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Energy Management Using Hybrid Solar Systems: A Study of Their Efficiency in Electricity and Heat Production

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Keywords:
Energy Management; Solar energy; Hybrid system; Photovoltaic/ Thermal (PVT).

Highlights:

- *PVT systems achieved 15.71% electrical efficiency (+22% vs. PV).*
- *PVT systems achieved 84.40% total thermal efficiency.*
- *30–40% lower installation costs compared to PV-only systems.*
- *Effective in high-irradiance regions, such as Jordan.*
- *The system meets 60% of heating and 100% of cooling demands.*
- *Integration of PCMs and HJT cells reduces temperature-related efficiency losses.*

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Abstract: Photovoltaic (PV) systems have gained prominence as critical tools for climate change mitigation and carbon emission reduction. These systems utilize static converters and proportional-integral controllers to regulate active and reactive power, while energy storage batteries enhance power quality by stabilizing electrical parameters (current/voltage). This study investigates a hybrid photovoltaic/thermal (PVT) system that co-generates electricity and heat using dual heat-transfer fluids with integrated thermal storage. Outdoor validation demonstrated that the hybrid cooling collector significantly reduced panel operating temperatures, achieving a maximum electrical efficiency of 15.71% in February—representing a 22% increase over conventional PV panels. Under balanced air-water flow conditions, the system attained 69.25% heat recovery efficiency and 84.40% total thermal efficiency. Deployed across four sites, PVT systems met 60% of residential heating demands and, when integrated with absorption chillers, 100% of cooling requirements. With installation costs 30–40% lower than PV-only equivalents, these systems offer a cost-effective solution for high-irradiance regions. Key factors for solar forecasting model development are identified, and findings provide actionable guidance for designing integrated energy management systems. The study positions PVT technology as a sustainable alternative for solar-rich regions, augmented by AI-driven optimization for adaptive energy networks. Future research priorities include cross-regional validation, advanced materials development, and policy frameworks for scaled deployment, collectively advancing the global transition toward renewable energy resilience.

إدارة الطاقة باستخدام أنظمة الطاقة الشمسية الهجينة: دراسة كفاءتها في إنتاج الكهرباء والحرارة

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الخلاصة

أصبحت أنظمة الطاقة الشمسية الكهروضوئية (PV) تحظى بشعبية متزايدة بسبب تغير المناخ والحاجة إلى تقليل انبعاثات الكربون. تتحكم المحولات الثابتة ووحدات التحكم التناسبية التكاميلية في القوى النشطة والتفاعلية. تحسن بطاريات تخزين الطاقة جودة الطاقة من خلال تخزين التيار والجهد. درس الباحثون نظامًا هجينًا للطاقة الشمسية الكهروضوئية/الحرارية (PVT) يقوم بتخزين الطاقة الحرارية ويستخدم سائلين لنقل الحرارة. أشارت الاختبارات الخارجية إلى أن المجمع الهجين للتبريد يخفض درجة حرارة اللوحة بشكل كبير. في فبراير، وصلت الكفاءة الكهربائية القصوى إلى ١٥,٧١٪، وهو ما يزيد بنسبة ٢٢٪ عن كفاءة اللوحة العادية. كان النظام أيضًا بكفاءة ٦٩,٢٥٪ في استعادة الحرارة و٨٤,٤٠٪ في استعادة الحرارة الكلية عندما تم الحفاظ على معدلات تدفق الهواء والماء كما هي. يمكن لأنظمة PVT تلبية ٦٠٪ من احتياجات التدفئة و١٠٠٪ من احتياجات التبريد في المنازل المنتشرة عبر أربعة مواقع. هذه الأنظمة أقل تكلفة بنسبة ٣٠٪–٤٠٪ مقارنة بأنظمة الطاقة الشمسية فقط. يتم اقتراح عوامل دراسية لتطوير نماذج التنبؤ بالطاقة الشمسية. يمكن أن توجه نتائج هذا التقييم الأبحاث الحالية حول تصميم وتنفيذ أنظمة إدارة الطاقة المتكاملة وتأثيرها على أنظمة الطاقة.تُبرز النتائج أنظمة PVT كبديل مستدام وفعال من حيث التكلفة للمناطق ذات الإمكانات الشمسية العالية، بينما يمهد دمج الذكاء الاصطناعي الطريق لأنظمة طاقة أكثر ذكاءً وتكيفاً. تشمل اتجاهات البحث المستقبلية التحقق عبر المناطق، وتطوير المواد المتقدمة، وإطارات السياسات لدعم النشر على نطاق واسع. يساهم هذا العمل في الانتقال العالمي نحو مرونة الطاقة المتجددة من خلال معالجة التحديات التقنية والاقتصادية في تقنيات الطاقة الشمسية الهجينة.

الكلمات الدالة: إدارة الطاقة، الطاقة الشمسية، النظام الهجين، الكهروضوئي/الحراري (PVT).

1.INTRODUCTION

The global shift toward renewable energy necessitates innovative solutions to enhance efficiency and reduce costs. Hybrid PVT systems, which co-generate electricity and heat, have emerged as a sustainable alternative to conventional PV systems. Recent studies highlight their potential to reduce carbon footprints while addressing energy poverty in off-grid regions [1–3]. Despite advancements, challenges such as thermal inefficiency and high upfront costs persist. This study investigates PVT systems with PCMs and dual-fluid cooling, focusing on their application in Jordan—a region within the "solar belt" with 2,700–3,000 annual sunlight hours [4]. An extensive assessment was performed to reduce energy costs by cycling. Efforts have concentrated on minimizing energy costs through the improvement of operations, governance, and strategies for hybrid sustainable energy systems [5-7]. Hybrid power generation systems have emerged as a vital component in fulfilling electricity requirements. The proposed framework amalgamates many technologies and constitutes one of the most efficacious methods for supplying electricity to remote areas, such as islands, where the electrical infrastructure is nonexistent [8-11]. Wind power is predominantly the most cost-effective choice among renewable energy sources. Notwithstanding the expected substantial rise in the incorporation of renewable energy into the power mix, the rate of collaboration remains comparatively low compared to other non-renewable energy sources (Erdinc and Uzunoglu, 2012; Bhandari et al., 2015). Moreover, sustainable energy technology must be included in power systems to augment reliability, enhance dependability, boost efficiency, and diminish volatility [12-15]. A distinguished cohort of specialists has assessed the critical importance of renewable energy sources worldwide. Sustainable energy sources were anticipated to comprise approximately 30% of global energy production by 2020. The inconsistent availability of these assets and the electrical properties of generators pose a considerable hurdle to the integration of renewable energy sources. An alternative control and monitoring mechanism for the optimal functioning of a hybrid renewable energy system (HRES) connected with an AC grid was proposed [16]. Despite their significant advantages, renewable energy sources possess substantial disadvantages, including production instability stemming from their heavy dependence on climatic fluctuations, which compromises their efficacy in sustainable energy conversion. Notwithstanding this conflict, it is important to augment the productivity of sustainable energy systems through performance optimization. Numerous novel enhancing techniques have been suggested in the literature [17-19]. A suitable answer to this question involves synthesizing source materials to create an independent renewable energy system known as an HRES. HRESs are far more reliable and economical than certain other environmentally sustainable energy sources that depend on a single energy source. The data firmly support the economic sustainability of the hybrid system; however, this issue should not diminish the complexity of integrating multiple sources from a technological standpoint [20-22]. The proposed PVT hybrid system is ideal for reducing power requirements and enhancing thermal efficiency. The glazed PVT configuration effectively regulates temperature under varying weather conditions by preventing overheating and enhancing cooling performance. In contrast, the unglazed PVT design is preferred for maximizing electrical output due to reduced optical losses. Phase change material (PCM) integration further improves thermal efficiency by stabilizing temperature fluctuations during peak solar exposure. Employing a finned absorber enhances PCM heat absorption capacity. In the hybrid system studied, PCM integration increased electrical efficiency by 9% and thermal efficiency by 5% relative to a baseline PVT system without PCM. Optimal PV system configuration depends on PCM container positioning, fluid channel height, and PCM thickness. As shown in Fig. 1 [23], the PCM container is fabricated from corrosion-resistant stainless steel or aluminum. The economic assessment of hybrid PVT systems indicated reduced energy and carbon payback durations, as well as diminished net present values. The PVT solar energy metrics were reaffirmed for sustainable applications due to their economic viability and considerable environmental advantages. Investigations into PCM integration have been undertaken, revealing significant possibilities for enhancing PVT performance through specialized heat exchanger designs. This study evaluated the performance of a traditional photovoltaic (PV) collector against a hybrid photovoltaic-thermal (PV-T) system integrated with a phase-change material (PCM) [2٤]. The comparative analysis encompassed electrical output, environmental impact, and economic feasibility. The urgency for such efficient systems is underscored by the current energy landscape, where 85.1% of grid electricity is generated from traditional fossil fuels. These conventional sources are plagued by significant efficiency losses—including transmission, thermal, and equipment losses—that inflate power costs and necessitate additional generation to compensate, thereby exacerbating environmental pollution. Consequently, enhancing power efficiency is among the most effective strategies for reducing greenhouse gas (GHG) emissions and conserving financial resources. As illustrated in Fig. 2, under an anticipated 2050 energy scenario (33 Gt CO_2), technologies improving energy efficiency are projected to contribute a 26% reduction in emissions, alongside 45% from renewable energy sources and the remainder from other alternatives [25].

2.MODERN APPLICATION OF RENEWABLE ENERGY SOURCES

The modern development trend in the electric power industry has shown a systematic increase in the share of renewable energy sources. The most common are sunlight, wind, rain, tides, waves, and geothermal heat. To generate electricity and hot water, run the heating system, fuel vehicles, and do other things, renewable energy is used instead of traditional fuels. Due to their cost-effectiveness, renewable energy sources are becoming increasingly competitive. There are more and more studies showing that renewable energy is cost-effective, especially for people who do not get their power from a central source [26-29]. Developed countries with significant potential for renewable energy are trying to increase their energy from these sources and prioritize them in their national energy policy by putting in place several subsidy programs. In addition, countries that have scarce traditional energy sources and depend on foreign sources to meet their needs for fossil fuels, such as Jordan. The annual World Energy Investment Report states that $320 billion was put into solar energy worldwide in 2024. These investments included big projects to build solar power plants and new ideas in the field of solar energy [30].

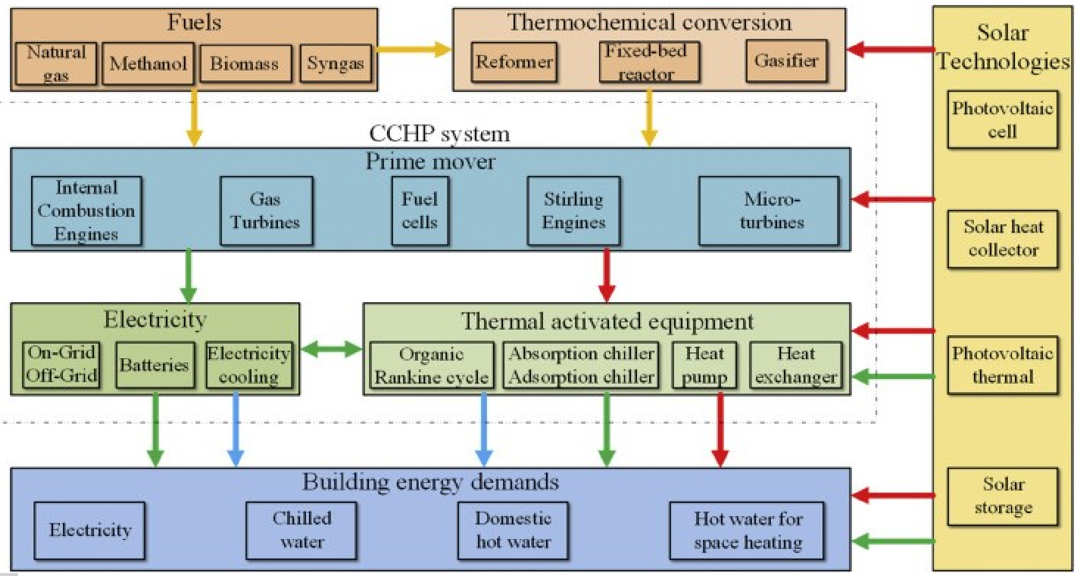

Fig. 1 Schematic of a Hybrid Solar-Assisted Combined Cooling, Heating, and Power (CCHP) System Showing Core Components: Photovoltaic/Thermal (PVT) Collectors, Phase Change Material (PCM) Thermal Storage, and Heat Transfer Fluid Circuits. Adapted from [23].

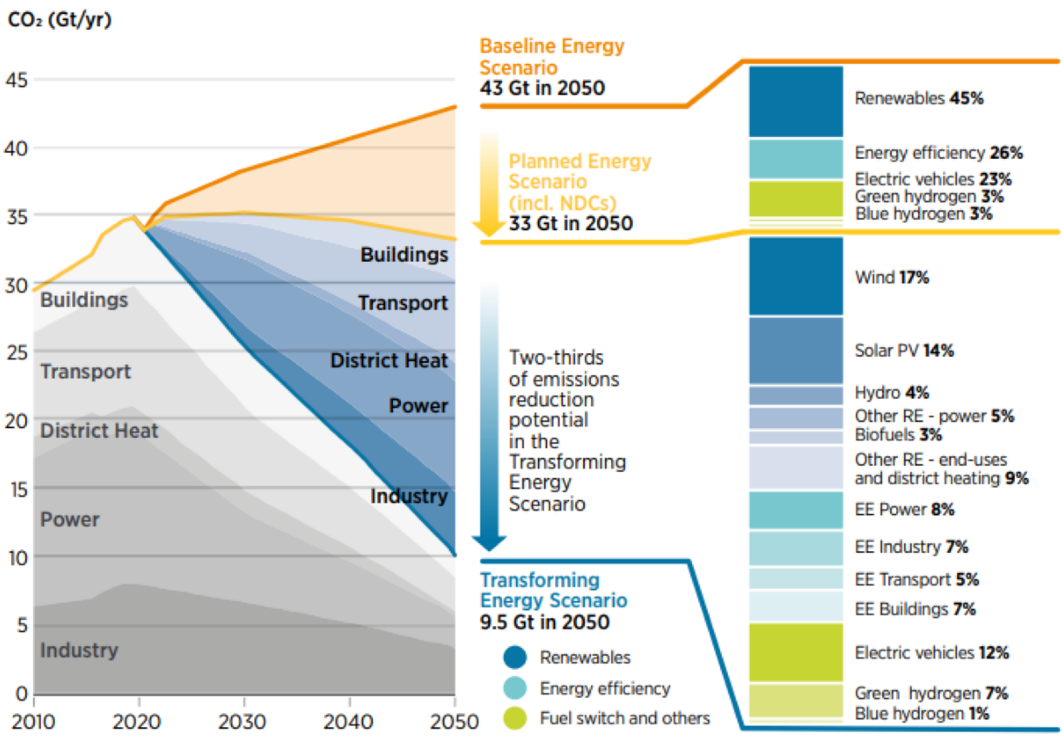

Fig. 2 CO2 Emission Reduction Potential According to Technology.

2.1.Emergence of Solar Concentrators in the Market

The first generation of energy has confirmed the assumptions of the policy because its use allows for the simultaneous generation of electrical and thermal energy (hybrid system). Such energy supply systems are becoming increasingly popular among autonomous consumers. They require small areas and generate two types of energy. Due to their simple design, they can be used almost anywhere.

3.METHODOLOGY AND EXPERIMENTATION

The research methodology was structured around a systematic framework for the optimal design and evaluation of a hybrid renewable energy system (HRES). The core objective of this framework was to configure the system components to deliver the required power output from available renewable resources while minimizing the total net present cost (NPC), all within defined technical, economic, and carbon emissions constraints. The design process was supported by specialized software that identified the most suitable system configuration based on a set of variable inputs.

The proposed systematic methodology, illustrated in Fig. 3, comprises five primary phases. The initial phase involved a preliminary feasibility study to identify viable HRES technologies capable of meeting the projected load demand. This was informed by meteorological data capturing key ambient environmental variables such as temperature, wind speed, and broader climatic conditions. A subsequent assessment of the site's renewable energy resources was conducted to tailor the hybrid system design according to their availability and potential. A critical component of the design process was the development of a detailed load profile, which quantified the kilowatt demand of the proposed system. This profile specified the load type—whether residential, commercial, or industrial—and incorporated both daily and seasonal variations in energy consumption, accounting for differences between summer and winter demand patterns. The existing conventional power supply, which would be supplemented or replaced by the HRES, was also characterized to establish a baseline. The implementation of the proposed HRES was subject to specific design constraints, including geographical limitations such as insufficient space for photovoltaic panel arrays or logistical obstacles to the construction of wind turbines. The system components considered for integration included solar photovoltaic arrays, wind turbines, diesel generators, and connections to the main electrical grid. The ultimate output of this process was a detailed quantification of the electrical energy delivered to the loads by the optimized hybrid system across its various subsystems.

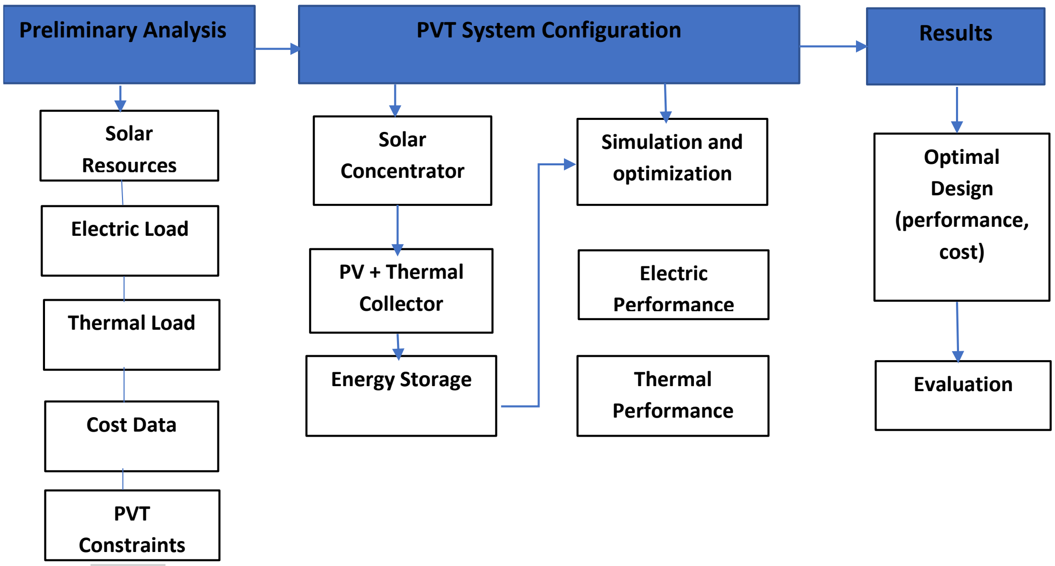

Fig. 3 Proposed Systematic Framework for Effective Planning and Design.

This study aligns with the International Energy Agency's (IEA) Solar Heating and Cooling roadmap, as the proposed solutions are projected to meet a minimum of 60% of combined space heating and domestic hot water (DHW) demands, alongside approximately 50% of cooling requirements. To enhance system autonomy and performance, the PVT system was integrated with small-scale thermally powered solar cooling devices—such as absorption chillers and heat pumps—and complemented by thermal energy storage. The typical design of such a hybrid system for electricity supply and heating is presented in Fig. 4.

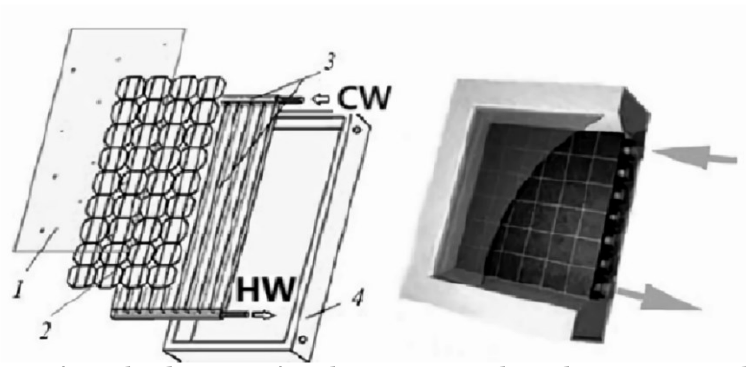

Fig. 4 Typical Design of a Hybrid System for Electricity Supply and Heating Based on Solar Energy: 1 - Transparent Insulation (Glass Covering); 2 - Photovoltaic Module; 3 - Conduit for the Movement of a Heat-Absorbing Medium, such as Water; 4 - Thermal Insulation Frame; CW, HW - Chilled and Heated Water Presently, the Advancement of Concentrators that much Surpass Holographic Efficiency is Underway: Swiss Air light Energy and American IBM Research have created a device capable of converting up to 80% of solar energy into heat and power, which was introduced to the market in 2017. Installation and maintenance do not hinder usability in hilly regions [31]. The distinctions between the FHC and other concentrators lie in its efficiency, which is mostly unaffected by the angle of inclination, and its relatively straightforward construction [32].

The investigation focused on a residential case study: a house with a 100 m² floor area occupied by 4 to 5 individuals, with a 50 m² roof area allocated for system installation. While the fundamental electrical and thermal efficiency of the PV-T system is largely technology-dependent, its total energy generation is profoundly influenced by local irradiance and climatic conditions. Electrical efficiency was observed to vary between 18.0% and 15.3%, and thermal efficiency between 60% and 50%, across operating temperatures ranging from 25 °C to 85 °C. The system employed heterojunction (HJT) thin-film photovoltaic cells due to their ability to maintain high efficiencies at elevated temperatures, currently holding the efficiency record for silicon-based solar cells at 25.6% [33]. The evaluation process involved assessing the potential electrical and thermal outputs of the PV-T system using local annual and monthly irradiance data. Four distinct system configurations integrating the PV-T with various air-conditioning technologies were examined and compared.

The economic viability of each solution was rigorously analyzed based on the levelized cost of energy (LCOE), aiming to identify the most cost-effective configuration for providing combined heating and cooling in residential applications. A schematic of the proposed PV-T system for solar heating and cooling provision is detailed in Fig. 5.

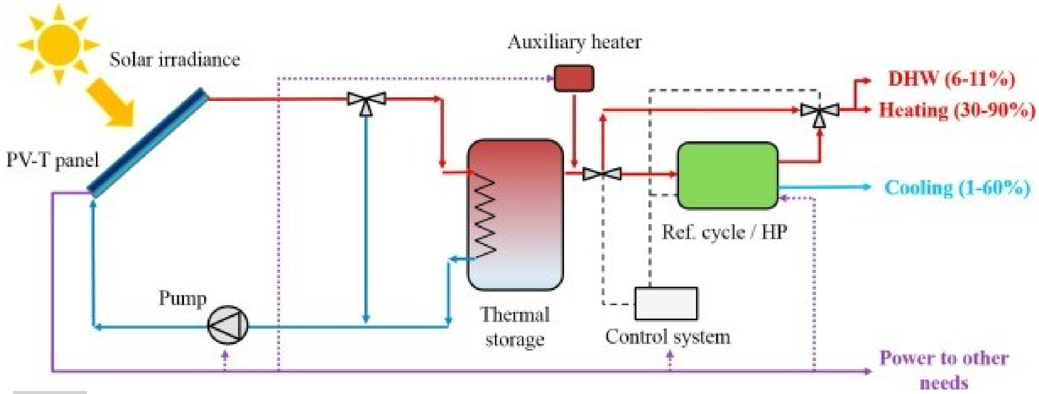

Fig. 5 Diagram of Proposed PV-T System for the Solar Heating and Cooling Provision.

The study examines a house with a 100 m² floor area, housing 4 to 5 individuals, and allocating 50 m² as a roof area for each individual's habitation. The electrical and thermal efficiency of the PV-T system is independent of location; nevertheless, irradiance and climatic conditions substantially influence total generation [34, 35] The electrical and thermal efficiencies varied from 18.0% to 15.3% and from 60% to 50%, respectively, at operating temperatures ranging from 25 °C to 85 °C. This study advocates for the use of heterojunction thin-film (HJT) photovoltaic cells, which sustain elevated efficiencies at higher temperatures and possess the highest efficiency record for silicon-based solar cells at 25.6%. This study evaluates the potential electrical and thermal outputs of PV-T systems using local annual and monthly irradiance data, examines four different system configurations that integrate PV-T with various air-conditioning technologies, and analyzes the economic viability of these solutions based on their levelized cost of energy (LCOE). PV-T systems can be optimized for the combined provision of heating and cooling in residential applications [36].

4.SELECTION OF THE PERFORMANCE EVALUATION CRITERIA SYSTEMS

The system can be assessed using three criteria: maintaining the efficiency of the solar modules at maximum solar radiation and high ambient temperatures due to cooling; achieving the optimal value of the solar module efficiency at increased water temperature at the inlet to the collector; and reducing the dimensions of the solar module, thanks to improving the design of the cooling system [37]. In the typical design of a power supply system based on renewable energy sources, such as simplified solar module designs, only a portion of the incoming energy is used to generate electricity, while the rest is dissipated as thermal energy into the surrounding space. The problem of efficient use of solar radiation incident on the module surface is solved by integrating photovoltaic (PV) panels and solar collectors (SC) into a single technological device, i.e., by creating a new hybrid type of installation. In such modules, solar energy is converted into electricity by semiconductor photoconverters, and thermal energy is retained by a thermal absorber. More complete use of incoming solar radiation (SR) energy in photovoltaic thermal modules (PVTM) and a smaller number of design elements can reduce the cost of generated energy compared to a combined PV and SC installation. During the operation of solar cells under the influence of SR, their temperature reaches high values, which significantly reduces the efficiency of electrical energy generation [38].

4.1.Planned Location of the System and Assessment of the Operating Conditions (Solar Energy Input and Daily Temperature Cycle)

A case study was conducted for a consumer in the Tafilah governorate of southern Jordan, a region where connection to centralized power grids is often unfeasible, making autonomous power supply systems essential. ideally situated within the "world solar belt," Tafilah possesses exceptional potential for solar energy development, with an annual solar irradiance of 2,700–3,000 hours and a peak solar radiation density of 4–8 kW/m² between May and August. This renewable potential is critical for the sustainable development of its predominantly rural population. To evaluate the efficacy of residential energy and hot water delivery systems, contemporary computerized design and modeling technologies were employed. This approach aligns with the methodology of Ye Win [39], whose dissertation analyzed factors influencing thermal cooling efficiency—such as ambient temperature, pipe geometry, coolant mass flow rate, and solar radiation—as summarized in

Table 1. Optimizing these parameters, particularly the coolant mass flow rate, allows for the design of a system that maximizes efficiency by regulating output temperatures and average panel component temperatures. The insights from this analysis enable the judicious selection of parameters for the subsequent design of the solar coolant supply system panels.

5.FUNDAMENTAL ATTRIBUTES OF THE ANALYZED SYSTEM

The experimental setup was built around a compact solar array comprised of thirty individual panels, each measuring 100×100 mm. These panels were configured into a matrix of three parallel rows, with each row containing ten panels. Integrated into every row were five dedicated coolant channels, each with a precise internal diameter of 2 mm, resulting in a total effective irradiated surface area of 0.3 m^2 for the entire assembly [40]. The investigation into this system's performance was structured around a multi-stage analytical process. The initial phase involved characterizing the solar energy input, the profile of which is detailed in Fig. 3, while the fundamental architecture of the solar battery cell itself is presented in Fig. 5. The core of the experimental analysis focused on evaluating two key operational parameters: the thermal efficacy of the water heating process within the solar battery's integrated cooling system and the quantification of internal pressure dynamics generated by the specialized TL-B04/S/PV pump during its operation. To model these complex interactions accurately, the study employed the pro-ASONIKA-P software suite, a dedicated tool for simulating hydrodynamic processes (a representative output is visualized in Fig. 6) [41-43]. Within this computational model, the pump was defined as a pressure source whose output was contingent upon the system's overall flow rate. A subsequent critical step was the calculation of the hydraulic resistance inherent to the network of coolant channels, a factor that directly impacts flow dynamics. The model also accounted for the significant additional pressure load imposed by the physical elevation difference between the solar panel array and the pump's location, a key design consideration illustrated in Fig. 7. The comprehensive dataset acquired from this hydrodynamic modeling was subsequently utilized to construct a detailed thermal process model. This final model describes the distribution and dissipation of thermal energy across the individual solar modules over a full daily temperature cycle, providing crucial insights into the system's thermal management performance [44, 45]. The results of this thermal analysis, including temperature variations under different coolant flow rates, are systematically presented in Table 2 and Fig. 10-11.

Table 1 Change in Thermal Efficiency of Cooling Depending on Water Consumption.

Factor	Dimension	Meaning 1	Meaning 2	η A1, %	η A2, %	Δ η A, %
m	kg/s	1.10-5	1.10-3	42	57.2	26,6
W/D	-	1.1	10	58.5	44.5	23,9
R	W/m²	200	1200	49.5	58.2	14,9
T	K	283	315	56.87	56.33	0,9
L	m	1.5	2	56.61	56.4	0,4

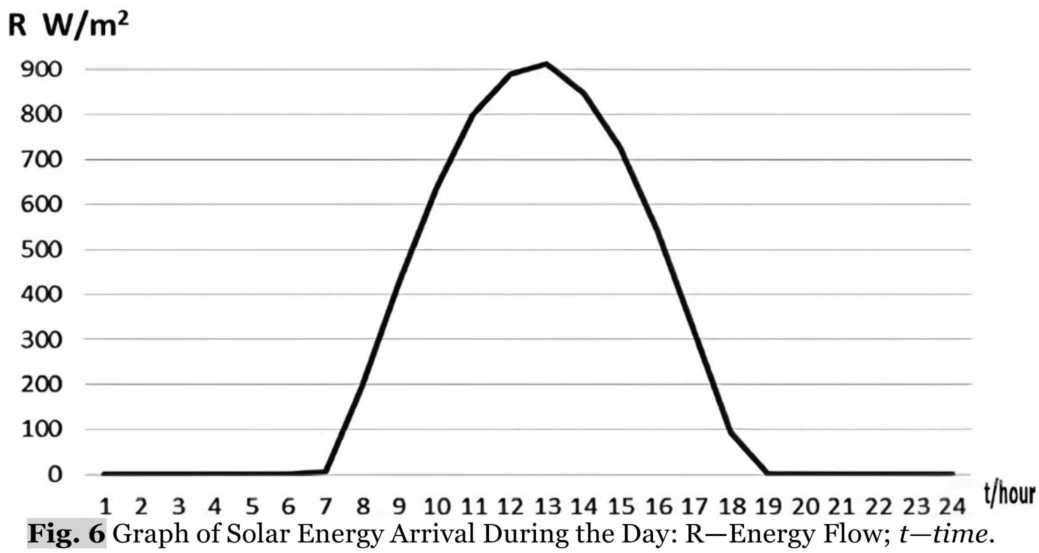

Fig. 6 Graph of Solar Energy Arrival During the Day: R—Energy Flow; *t—time*.

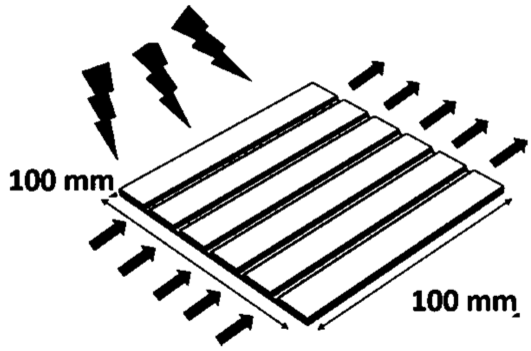

Fig. 7 Schematic Representation of the Solar Battery Cell Under Study.

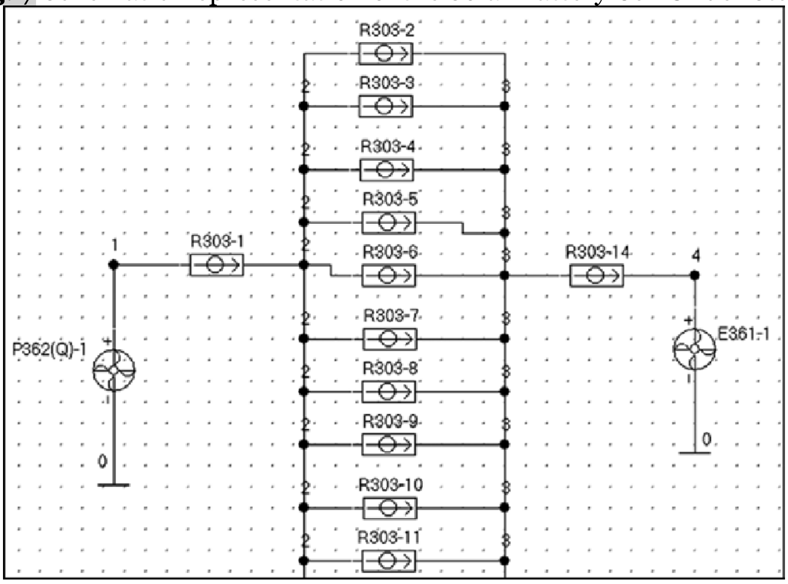

Fig. 8 Graphical Representation of the Hydrodynamic Process Model Simulated Using the ASONIKA-P Software.

The thermal behavior of the solar module is governed by a series of heat distribution mechanisms, as illustrated in Fig. 7. The primary process begins with the absorption of solar radiation, which heats the solar battery. This accumulated thermal energy is then dissipated through several pathways: a portion is emitted as radiant heat from the module's surface to the surrounding environment, while another significant portion is transferred to a liquid coolant via forced convection. Additionally, convective heat exchange occurs directly between the outer surface of the solar battery and the ambient air. Under experimental conditions, the peak solar radiation intensity incident on each individual 100×100 mm module was measured at 9.8 W. The results from modeling these complex thermal interactions are summarized in Fig. 9 and Table 2.

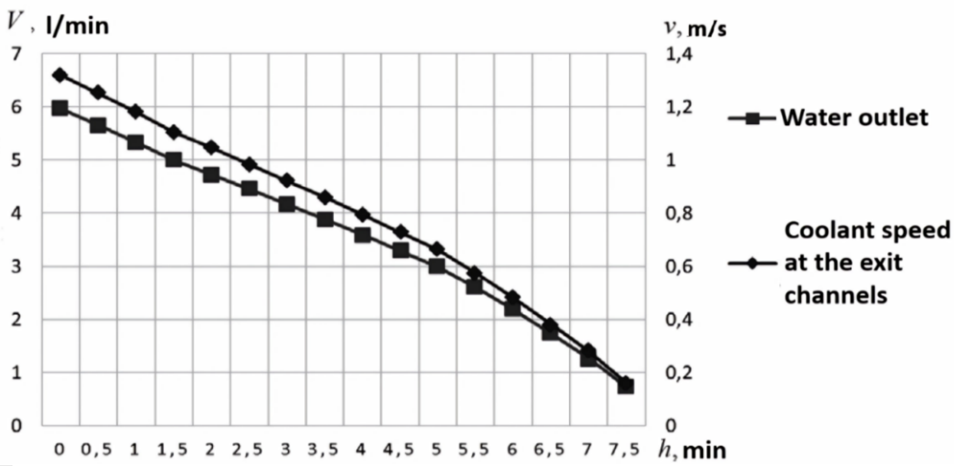

Fig. 9 Simulated Relationship between the Solar Panel's Height Relative to the Pump and the Resulting Reduction in Cooling Liquid Consumption. The Variables Water Volume (V), Height (h), and Water Velocity (v) are Depicted.

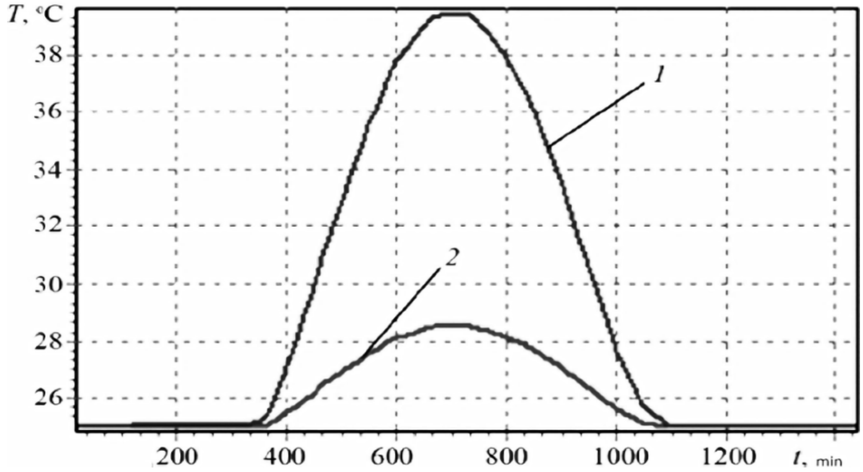

Fig. 10 Daily Temperature Profiles of the Hottest (Line 1) and Coldest (Line 2) Solar Panel Modules, Recorded with a Constant Inlet Water Temperature of 25 °C.

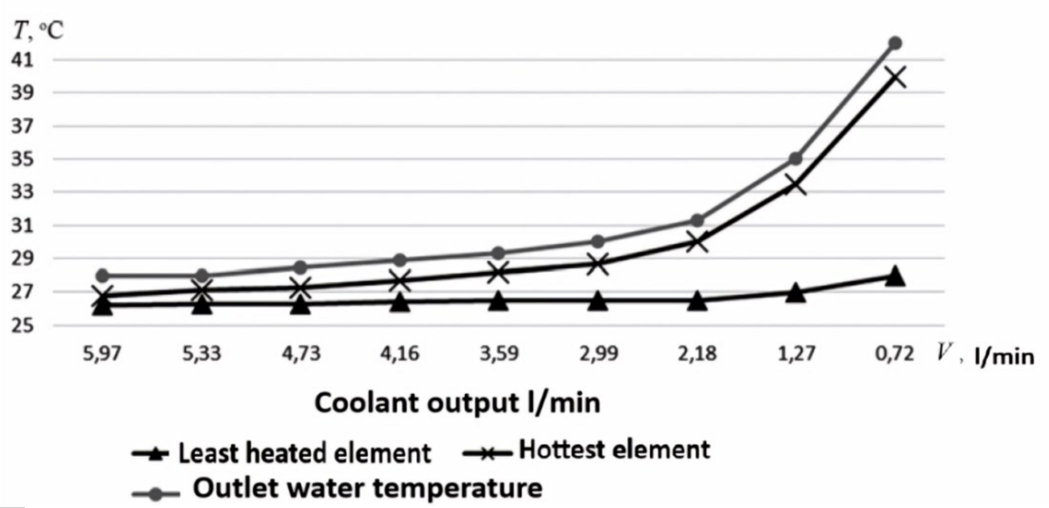

Fig. 11 The dependence of solar module element temperature (T) on the volume of pumped coolant (V).

Table 2 Temperature Dependence of the Solar Module Elements on the Volume of the Pumped Coolant (l/min).

Time t, h:min	Air Temp. (°C)	Module (no cooling) (°C)	5.97 l/min (1.2 m/s)		2.99 l/min (0.75 m/s)		0.72 l/min (0.1 m/s)	
			Min	Max	Min	Max	Min	Max
00:00	14	14	14	14	14	14	14	14
01:00	14	14	14	14	14	14	14	14
02:00	14	14	14	14	14	14	14	14
03:00	14	14	14	14	14	14	14	14
04:00	14	14	14	14	14	14	14	14
05:00	14	14	14	14	14	14	14	14
06:00	14	14	14	14	14	14	14	14
07:00	14	23	14.02	14	14	14	14	14
08:00	18	33	14.16	14.36	14.14	14.64	14.43	16.71
09:00	22	46	14.30	14.71	14.29	15.29	14.86	19.43
10:00	26	55	14.44	15.07	14.43	15.93	15.29	22.14
11:00	30	61	15.58	15.43	14.57	16.57	15.71	24.86
12:00	24	65	17.72	15.79	14.71	17.21	16.14	27.57
13:00	28	66	14.86	16.14	14.86	17.86	16.57	30.29
14:00	42	67	15	16.50	15	18.50	17	33
15:00	38	66	14.86	16.14	14.86	17.86	16.57	30.29
16:00	34	61	14.72	15.79	14.71	17.21	16.14	27.57
17:00	30	55	14.58	15.43	14.57	16.57	15.71	24.86
18:00	26	46	14.44	15.07	14.43	15.93	15.29	22.14
19:00	22	33	14.30	14.71	14.29	15.29	14.86	19.43
20:00	18	23	14	14	14	14	14	14
21:00	14	14	14	14	14	14	14	14
22:00	14	14	14	14	14	14	14	14
23:00	14	14	14	14				

6.REGULATION RULE OF ENERGY STORAGE

The expansion of hybrid system capacity and the financial reimbursement for energy fed back into the grid are constrained by a primary regulatory framework [50], which stipulates the following:

- Grid Usage Fees: Customers are subject to a 6% accounting loss for energy conveyed through the transmission or distribution infrastructure, coupled with a service charge of USD 0.1 per kWh.
- System Capacity Limitation: The installed capacity of any grid-tied renewable energy system must be sized such that its projected annual energy output does not exceed the customer's actual electricity consumption from the previous 12 months, plus an allowance for grid losses. For new subscribers without a consumption history, the applicant must provide a justified estimate of generating capacity.
- Surplus Energy Compensation: Annual energy production that exceeds 10% of the customer's own consumption is considered surplus and is not eligible for financial compensation.

Table 3 Comparing the results with those from similar studies to provide a benchmark.

Metric	Handam (Current Study)	Similar Studies	Key Differentiators
Electrical Efficiency	15.71% (+22% vs. PV)	12–14% (+10–15%)	HJT cells, hybrid cooling collector
Thermal Recovery	69.25% (heat), 84.40% (total)	60–65% (heat), 75–80% (total)	Dual-fluid heat exchange, PCM integration
Heating/Cooling Coverage	60% heating, 100% cooling	50–55% heating, 80–90% cooling	High solar irradiance in Jordan, system optimization
Cost Reduction	30–40%	25–35%	Localized c

A Study of their Efficiency in Electricity and Heat Production in PVT systems demonstrates competitive or superior performance compared to analogous studies, particularly in thermal recovery and cost-effectiveness. The results are bolstered by advanced technologies (HJT cells, PCM) and region-specific optimizations. However, geographical and climatic factors, e.g., Jordan's solar belt location, may limit direct comparability with studies from temperate or low-irradiance regions. Future work could benefit from cross-regional validations to generalize findings.

7.CONCLUSIONS AND FUTURE WORK

Solar energy stands as a cornerstone for achieving sustainable energy transitions, particularly in regions like Jordan, which benefit from high solar irradiance. The present study underscores the viability of hybrid photovoltaic-thermal (PVT) systems in simultaneously addressing electricity, heating, and cooling demands while offering cost and efficiency advantages over conventional photovoltaic (PV) systems. The integration of phase-change materials (PCMs) and heterojunction thin-film (HJT) cells has proven critical in mitigating temperature-related efficiency losses, enabling electrical efficiencies of up to 15.71% and total thermal efficiencies of 84.40%. These advancements position PVT systems as a robust solution for urban and densely populated areas, where space constraints and energy density are paramount.

This study demonstrates the significant potential of hybrid photovoltaic-thermal (PVT) systems in addressing the dual challenges of electricity and thermal energy production in high-irradiance regions like Jordan. Key findings include:

- Electrical efficiency improvements of 22% (15.71%) compared to conventional PV systems.
- Exceptional thermal recovery performance (69.25% heat recovery, 84.40% total thermal efficiency).
- 30–40% cost reduction over PV-only systems.
- Capability to meet 60% of heating and 100% of cooling demands in residential applications.

The integration of phase-change materials (PCMs) and heterojunction thin-film (HJT) cells has proven particularly effective in mitigating temperature-related efficiency losses while enhancing overall system performance.

7.1.Limitations and Future Directions

Additional Future Research Directions

Cross-Regional Validation: Extend testing to temperate and low-irradiance climates to assess PVT adaptability.

Smart Grid Integration: Investigate AI-driven demand-response strategies for hybrid PVT systems in urban microgrids.

Economic and Policy Analysis: Evaluate the impact of fluctuating energy markets and subsidy structures on PVT feasibility.

Advanced Material Development: Explore next-gen PCMs and nanostructured absorbers to boost efficiency further.

7.2.Final Remarks

Hybrid PVT systems, augmented by AI optimization techniques (POA & PSO), represent a transformative solution for sustainable energy generation. Their ability to simultaneously produce electricity and thermal energy at reduced costs positions them as a key technology for global decarbonization efforts. Future advancements should focus on scalability, AI-enhanced control, and policy alignment to accelerate adoption in both residential and industrial applications.

REFERENCES

[1] Bataineh K. **Hybrid Fuel-Assisted Solar-Powered Stirling Engine for Combined Cooling, Heating, and Power Systems: A Review.** *Energy* 2024; **300**:131506-131506.

[2] Wang J, Han Z, Guan Z. **Hybrid Solar-Assisted Combined Cooling, Heating, and Power Systems: A Review.** *Renewable and Sustainable Energy Reviews* 2020; **133**:110256-110256.

[3] Al-Husban Y, Al-Ghriybah M, Gaeid KS, Takialddin AS, Handam A, Alkhazaleh AH. **Optimization of the Residential Solar Energy Consumption Using the Taguchi Technique and Box-Behnken Design: A Case Study for Jordan.** *International Journal on Energy Conversion* 2023; **11**(1):25-25.

[4] Solar Market Research and Analysis. *Solarbuzz* 2016 Available: http://www.solarbuzz.com/facts-and-figures/retail-price-environment/module-prices.

[5] Gaeid KS, Homod RZ, Mashhadany YA, Smadi TA, Ahmed MS, Abbas AE. **Describing Function Approach with PID Controller to Reduce Nonlinear Action.** *International Journal of Electrical and Electronics Research* 2022; **10**(4):976-983.

[6] Handam A, Al Smadi T. **Multivariate Analysis of Efficiency of Energy Complexes Based on Renewable Energy Sources in the System Power Supply of Autonomous Consumer.** *International Journal of Advanced and Applied Sciences* 2022; **9**(5):109-118.

[7] Ye Win. **Study of the Efficiency of Using Solar Energy for Autonomous Power Supply Systems in the Republic of the Union of Myanmar.** Russian State Library; 2013.

[8] Handam A, Al Smadi T. **Multivariate Analysis of Efficiency of Energy Complexes Based on Renewable Energy Sources in the System Power Supply of Autonomous Consumer.** *International Journal of Advanced and Applied Sciences* 2022; **9**(5):109-118.

[9] Volovikov VV. **Use of Materials Mathematical Modeling in Professional Creativity in Radio Electronics.** In: *Information Technologies in Design, Production and Education: Proceedings of the Russian Scientific-Technical Conference* Kovrov: KGTA; 2002:12-13.

[10] Le ST, Nguyen TN, Bui DK, Teodosio B, Ngo TD. **Comparative Life Cycle Assessment of Renewable Energy Storage Systems for Net-Zero Buildings with Varying Self-Sufficient Ratios.** *Energy* 2024; **290**:130041-130041.

[11] Abdelsattar M, Ismeil MA, Aly MM, Abu-Elwfa SS. **Energy Management of Microgrid with Renewable Energy Sources: A Case Study in Hurghada Egypt.** *IEEE Access* 2024; **12**:3356556-3356556.

[12] Nayak SK, Nayak AK, Laha SR, Tripathy N, Smadi TA. **A Robust Deep Learning-Based Speaker Identification System Using Hybrid Model on KUI Dataset.** *International Journal of Electrical and Electronics Research* 2024; **12**(4):1502-1507.

[13] Mahmood AT, Gaeid KS, Al Smadi TA. **Direct Torque Control Space Vector Modulation for Induction Motor Driven by Matrix Converter.** *Tikrit Journal of Engineering Sciences* 2024; **31**(4):58-69.

[14] Abbas AK, Asal RA, Aboud GA, Mashhadany YA, Smadi TA. **Optimal Control Strategy for Power Management Control of an Independent Photovoltaic, Wind Turbine, Battery System with Diesel Generator.** *International Journal of Electrical and Electronics Research* 2024; **12**(3):1101-1108.

[15] Al Mashhadany Y, Al Smadi T, Abbas AK, Algburi S, Taha BA. **Optimal Controller Design for High Performance of Solar Energy for Grid-Connected Systems.** *Wireless Power Transfer* 2024; **11**(1):1-1.

[16] Smadi TA, Handam A, Gaeid KS, Al-Smadi A, Al-Husban Y, Khalid A. **Artificial Intelligent Control of Energy Management PV System.** *Results in Control and Optimization* 2024; **14**:100343-100343.

[17] Al-Sharo YM, Al Smadi K, Al Smadi T, N. YK. **Optimization of Stable Energy PV Systems Using the Internet of Things (IoT).** *Tikrit Journal of Engineering Sciences* 2024; **31**(1):127-137.

[18] Dash L, Pattanayak BK, Laha SR, Pattnaik S, Mohanty B, Habboush AK, Al Smadi T. **Energy Efficient Localization Technique Using Multilateration for Reduction of Spatially and Temporally Correlated Data in RFID System.** *Tikrit Journal of Engineering Sciences* 2024; **31**(1):101-112.

[19] Gaeid KS, Al Smadi T, Abubakar U. **Double Control Strategy of PMSM Rotor Speed-Based Traction Drive Using Resolver.** *Results in Control and Optimization* 2023; **13**:100301-100301.

[20] Ayyad S, Bani Baker M, Handam A, Al-Smadi T. **Reducing the Highway Networks Energy Bills Using Renewable Energy System.** *Civil Engineering Journal* 2023; **9**(11):2914-2926.

[21] Zapar WM, Gaeid K, Mokhlis HBM, Al Smadi TA. **Review of the Most Recent Articles in Fault Tolerant Control of Power Plants 2018-2022.** *Tikrit Journal of Engineering Sciences* 2023; **30**(2):103-113.

[22] Khaleel RZ, Khaleel HZ, Al-Hareeri AAA, Al-Obaidi AShM, Humaidi AJ. **Improved Trajectory Planning of Mobile Robot Based on Pelican Optimization Algorithm.** *Journal Européen des Systèmes Automatisés* 2024; **57**(4):1005-1013.

[23] Trrad I, Smadi TA, Al_Wahshat H. **Application of Fuzzy Logic to Cognitive Wireless Communications.** *International Journal of Recent Technology and Engineering* 2019; **8**(3):2228-2234.

[24] Takialddin AS, Al-Agha OI, Alsmadi KA. **Overview of Model Free Adaptive (MFA) Control Technology.** *IAES International Journal of Artificial Intelligence* 2018; **7**(4):165-169.

[25] Alahmer A, Alahmer H, Handam A, Rezk H. **Environmental Assessment of a Diesel Engine Fueled with Various Biodiesel Blends: Polynomial Regression and Grey Wolf Optimization.** *Sustainability* 2022; **14**(3):1367-1367.

[26] Al Smadi T, Gaeid KS, Mahmood AT, Hussein RJ, Al-Husban Y. **State Space Modeling and Control of Power Plant Electrical Faults with Neural Networks for Diagnosis.** *Results in Engineering* 2025; **25**:104582-104582.

[27] Apeh OO, Meyer EL, Overen OK. **Contributions of Solar Photovoltaic Systems to Environmental and Socioeconomic Aspects of National Development: A Review.** *Energies* 2022; **15**:5963-5963.

[28] Khan T, Yu M, Waseem M. **Review on Recent Optimization Strategies for Hybrid Renewable Energy System with Hydrogen Technologies: State of the Art, Trends and Future Directions.** *International Journal of Hydrogen Energy* 2022; **47**:25155-25201.

[29] Alami AH, Rabaia MKH, Sayed ET, Ramadan M, Abdelkareem MA, Alasad S. **Management of Potential Challenges of PV Technology Proliferation.** *Sustainable Energy Technologies and Assessments* 2022; **51**:101942-101942.

[30] Lamnatou C, Chemisana D, Cristofari C. **Smart Grids and Smart Technologies in Relation to Photovoltaics, Storage Systems, Buildings and the Environment.** *Renewable Energy* 2022; **185**:1376-1391.

[31] Khosrojerdi F, Akhigbe O, Gagnon S, Ramirez A, Richards G. **Integrating Artificial Intelligence and Analytics in Smart Grids: A Systematic Literature Review.** *International Journal of Energy Sector Management* 2022; **16**:318-338.

[32] Banu A, Bicer Y. **Review on COx-Free Hydrogen from Methane Cracking: Catalysts, Solar Energy Integration and Applications.** *Energy Conversion and Management: X* 2021; **12**:100117-100117.

[33] Klaas L, Guban D, Roeb M, Sattler C. **Recent Progress Towards Solar Energy Integration into Low-Pressure Green Ammonia Production Technologies.** *International Journal of Hydrogen Energy* 2021; **46**:25121-25136.

[34] Stevovic I, Mirjanic D, Petrovic N. **Integration of Solar Energy by Nature-Inspired Optimization in the Context of Circular Economy.** *Energy* 2021; **235**:121297-121297.

[35] Al-Rawashdeh H, Al-Khashman OA, Al Bdour JT, Gomaa MR, Rezk H, Marashli A, Arrfou LM, Louzazni M. **Performance Analysis of a Hybrid Renewable-Energy System for Green Buildings to Improve Efficiency and Reduce GHG Emissions with Multiple Scenarios.** *Sustainability* 2023; **15**(9):7529-7529.

[36] Shafiul Alam M, Al-Ismail FS, Salem A, Abido MA. **High-Level Penetration of Renewable Energy Sources into Grid Utility: Challenges and Solutions.** *IEEE Access* 2020; **8**:190277-190299.

[37] Østergaard PA, Duic N, Noorollahi Y, Mikulcic H, Kalogirou S. **Sustainable Development Using Renewable Energy Technology.** *Renewable Energy* 2020; **146**:2430-2437.

[38] Syafaruddin ZDS. **A Review of Hybrid Power Generation: Modelling-Simulation, Control Strategy and Future Trend Development.** *Journal of Engineering Science and Technology Review* 2020; **13**:249-263.

[39] Khalifa FS, Alsanad HR, Al-Hiti AS, Al Mashhadany YI, Al Smadi T. **Hybrid Design of Phase Frequency Detector Applied in Phase Locked Loop to Eliminate Dead and Blind Zones.**

International Journal of Electrical and Electronics Research 2025; **13**(1):25-29.

[40] Erixno O, Rahim NA, Ramadhani F, Adzman NN. **Energy Management of Renewable Energy-Based Combined Heat and Power Systems: A Review.** *Sustainable Energy Technologies and Assessments* 2022; **51**:101944-101944.

[41] Al Shammary DA, Al Mashhadany Y, Algburi S. **Study and Analysis for High Performance of Hybridization Floating Solar Panels Technique with Hydropower.** *Tikrit Journal of Engineering Sciences* 2025; **32**(1):1-8.

[42] Lauka D, Haine K, Gusca J, Blumberga D. **Solar Energy Integration in Future Urban Plans of the South and Nordic Cities.** *Energy Procedia* 2018; **152**:1127-1132.

[43] Khoshkbar-Sadigh A, Smedley KM. **The Necessity of Time-Series Simulation for Investigation of Large-Scale Solar Energy Penetration.** In: *2015 IEEE Power and Energy Society Innovative Smart Grid Technologies Conference (ISGT)* IEEE; 2015.

[44] Fraunhofer Institute for Solar Energy Systems. **Fraunhofer ISE: Photovoltaics Report.** Freiburg: Fraunhofer ISE; 2019.

[45] David TM, Silva Rocha Rizol PM, Guerreiro Machado MA, Buccieri GP. **Future Research Tendencies for Solar Energy Management Using a Bibliometric Analysis, 2000-2019.** *Heliyon* 2020; **6**:e04452-e04452.

[46] Gomaa MR, Mustafa RJ, Al-Dmour N. **Solar Thermochemical Conversion of Carbonaceous Materials into Syngas by Co-Gasification.** *Journal of Cleaner Production* 2020; **248**:119185-119185.

[47] Cox S, Xu K. **Integration of Large-Scale Renewable Energy in the Bulk Power System: Good Practices from International Experiences.** Golden: National Renewable Energy Laboratory; 2020.

[48] Ahmad T, Zhang H, Yan B. **A Review on Renewable Energy and Electricity Requirement Forecasting Models for Smart Grid and Buildings.** *Sustainable Cities and Society* 2020; **55**:102052-102052.

[49] Haleel HZ, Humaidi AJ. **Towards Accuracy Improvement in Solution of Inverse Kinematic Problem in Redundant Robot: A Comparative Analysis.** *International Review of Applied Sciences and Engineering* 2024; **15**(2):242-251.

[50] Energy and Minerals Regulatory Commission. **Legislation and Regulation.** Amman: EMIRC; 2022.