maximizing the efficiency.

Applications in both urban and rural locations will find modular collector units fit as they enable simple assembly, transportation, and scalability. Flexible mounting methods combined with plug-and-play designs help to reduce system downtime by reducing the time of installation and simplifying maintenance [21, 22].

C. Improved Hybrid PVT Compounds — Bifacial PVT Compounds

Hybrid PVT systems are solar PV collectors that generate simultaneously both heat energy and electricity. Bifacial PVT system, being one of them, is a dual-sided PVT system that produces electricity from both sides of the panel. One type of these systems is equipped with a mirror reflector where air can be used as a cooling fluid. For example, there is a design of this system with a V-shaped groove that has a mirror serving as a reflector, in which air is used to cool the fluid and to enhance the heat transfer efficiency.

To study and evaluate the performance of these systems, mathematical modeling is considered as one of the critical methods. A mathematical model was applied using the first and second laws of thermodynamics to predict the energy output [23]. Data on energy yield from bifacial PV module were examined and compared to those for monofacial PV systems under the climate conditions of west Africa [17].The study utilizes an analytical mathematical model, which relies on energy balance equations. This model uses real data from Ghana in Africa in the prediction of energy yield. The model reveals that the bifacial PV system oriented to the south outperforms the monofacial PV systems. Experimental studies report that the photovoltaic thermal collector achieves an operating efficiency of 57% at a solar radiation of 863 W/m² at a mass flow rate ranging from 0.02 kg/s to 0.08 kg/s[24]. By comparison, the double-sided photovoltaic thermal collector operates at an efficiency of 70% versus 50% for the single-sided type[25].

Another study on a water based photovoltaic thermal collector is based on experimental and theoretical analysis [26].It involves physical testing and MATLAB simulations to investigate hybrid photovoltaic thermal collector that utilizes water as a working fluid and introduces a new absorber pipe design. The key findings of the work indicate a total efficiency obtained of approximately 67% [27]. The studies aim to employ the hybrid PVT collector type of solar collectors, in particular a solar-thermal collector, to cool photovoltaic cells with fluids that transfer thermal energy effectively. In some PVT designs, nanofluids are used to boost photovoltaic cell efficiency and simultaneously produce thermal energy through a hybrid method.

Integrating photovoltaic and thermal energy technologies results in a greater increase in overall efficiency when compared to two systems operating separately. This work is classified as an advanced pathway, addressing the significantly growing importance of solar energy and its role in clean renewable energies. Additionally, this field of research highlights a large group of factors, such as cell temperature and thermal energy transfer mechanisms, to enhance the efficiency and thermal performance of these systems [28].

III. Flat-Plate Solar Collector Challenges

A. *Limitations in Performance and Efficiency*

Loss of heat through conduction, convection, and radiation lowers the general efficiency. A smaller temperature difference between the absorber plate and the inlet fluid caused by the increasing temperature as the fluid enters is a major cause of the dropping thermal efficiency [29]. As the inlet fluid temperature rises, the difference in temperature between the absorber plate and fluid decreases. This leads to the reduction in heat transfer to the fluid. As a result, the absorber plate gets hotter and therefore loses more heat to the surrounding via conduction, convection, and radiation. Developing materials with low thermal emissivity and designing sophisticated insulating methods remain difficult. However, expensive, multi-layer transparent coverings with vacuum sealing demonstrate promise. Performance is somewhat reliant on the state of the weather, especially in areas with little sun irradiation or high ambient temperatures. Adaptive solutions using angle-adjustable collectors can address this restriction [30, 31].

B. *Material Degradation and Durability*

Harsh environments, such as extreme temperatures and humidity can affect material durability and cause degradation. Metals like copper and aluminum are easily corroded, particularly in humid and saline conditions. Important solutions to this problem include protective coatings, anti-corrosion treatments, and non-metallic substitutes, such as polymer composites. The durability of flat-plate solar collectors with Ni-Co coating and without coatings is examined in [32]. The results reveal that the coated Ni-Co collector is about 50% more efficient than the uncoated one, with this enhanced efficiency maintained throughout the day and evening regardless of a decline in solar irradiance in the evening. This demonstrates the durability of this coating for flat plate solar collectors.

C. *Environmental and Financial Difficulties*

Carbon footprint, particularly for metals, coatings, and manufacturing techniques, may have a major environmental effect. Carbon impact of FPCs systems can be minimized by means of lifecycle assessment (LCA).Long payback times and high starting expenses might make broad adoption difficult in underdeveloped areas. To make FPCs more accessible, governments and companies are looking at subsidies and incentives. The End-of-Life management and recycling of polymers and coatings remain a significant challenge for sustainable FPCs deployment. Innovative recycling techniques and eco-design principles gain traction in addressing this issue [33, 34].

D.Fluid Usage and Climate

There are significant challenges related to heat transfer fluids in FPCs, particularly in cold climates and hard water areas. The main of them are outlined below:

One challenge facing specialists and researchers in this field is the type of fluid used in flat-plate solar collectors and the climate conditions to which these fluids are exposed, particularly in areas with hard water. A significant concern is the freezing of these fluids in cold weather. When these fluids freeze, they expand, which can damage the pipes that transport them, potentially leading to a system failure. To mitigate this issue, some studies suggest using antifreeze agents, such as propylene and ethylene glycol, which lower the freezing point of water and enable the system to function under moderately cold conditions without freezing. However, these antifreeze fluids increase maintenance costs, as they lose their effectiveness over time and need replacing.

Sedimentation and contamination are additional challenges in areas with hard water. The presence of minerals, like magnesium and calcium, can lead to scaling inside the fluid transport pipes, hindering fluid movement and reducing the efficiency of thermal energy transfer. The accumulation of pollutants, such as biofilms, can further exacerbate the contamination issue. Some studies propose implementing cleaning programs, treating the fluids, or introducing measures to prevent sedimentation.

As these fluids are used over time, another issue arises: they may lose some of their beneficial properties due to mixing with antifreezes like glycol or fail to prevent sedimentation due to exposure to high temperatures or UV radiation. Additionally, these fluids can produce acidic byproducts that may erode certain metals in the system's structure. The viscosity of the fluids, particularly those containing glycol, can also increase, especially in frigid climates. This problem can be addressed by regularly monitoring the acidity of the fluids, scheduling timely replacements, and carefully selecting the appropriate fluid type, especially for systems operating in low-temperature environments [35–38].

IV. Future Research Approaches

Although there are numerous studies on PVT collectors, the future trend should focus closely on cost-effective advanced materials integrated with smart technologies that improve the overall performance efficiency.

A. Novel Materials

The development of lower-emissivity and higher-absorptivity nanostructured coatings, for example, graphene, carbon-based nanomaterials, and biopolymers, show a promising potential for improving thermal qualities. Investigation of transparent coverings based on biopolymers will aid in increasing the sustainability and lessening the reliance on fossil fuels. Research of self-cleaning coatings is crucial to lower maintenance needs and enhance performance in dusty surroundings [39, 40].

B. Compatibility with Novel Technologies

1) Hybrid Solar Systems

The studies explore combining FPCs with hybrid PVT collector systems for simultaneous thermal and electric energy production. Applications demanding both heat and electricity find hybrid systems especially appealing. Integration with Internet of Things (IoT) is one of the strategies for real-time collector performance enhancement. By means of temperature, fluid flow, and weather condition data offered by IoT-enabled devices, proactive maintenance, and efficiency enhancements are made possible [41, 42].

2) Nanofluids

The studies demonstrate that flat-plate solar collectors are highly effective with a variety of developed fluids, particularly nanofluids. Nanofluids consist of tiny particles that disperse evenly within the fluid, enhancing heat transfer efficiency. These fluids possess higher thermal conductivity and heat capacity compared to other fluids commonly used in solar collectors. However, it is crucial to handle them carefully to prevent sedimentation and corrosion problems over time [43, 44].

3) AI Integration in Solar Collectors

The integration of AI in the development of solar collectors enhances both the operating and control systems. AI algorithms can accurately predict optimal flow rates based on operating conditions, maximizing thermal efficiency. Additionally, these algorithms can forecast maintenance needs and potential malfunctions, allowing for proactive measures to prevent issues before they arise [45, 46].A study confirms the effectiveness of applying artificial intelligence (AI) as a promising method through studying the electrical and thermal efficiency of PVT collectors operating with nanofluids [47]. The accuracy of the AI generated models in predicting thermal and electrical efficiency is assessed by introducing a value of correlation coefficient (R2). Three models were generated namely, extreme gradient boosting (XGB), extra tree

TABLE 1. Comparative Efficiency

Collector Type	Average Thermal Efficiency (%)	Operation Conditions	Notes
Flat Plate Collectors (FPCs)	45–70	Standard outdoor testing	Low cost, widely available
Evacuated Tube Collector (ETC)	60–75	Cold climates	Better for diffuse radiation
PVT Hybrid Collector	50–65 (thermal) 10–20 (electrical)	Under sunlight + cooling	Combines heat and power
CSP with PCM	70–85	Concentrated solar input	High cost, stable storage

regression (ETR), and k-nearest Neighbor (KNN). The XGB model accuracy reached 0.99997 and 0.99995 for electrical and thermal efficiency, respectively. The ETR model accuracy stood at 0.99999 and 0.99999 for electrical and thermal efficiency, respectively. The KNN model accuracy was 0.92682 and 0.94726 for electrical and thermal efficiency, respectively. These results indicate that integrating AI models into renewable energy technologies is a promising way for parameter prediction. Another study demonstrates the high accuracy of AI models predicting the electrical efficiency of solar PVT systems [48]. The researchers generated a model that used over 350 data samples from literature on PVT systems using water as a working fluid. The results show that the models can be applied to improve the efficiency prediction of solar PVT collectors.

4) Coatings and Advanced Materials

The development of materials and coatings with superior thermal properties increases the heat absorption from radiation on solar collectors. This improvement enhances the efficiency of solar collectors, particularly in colder regions where solar radiation is weaker. Importantly, applying these coatings to the absorbing panels of solar collectors does not involve complex techniques. In contrast, effective solutions can be achieved through simple and straightforward methods [49, 50].

Consideration is also given to the cost reduction strategies proposed in the studies on reasonably priced substitutes for coatings and absorber materials. Investigating composite materials with thermal performance comparable to metals, for instance, manufacturing process optimization, enables the improvement in price and scalability. Additive manufacturing (3D printing) is explored as a possible alternative for manufacturing intricate components with little waste [53].

C. Climate– Adapted Designs

The studies focus on the creation of regionally tailored designs to handle different climatic conditions, including desert regions or those with excessive humidity. These designs include improved cooling systems and anti-condensation strategies. Ideas on modular construction are proposed, providing simple transit and installation at far-off locations [51, 52].

D. Policy and Regulatory

Support is needed in creating regulations that foster the adoption of FPCs through subsidies, tax incentives, and mandatory renewable energy goals. Development of criteria for certification and performance tests is key to guaranteeing dependability and quality [54].

V. COMPARISON OF CATEGORIES AND OPERATORS

A comprehensive scientific comparison of some types of solar collectors included in previous studies can be made in terms of thermal performance, operating factors, and variables. Table 1 compares various types of solar collectors in terms of thermal efficiency, operational variables, and technical characteristics. As seen in the Table, the flat-plate collectors (FPCs) have an efficiency ranging from 45% to 70% and is a low-cost and widely used option. The evacuated tube collector (ETC) achieves higher efficiency in cold climates due to its ability to absorb diffuse radiation. The hybrid PVT collector combines thermal (50–65%) and electrical (10–20%) efficiencies, enhancing the overall system benefit. Finally, the concentrated solar power (CSP) collector supported by phase-change storage materials (PCM) stands out with its high efficiency of up to 85%. High radiation concentration and high operating costs are necessary, but advanced storage technologies allow for high thermal stability.

VI. INCONSISTENCIES AND UNRESOLVED DISPUTES IN THE LITERATURE

The following key points summarize some of the conflicting issues related to the studies:

- Contradiction remains regarding whether nanofluids have a positive effect on improving the thermal efficiency of solar collectors or whether the effect is negative due to obstruction.
- Scientific opinion differs regarding the performance of photovoltaic/thermal cells when operating under partial shade conditions.
- There is no clear consensus in researchers' conclusions regarding the best type of material to use in PCM applications in specific climate zones.

VII. FUTURE TECHNOLOGICAL DEVELOPMENT PATH IN THE ENERGY SECTOR

The evolutionary diagram (Fig. 1) compellingly shows the significant strides made in solar thermal energy technology over the years in four major areas: enhancing coating technologies, which progressed from standard black paint to selective coatings and finally to innovative nanocoatings; evolving systems from single collectors to hybrid photovoltaic/thermal (PVT) systems, and subsequently to intelligent systems utilizing artificial intelligence; advancing storage technologies from basic thermal storage to phase-change materials, culminating in efficient chemical storage; and revolutionizing control systems from manual operations to automated tracking, ultimately integrating IoT and machine learning systems.

VIII. PRINCIPAL CONSTRAINTS IN EXISTING STUDIES

A thorough review of the studies reveals the following limitations and weaknesses:

- The data available from the studies are limited to short-term observations and are considered as weak regarding nanoscale thermal absorption materials.
- The scientific analysis of the scalability of solar collectors, especially hybrid ones, is quite inadequate with multi-layer collectors facing even greater deficiency in research.
- Most studies that focus on practical applications do not fully model performance, operation, and maintenance costs.

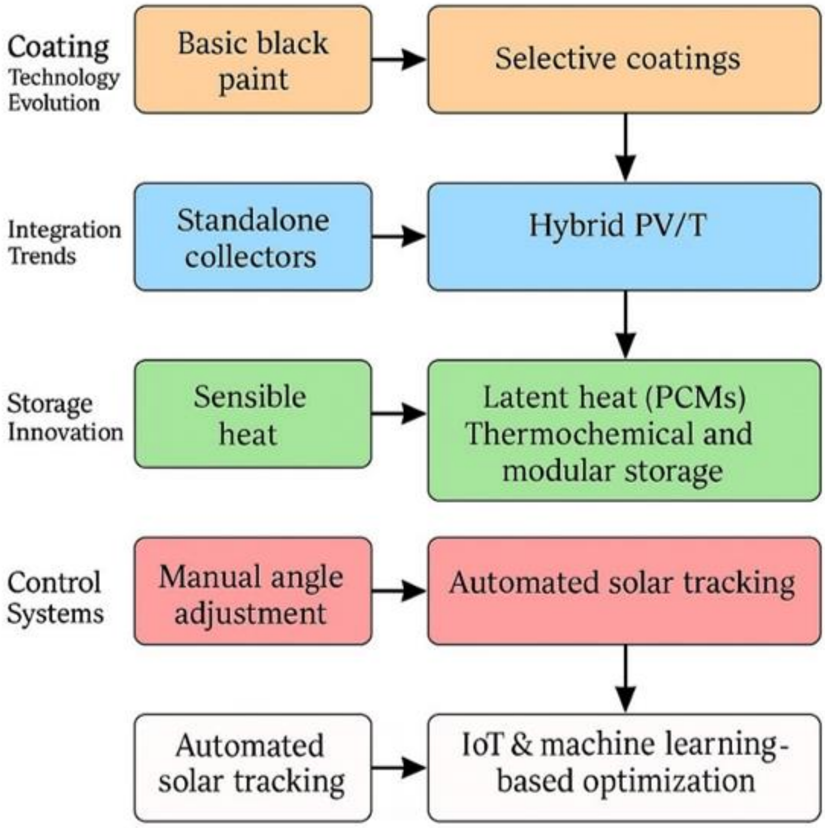

Fig. 1. Conceptual map of technological development.

- The evaluation of the thermal performance of solar collectors in terms of weather factors and geographical diversity is insufficient and requires enhancement.

IX. Future Pathways of Addressing Key Challenges

Based on a review of previous research addressed in this study, the following innovations are expected to address key issues in solar photovoltaic and thermal (PVT) systems:

- Adopting nanoscale coatings to reduce the degradation of materials exposed to high thermal energy, especially ultraviolet radiation.
- Using phase-change materials (PCMs) and combining them with solar collectors to better control and improve thermal energy and performance.
- Leveraging artificial intelligence, smart tracking systems, and intelligent operation to increase the efficiency of solar collectors.
- Developing hybrid systems, such as solar thermal systems integrated with photovoltaics, as well as concentrated solar power systems integrated with energy storage systems, to provide more realistic and scalable options and solutions.

X. Conclusion

Flat-plate solar collectors are still an essential component of the worldwide transition to renewable energy. Their simplicity, cost-efficiency, and adaptability make them suitable for diverse applications spanning industrial thermal energy systems and home water heating. Improvements in materials, design optimization, and integration with contemporary technology over years have greatly improved their performance and expanded their use.

To fully utilize these potential benefits, however, it is essential to tackle persistent challenges like heat losses, material deterioration, and financial constraints. Promising avenues to overcome them include innovations in advanced materials, hybrid system integration, and climate-specific designs. Furthermore, adopting smart technology and using sustainable manufacturing techniques will be crucial for increasing the lifetime and efficiency of flat-plate solar collectors.

Future studies should concentrate on designing affordable and sustainable methods to raise the acceptance of FPCs across many uses and areas. Scaling up these technologies and reaching worldwide renewable energy objectives would depend much on cooperation among academics, legislators, and businesses. Flat-plate solar collectors can greatly contribute to building a sustainable and energy-efficient future by addressing current problems while taking advantage of the possibilities offered by contemporary advancements.

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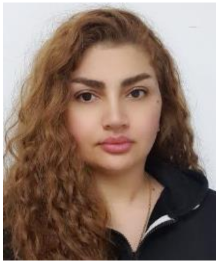
Aya A. Saad, born in Baghdad in 1995, holding B.Sc. in Energy Engineering from the American University of Iraq Sulaimaniyah in 2019, and MSc in Energy Engineering from University of Baghdad in 2023, current job is lecturer at the Middle Technical University of Baghdad/ Department of Artificial Intelligence Engineering Techniques. My research interest is on energy engineering, specifically renewable energies including solar and wind energies, and the production of hydrogen fuel from renewable energy resources.

Mahmood H. Khaleel, born in Baghdad in 1983, holds a B.Sc. in Refrigeration and Air Conditioning Engineering Techniques from the Northern Technical University in Kirkuk, Iraq (2007), and an M.Sc. in Thermal Engineering Techniques from the Middle Technical University in Baghdad, Iraq (2014). He is an assistant professor and currently serves as the head of the Mechanical Techniques Department at Kirkuk Technical College of Polytechnic, Northern Technical University, Kirkuk, Iraq. His main fields of specialization include building thermal performance, building envelope technologies, refrigeration systems, air-conditioning systems, solar collectors, and the utilization of clean and renewable energy sources.



Aveen M. Abdulwahaab, born in 1986 in Kirkuk, holds a B.Sc. in Petroleum Engineering from Kirkuk University in Kirkuk, Iraq (2009), and an M.Sc. in Engineering Management from Gedik University in Istanbul, Turkey (2021). She is a teaching assistant and currently serves as the department head deputy in the Mechanical Techniques Department at Kirkuk Technical College of Polytechnic, Northern Technical University, Kirkuk, Iraq. Her main fields of specialization include petroleum engineering, engineering management.

Shereen E. Kaska, born in 1973 in Iraq, holds a B.Sc. in Mechanical Engineering (University of Technology, Baghdad, 2004) and an M.Sc. in Thermal Engineering (Technical College, Baghdad, 2012). She previously worked as a laboratory engineer and assistant lecturer in the fields of mechanical engineering, refrigeration and air conditioning, and fuel and energy engineering at technical colleges in Baghdad and Kirkuk. She also gained industrial experience as a mechanical engineer at Bluefiregas Company in Sulaymaniyah. Her main fields of interest include thermal engineering,