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RESEARCH ARTICLE

Advancements in internet of things integrated solar thermal systems

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Abstract

This paper investigates how the Internet of Things (IoT) can transform solar thermal systems, which is a critical gap in the research because it offers a robust literature review of the integration of IoT since 2010 and 2024. This work is important because it has provided a detailed discussion on the role of IoT in improving real-time monitoring, automation, predictive maintenance, and energy management of photovoltaic panels, solar dryers, solar stills, and solar heaters. An approach of systematic review had been utilized, and more than 142 studies were analyzed to determine the trends, challenges and developments in the field. The findings show that there is a significant growth of the implementation of Solar PVT systems (5% in 2010 and 75% in 2024), energy efficiency, fault detection, and smart grid integration. Moreover, further IoT applications in the field of sustainable energy presence are shown by the development of AI-based optimization, remote access over the cloud, and P2P energy trading. Although these advantages exist, the task of cybersecurity risks, interoperability and high implementation costs still exist. This review brings forward the most efficient software products used in analyzing IoT-based solar, such as the MATLAB/Simulink, LabVIEW, and internet of things platforms, such as the Amazon Web Services (AWS) IoT and Google Cloud IoT. The results can be of great benefit to the researchers and industry participants, as the writers claim that more developments should be made in AI, blockchain security, and low-power IoT devices to fully utilize the potential of IoT in solar thermal use as part of the industry 4.0 model.

Keywords: IoT-based solar energy optimization, predictive maintenance in solar thermal systems, solar still, solar dryer, solar water heater, pv-panel

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1. Introduction

The advances in the IoT-based solar thermal systems are a significant breakthrough in the energy sector based on renewable sources and smart technologies. IoT-integrated solar thermal systems use various sensors and special connectivity which form the technology more efficient and flexible. They combine solar-thermal laws with IoT so the system can monitor various parameters. Remote control features let operators adjust settings instantly based on weather or energy needs. Continuous data from IoT sensors also supports predictive maintenance, helping identify problems early, reduce downtime [1] [2][3].

Smart algorithms powered by IoT data allow solar thermal systems to respond to changing climatic conditions and energy consumption patterns. Dynamic modifications, such changing collector angles or adjusting heat storage, help to improve energy efficiency and overall system performance. IoT-enabled solar thermal systems may connect smoothly with energy storage technologies, improving thermal energy management and consumption. This integration ensures a continuous energy supply, even during periods of low solar radiation [4][5]. Data collected from IoT sensors can be evaluated with advanced analytics tools. Data analytics insights help to improve system design, operation, and overall efficiency on a constant basis. The incorporation of IoT provides users with simple interfaces

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for tracking and managing solar thermal systems. These systems can interact with other smart devices and systems for energy management thanks to interconnectivity, which makes the energy system more extensive and networked [6,7].

Smart grids may easily incorporate IoT-integrated solar thermal systems, making the energy distribution network more adaptable and durable [8]. By responding to grid needs, these technologies assist the integration of renewable energy into mainstream power networks and help maintain grid stability. IoT-integrated solar thermal systems minimize environmental impact and lessen dependency on non-renewable energy sources by optimizing energy output and consumption. Improved performance and efficiency help achieve the more general objectives of climate change mitigation and sustainability [9–11].

In order to minimize energy costs, Ahmadi et al. [12] investigated coordinating electricity consumption with the intermittent profile of solar-based renewable resources. Addressing the uncertainty related to thermal loads in smart buildings is the main innovation of the suggested model. This is accomplished by adding load categories, such as ventilation, heating, and hot water loads. Buildings become adjustable loads instead of passive consumers in the context of smart grids, supporting demand-side energy management. In the context of Internet of Things (IoT) applications, smart houses enable building energy systems to operate as active loads in smart grids. The development, testing, and Internet of Things (IoT) deployment of a multi-source ambient energy harvesting system using thermal and radiofrequency energy, written by Bakytbekov et al. [13]. The author describes a multi-source ambient energy harvesting device that can use daily temperature variations and radio frequency signals to power Internet of Things sensor nodes. By combining RF and thermal energy harvesters into a single module that protects against any deterioration in each other's performance, the author accomplishes complex system integration.

An IoT-powered thermal heating monitoring system for buildings was created by Correia et al. [14]. The arrangement of these photonic sensors in the context of luminescent solar concentrators, which are widely suggested to incorporate energy-producing elements into structures like windows or facades, has been shown by the author. The author of this study created a mobile sensor that has been smoothly incorporated into the Internet of Things (IoT) environment. The author's development of a self-powered system that can measure, record, and send data to an intuitive website is part of this integration.

Vahidinia et al. [15] studied a parabolic trough collector using a Syltherm-800–based hybrid nanofluid containing Al_2O_3 and SiO_2. The results show that hybrid fluid performs better than pure Syltherm-800 and single-nanoparticle fluids. It increases energy efficiency by about 5.2% and exergy efficiency by about 5.5%, and it achieves the highest PEC value of 1.76, indicating stronger overall performance. At 600 K the hybrid nanofluid gives the best results among all tested options.

The performance of a parabolic trough solar collector using Ag - ZnO/Syltherm 800 hybrid nanofluid was investigated by Ekiciler et al. [16] tested Ag–ZnO/Syltherm 800 and two other hybrid nanofluids in a parabolic trough collector at 500 K. All three hybrid fluids showed better heat transfer than pure Syltherm 800. Higher nanoparticle amounts improved performance, while very high Reynolds numbers reduced efficiency. Papingiotis et al. [17] used syltherm 800/CuO and H_2O/CuO nanofluids in photovoltaic elements based solar collector. This study analyzed the performance of a concentrating solar collector with an asymmetric reflector, comparing two receivers—one with photovoltaic cells on both sides and one without. A numerical model using COMSOL integrated three-dimensional optical and thermal analyses. The study examined the effects of CuO/water and CuO/Syltherm 800 nanofluids on thermal efficiency for the non-PV receiver and both thermal and electrical efficiencies for the hybrid receiver. Nanoparticle concentrations of 3% and 5% were tested with inlet temperatures ranging from 20°C to 80°C for the hybrid system and up to 140°C for the thermal system. Nanofluids improved performance over base fluids.

Panagopoulos et al. [18] investigated a cost-effective data acquisition system designed for solar thermal collectors. In this study, the author conducted the design and testing of a decentralized, budget-friendly Advanced Driver Assistance System (ADAS) using the ESP32 microcontroller and open-source software. The system, devised by the author, is suitable for experimentally characterizing water (or air) operated solar thermal collectors, aligning with the ISO 9806:2017 standards. Furthermore, it is adaptable to sensors with lower. The outcomes indicated that the system proposed can obtain precise measurements of high quality and offering real-time access to data.

Maraveas et al. [19] investigates the progress and future trajectory of intelligent and solar greenhouse covers. This study concerns investigating materials for greenhouse coverage with a focus of intelligent PhotoVoltaic (PV) systems. The study assessed the correlation of various smart covers, heat loading and IoT by optimizing these material properties to mitigate the operational cost of greenhouses.

The analysis clearly shows development into IoT applications for smart solar thermal coverage, despite noting significant progress, much remains to be achieved and more work is required. The chapter reviewing the IoT application in solar stills highlights the advantages of implemented intelligent control, real-time monitoring, and predictive maintenance. Through sensor integration, IoT in solar dryers can provide process optimization and sustainability. The paper highlights that IoT has played a transformative role in almost all aspects of the PV panels including predictive maintenance, energy optimization, fault detection and integration with smart grids. The incorporation of I in solar heaters is presented as state-of-the-art, providing real-time data for remote control and intelligent decision-making. Overall, the report acknowledges the significant impact of IoT and imagines a more efficient and sustainable future for renewable energy technologies as IoT develops.

This article examines how the Internet of Things (IoT) facilitates solar thermal systems and provides a comprehensive state-of-the-art by reviewing IoT integration from 2010 to 2024. Based on an analysis of 142 research publications, the study emphasizes the prospective trends, difficulties, and advancements in IoT-based solar technologies, including photovoltaic (PV) panels, solar dryers, solar stills, and solar heaters. The work fills a major research gap in literature by contributing to topics including real-time monitoring, automated systems, maintenance planning, and IoT energy management. The deployment of solar PVT systems increased from 5% in 2010 to 75% in 2024, according to the findings, along with advancements in energy efficiency, identifying faults, and smart grid connectivity. IoT's growing significance in sustainable energy technologies is further demonstrated by developments in AI-driven optimization techniques, cloud-based remote access, and smart energy trading. However, there are still obstacles to large-scale applications, such as high deployment costs, interoperability problems, and cybersecurity risks.

The study finds the best software tools for IoT-based solar analysis, including LabVIEW, MATLAB/Simulink, and IoT platforms like Google Cloud IoT and Amazon Web Services (AWS) IoT. Even though IoT has made significant strides in solar applications, further study is required to improve security through blockchain solutions, provide AI-driven analytics, and optimize energy software in real-time. Adoption is still hampered by ineffective problem detection, poor predictive maintenance capabilities, and expensive implementation.

In order to increase efficiency, security, and scalability, future research should concentrate on AI-based system optimization, blockchain for safe transactions, open-source IoT frameworks, low-power hardware, and sophisticated fault detection. Integrated Internet of Things (IoT) improves optimization of processes and sustainability in sun dryers and has proven useful for intelligent control and predictive maintenance in solar stills. IoT enables problem diagnostics, energy management, predictive maintenance, and smart grid integration in PV panels. IoT makes it possible to collect data in real time for solar heaters, allowing for intelligent decision-making and remote monitoring.

This paper highlights how IoT is revolutionizing the solar energy industry by bridging the gap between renewable energy and Industry 4.0. The results highlight the need for ongoing developments in AI, blockchain security, and low-power IoT devices to optimize IoT's possibilities in solar thermal applications, offering insightful information to researchers and business people.

2. Methodology

The study follows a simple step-by-step process, and Figure 1 shows this flow clearly.

- i Problem Identification: Identify limitations in current solar thermal systems, focusing on efficiency, real-time monitoring, and data acquisition.
- ii Literature Review: Analyze existing studies on IoT applications in renewable energy systems and solar thermal technologies to identify research gaps.
- iii Comparison of IoT Cloud Technologies: In this section, reader can find the detailed comparison of different IoT cloud technologies. The functionality and implementation of various cloud systems are elaborated in order to give the readers knowledge about the working of cloud and its suitability in integration with IoT based solar thermal systems.
- iv Mathematical Relations: This section illustrates the key mathematical relations useful to this study. Among these are formulas for calculating the thermal efficiency of various solar thermal fields. These relations can be used by readers to analyse and evaluate system performance.
- v Some Previous Work on IOT Based Solar Thermal System: This section discusses the status of IoT-integrated solar thermal systems by summarizing previous studies. The review highlights opportunities and obstacles in the integration of IoT with the solar thermal system.
- vi Different Software Commonly Used in Research on IoT: Their application in IoT-integrated research is briefly discussed, as well as the software tools that are commonly used. When it comes to the analysis and simulation of IoT-based solar thermal systems, there are numerous software available; this section provides an insight into commonly used software.
- vii Allocation of Reviewed Papers Used in Current Manuscript: This part describes the number of reviewed papers that appear in the manuscript. It organizes studies based on the type of solar thermal systems studied, allowing readers to see the research background clearly.
- viii Conclusion: The paper concludes by presenting important recommendations to enhance the utilization of IoT in solar thermal systems. Additionally, it examines the potential of IoT to drive further progress in solar energy research and its practical applications.

This stepwise methodology ensures systematic exploration, innovative design, and practical evaluation of IoT-integrated solar thermal systems.

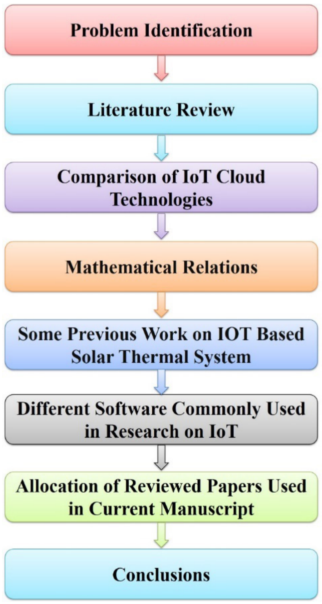

Figure 1. Flow chart of methodology of current manuscript

3. Applications for IoT in solar dryer

The integration of the IoT (Internet of Things) technology into solar dryers is an important development that provides several benefits and improves the drying process. The use of IoT enhances the effectiveness and performance of the traditional solar dryer [20]. Add sensors to measure such crucial parameters as solar radiation, humidity, and temperature. Use the moisture sensors to monitor the drying process of the materials in the solar dryer. Sensory information may be analysed with the help of IoT analytics tools. Acquired knowledge can lead to better performance, more efficiency of energy use, and optimality of processes. By performing constant system health checks, the IoT integration allows predictive maintenance [21][22]. Early detection of the problem reduces the downtime and reduces the chances of a major equipment failure. The solar dryer system can be operated remotely and automatically at any place that has got an internet connection. The users are able to diagnose remotely, adjust parameters and initiate or halt drying processes [23]. By enhancing efficiency, control, and sustainability, the creation of solar dryers that are IoT-based proves to be revolutionary in changing the traditional drying methods.

Miano et al. [24] studied the performance of an IoT-based solar dryer with the assistance of a data logger and a setup incorporating SMS notification features. Authors studied the performance and efficiency of a drying system for Sardinella fish. The SMS notifications enhance the system's monitoring and notification capabilities, facilitating efficient data collection and display through both physical and remote monitoring. Consequently, the integration of IoT technology into conventional sun drying can aid in mitigating the challenges and drawbacks encountered by farmers engaged in fish drying. A block diagram of an IoT based box type solar dryer is shown in Figure 2.

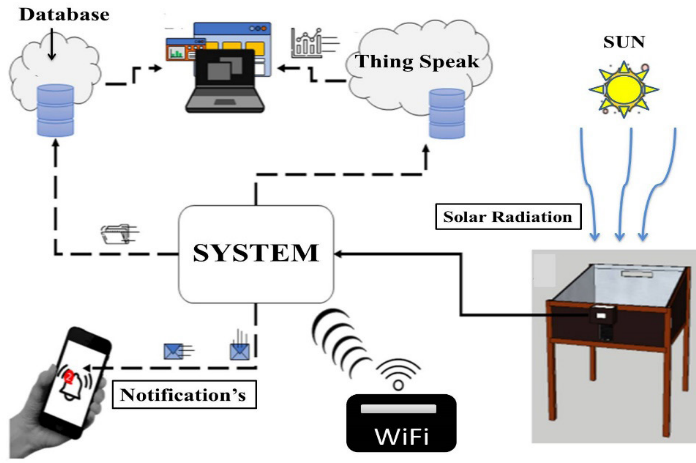

Figure 2. Block diagram of IoT based box type solar dryer [24]

Patil et al.[25]compared the data obtained from IoT technology and the digital reader of the solar dryer while drying banana pieces or slices. They found that the temperature readings differed by only 0.32% to 3.11% between the IoT-based sensor and the digital sensor, falling within the range of ±1 to 2 °C. Regarding humidity, the highest percentage of variation in readings between the sensor and the humidity meter was 1.41%. The arrangement of the setups is shown in Figure 3.

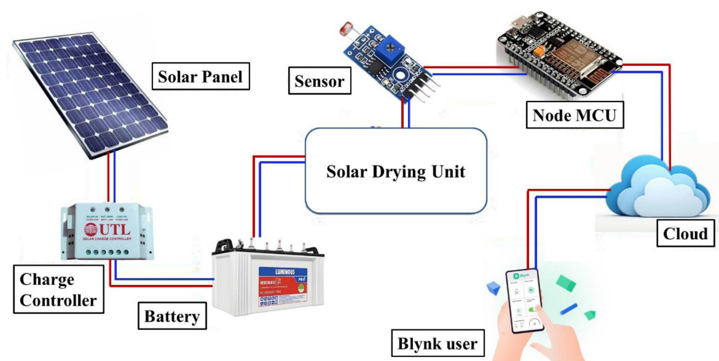

Figure 3. Design of the IoT based solar dryer [25].

Elwakeel et al. [26] conducted a comparative analysis of the open solar dryer and the automatic solar dryer (ASD) for date fruit. DHT-22 sensors were employed to measure and regulate temperature and humidity at different positions within the dryer. Utilizing DHT-22 sensors and Bluetooth units, data from the setup could be effortlessly received on both a smartphone and a laptop. Through the IoT system, the weight of date fruits was automatically transmitted to the smartphone at hourly intervals, allowing for remote operation of the dryer fan. Schematic diagram of the setup is shown in Figure 4 (a) and (b) shows the different DHT-22 sensors positioned at various locations within the solar dryer. Some previous work on IoT based solar dryers is listed in Table 1.

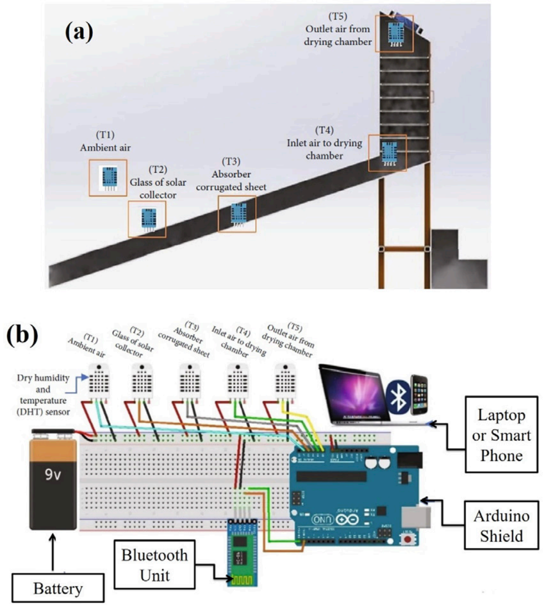

Figure 4. (a) Schematic diagram of the dryer with different positioned sensors, **(b)** DHT-22 sensors are positioned at various locations within the solar dryer. [26]

Table 1. Previous work on IoT based solar dryer system

S. No.	Author(s)	Study Title	Key Focus/Objective	Methodology	Key Findings/Outcomes
1.	B.López-Velasco et al. 2024, [27]	IoT-Driven Monitoring and Prediction of Banana Moisture Content in a Solar Greenhouse Dryer	Utilizing IoT technology to monitor and forecast the moisture levels of bananas during drying in a solar greenhouse environment.	IoT sensors for environmental monitoring, machine learning models for moisture prediction, and data analysis to optimize drying	IoT and predictive models improved drying efficiency and moisture control accuracy in solar greenhouse dryers.
2.	G. Srinivasan et al. 2021, [28]	IoT in Solar Dryers for Agricultural Products	Enhancing energy efficiency in solar dryers	IoT integration with thermal storage	Increased thermal efficiency and precise monitoring
3.	I. Joel Miano, et al. 2023, [29]	Optimizing Drying Efficiency Through an IoT-based Direct Solar Dryer System	Enhancing solar drying efficiency through IoT technologies such as web data logger and SMS notifications for real-time monitoring.	Used Arduino Uno, ESP-32, and GSM modules to monitor temperature and humidity.	Maintained optimal drying conditions, enhanced usability through SMS and web applications, and improved overall reliability compared to traditional methods.
4.	S. Balachandran et al. 2023, [30]	Design and Analysis of IoT-Based Solar Dryer for Sustainable Farming	Development of an indirect solar dryer integrating IoT and energy storage systems.	IoT-enabled monitoring systems with energy storage technologies.	Improved drying efficiency, enhanced sustainability, and optimized resource use for agricultural applications.
5.	Meena Ugale et al. 2022, [31]	IoT-Based Solar Dryer and Irrigation System	Integration of solar dryer with irrigation	IoT sensors and GSM module for monitoring	Efficient resource use and remote monitoring
6.	Brijesh Sharma et al. 2022, [32]	IoT-Based Crop Classification for Solar Drying	Crop classification for solar drying	Deep learning integrated with IoT	Improved crop classification accuracy
7.	V. Ngo et al. 2021, [33]	Design and Construction of IoT Solar Dryer	Developing IoT-enabled drying for jerky	IoT-enabled temperature and humidity sensors	Improved drying efficiency and product safety
8.	S. Nikumbh et al. 2021, [34]	IoT-Based Solar Energy Dryers	Innovations in solar energy storage	IoT and renewable energy integration	Increased drying speed and renewable energy use
9.	S.Obayopo and O.I. Alonge, 2018, [35]	CFD Analysis of IoT Solar Dryer	Computational modelling of IoT-enabled dryers	IoT and CFD integration	Accurate drying simulations and real-time data
10.	T.Hue Duong et al. 2021, [36]	IoT-Based Drying for Sustainable Development	Sustainability in food drying	IoT-based real-time monitoring	Enhanced sustainability and energy savings

4. Application of IoT in solar still

A solar still is a passive solar desalination system that harnesses solar energy to purify water through evaporation and condensation. It operates on the greenhouse effect, where solar radiation increases water temperature, enhancing evaporation. Distilled water is produced when the water vapor is condensed on a cooled surface. Particularly in arid areas, solar stills provide an affordable and sustainable way to produce freshwater [37–43]. IoT integration in solar stills can have several benefits, including increasing the desalination process's intelligence, automation, and data-drivenness.

IoT sensor integration with solar still IoT sensors can therefore be incorporated with all the solar still's components, including the water storage units, condensation chambers, and solar collectors. A centralized control system will access real-time data on the temperature, humidity, water levels, and the sun radiation with a dispersal of communication technologies. The solar still can be remotely monitored to enable its operators to adjust it to suit their requirements. Predictive maintenance algorithms can be applied with IoT capabilities in devices to analyze the data and determine when the parts require replacement or maintenance. The downtime of the solar still is reduced through the elimination of the breakdowns. Finally, through proper integration, IoT can enhance the traditional methods of desalination to intelligent and automated systems, which are less scale dependent. The distant control, monitoring, and optimization of operations can enhance the overall performance, reduce their maintenance levels, and raise their reliability. The training, validation, and testing sets of data were randomly distributed, and the ANFIS models were developed using a hybrid learning technique that combines various functions [44]. In a different experiment, Fang et al. [45] added lenses and mirrors to a single-slope solar still basin to increase the concentration impact of solar radiation. The distilled water productivity was closely monitored throughout the experiment.

Mohamed et al. [46] developed a hybrid solar still incorporates a developed monitoring system to oversee its online progress and assess the freshwater quality by examining measured factors like pH. Utilizing IoT technology, the monitoring system transmits collected parameters (such as air temperatures, relative humidity, etc.) to the cloud for remote monitoring. Users receive status notifications, including water level in the basin and tank status, through SMS alerts facilitated by a GSM module as shown in Figure 5 and Figure 6.

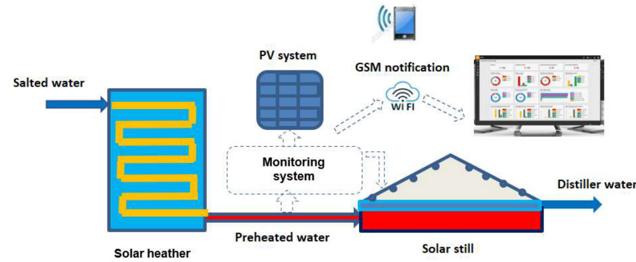

Figure 5. Advanced IoT based solar still [46]

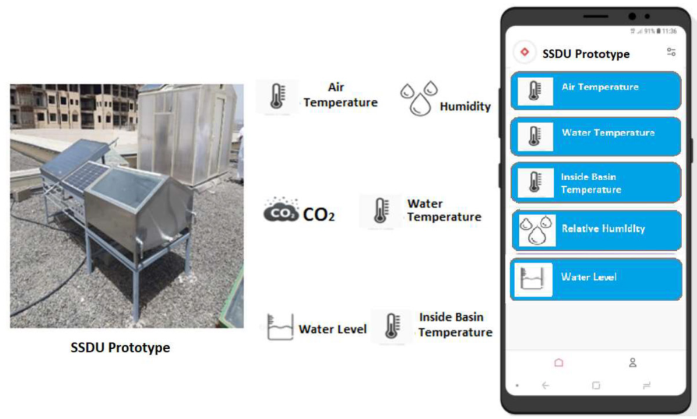

Figure 6. The primary screen of the Android application for the engineered intelligent solar still desalination system [46]

Rastegar et al. [47] study the performance of advanced heat exchanger coupled solar still. The experimental setup is fully operated with the help of data loggers and K-type thermocouples are used to collect various data. The data logger is directly connected to the desktop or laptop which provide 24 hours data of the experimental setup. The modified setups give 65.6% higher thermal efficiency as compared to conventional solar still. The experimental setup is shown in Figure 7. Some previous work on IoT based solar still is listed in table 2.

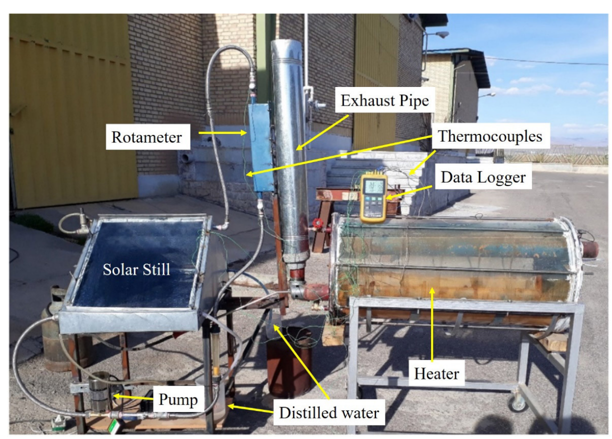

Figure 7. Solar still with heat exchanger [47]

Table 2. Previous work on IoT based solar still system

S. No.	Author(s)	Study Title	Key Focus/Objective	Methodology	Key Findings	Outcomes
1.	Alaa M. Odeh, Isam Ishaq, 2024, [48]	Integration of IoT Technologies for Enhanced Monitoring and Control in Hybrid-Powered Desalination Systems.	Develop a hybrid desalination system with IoT for real-time monitoring.	Combined solar energy with IoT-based sensor networks to monitor system performance and water quality in real time.	Solar-powered desalination reduced energy consumption; IoT integration ensured consistent water quality and immediate issue detection.	Water production: 10–12 L/day, IoT efficiency improvement: 20–25%
2.	I. Roihan and R. Artono Koestoer [49]	Data Logger Multichannel Based on Arduino-Uno Applied in Thermal Measurement of Solar Still Carocell L3000	To design and evaluate an Arduino-based multichannel data logger for thermal measurements in solar still systems.	Utilized three Arduino Uno boards with DS18B20, DHT22, and K-type thermocouple sensors to measure and store thermal data in real time.	Data loggers operated reliably for 24 hours with accurate real-time sensor readings stored on SD cards.	Thermal data accuracy achieved within ±0.5°C for DS18B20 sensors and ±2°C for K-type thermocouples.
3.	Benghanem et al. 2021, [50]	IoT-based Hybrid Solar Still	IoT-enhanced monitoring in hybrid systems	Low-cost IoT microcontroller integration for parameter monitoring	Increased efficiency and daily freshwater production with hybrid designs .	Yield: 6.5 L/day IoT monitoring improved system efficiency by 15–20%
4.	M. Benghanem, et al. 2021, [51]	IoT-based performance analysis of hybrid solar heater-double slope solar still	Remote monitoring of solar still performance	Integrated IoT monitoring system using ThingSpeak platform to analyze parameters like temperature and humidity	Groundwater desalination matched the quality of mineral and household drinking water; solar preheater enhanced evaporation efficiency	Yield: 6.5–7.0 L/day, Solar preheater increased evaporation rate by 20–25%
5.	R. D. Pimienta Barros [52]	Design and Implementation of an IoT Monitoring System for the Optimization of Solar Stills for Water Desalination	To improve the efficiency of solar distillation in La Guajira, focusing on water scarcity solutions.	Developed a prototype solar still integrated with IoT for real-time monitoring of variables like temperature, humidity, and water levels.	IoT system improved solar still efficiency to 60% using a Fresnel lens, compared to 28.27% without lenses.	Demonstrated scalability and adaptability of IoT-based distillation systems; socioeconomically benefitted La Guajira communities while aligning with UN SDGs.

5. Application of IoT in PV panels

A PV panel is a piece of equipment that uses semiconductor materials (usually silicon) to convert sunlight into electricity. It is made up of many solar cells that produce direct current (DC) power that can be used immediately or converted to alternating current (AC) for homes and businesses. PV panels are also a source of sustainable, renewable energy that lessens our reliance on fossil fuels [53][54]. The application of the Internet of Things (IoT) in photovoltaic (PV) panels involves integrating smart technologies to enhance the monitoring, management, and performance of solar energy systems. IoT enables real-time monitoring of PV panels remotely.

From the PV panel the different parameters such as voltage, energy supply, temperature and current can be remotely achieved by the help of sensors placed on the PV panel. By the help of remote monitoring system various problems generated from the solar installation site like troubleshoot and different adjustments can easily access by the sensors.

Following are some of the advantages and advancements of IoT installation on PV panels:

Predictive Maintenance:

- i The measured data on PV panels can be analyzed using IoT applications to anticipate the necessity to carry out maintenance. This assists in detecting any possible defects or inefficiency before it causes any major breakdown of the system.
- ii Predictive maintenance improves the overall reliability of the solar energy system and reduces downtime.

Energy Optimization:

- i IoT technology helps to improve energy production by calculating environmental conditions and then automatically adjusting the panel angles and other parameters.

ii Analytics help the system use up energy more efficiently. When paired with PV panels, they can determine when to store or consume energy so that the entire setup works more efficiently and the waste is reduced considerably.

Fault Detection and Diagnostics:

i IoT sensors can detect faults or malfunctions in PV panels promptly. This allows for quick diagnosis and troubleshooting minimizing system downtime.

ii Diagnostics capabilities help in identifying the root causes of issues, leading to more effective maintenance strategies.

Data Analytics and Reporting:

i IoT platforms can process large amounts of data generated by PV panels, providing valuable insights through data analytics.

ii Reporting features help in presenting performance metrics, energy production trends, and other relevant information for better decision-making.

Integration with Smart Grids:

i Integration of IoT in PV panels facilitates communication with smart grids. This allows for bidirectional flow of information between the solar energy system and the grid.

ii Smart grids can dynamically manage energy distribution, incorporating electricity generated by PV panels seamlessly.

Security and Anti-Theft Measures:

i IoT technologies can enhance the security of PV panels by incorporating features such as surveillance cameras, motion sensors, and alert systems.

ii Anti-theft measures, such as GPS tracking, can be integrated to deter and track stolen solar panels.

Environmental Monitoring:

i IoT sensors can monitor environmental conditions around PV panels, helping to assess the impact of factors like weather, pollution, and shading on energy production.

ii This information aids in optimizing the overall performance and longevity of the solar energy system.

IoT helps to improve the efficiency of the PV panels and PV panels-based applications, it also improves sustainability of the renewable energy-based systems. Due to predication of maintenance and failure of the system IoT helps reduce unwanted operational cost.

Dust particles on the PV panel greatly affect the efficiency of the panel. To keep in mind Samuel and Rajagopal [55] worked on the IoT based sensor (GP2Y1010AU0F) of optical air quality which detects the dust particles and automatically clean it from the panel surface. This IoT based sensing device has an infrared emitter and a diagonally positioned phototransistor. The configuration is designed to identify dust particles on the surface of the solar panel by analyzing the average reflection of dust. The findings from the proposed system suggest that maintaining regular cleaning of the PV module could lead to an increase in the measured output voltage ranging from 9% to 18%. The proposed setup is shown in Figure 8.

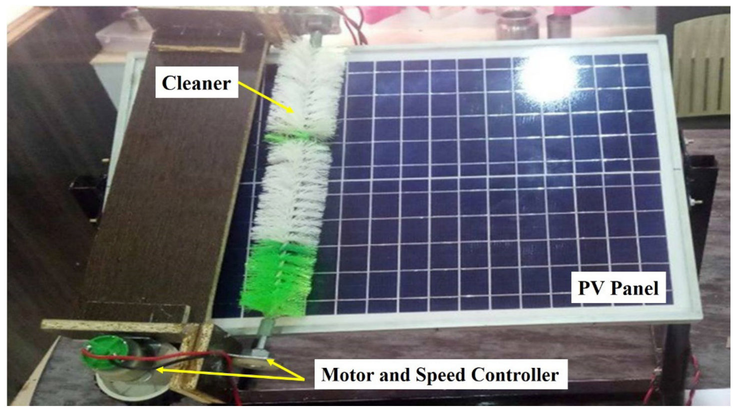

Figure 8. PV panel with cleaning system arrangement [55]

El-mawla et al. [56] developed an automatic power supply control system from PV panels to power grid. Authors utilized a Wi-Fi network and mobile application for communication, control and data collection from various sensors. This smart grid system enhances energy distribution across different units and aids in controlling potential serious and hazardous accidents in power plants. The smart grid systems with PV panel are shown in Figure 9.

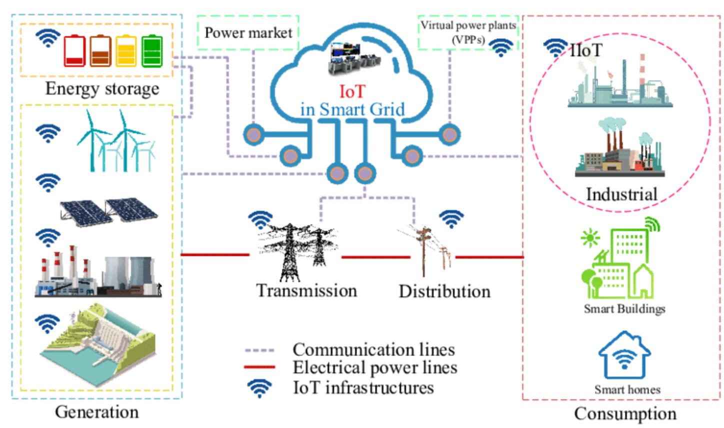

Figure 9. Smart grid system with PV panel [56]

Basnet et al.[57] and Balakrishnan et al. [58] focused on the fault detection system of the PV panel. The performance of the PV panel may be reduced by various faults such as soiling, shading, degradation, and various electrical faults. Sensors are employed to detect these faults, and based on the collected data, machine learning algorithms predict the faults and suggest maintenance. This helps in reducing maintenance costs and predicting potential further damage or downtime. The block diagram of fault detection and diagnosis system is shown in Figure 10. Some previous work on IoT based PV panel is listed in Table 3.

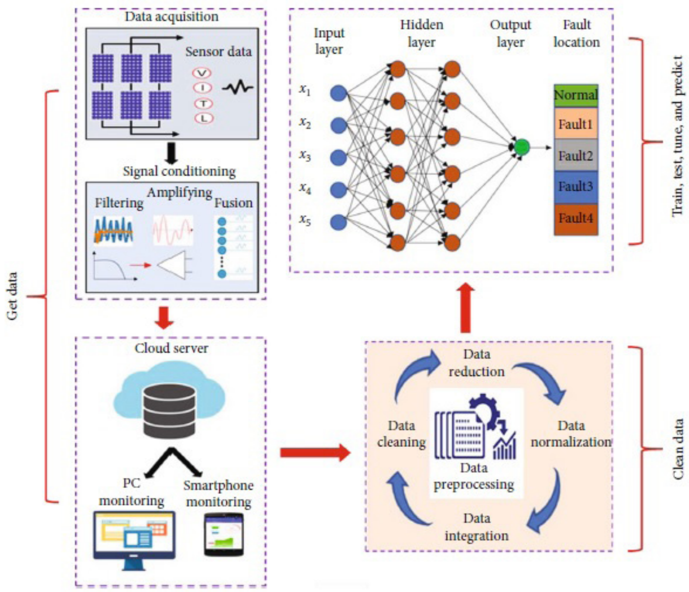

Figure 10. Block diagram of fault detection and diagnosis system [57]

Table 3. Previous work on IoT based PV panel

S. No.	Author(s)	Study Title	Key Focus/Objective	Methodology	Key Findings
1.	M. T. Ágreda et al. 2024, [59]	High-Performance IoT Module for Real-Time Control and Self-Diagnose PV Panels	To design an IoT module for individual PV panel monitoring, self-diagnosis, and optimization under daylight and dark conditions	Developed an IoT module with local processing, Wi-Fi/BLE communication, distributed algorithms, and active panel control. Included functions like I–V curve tracing, anomaly detection, and dark EL testing automation. Verified through simulations and experimental tests.	Enabled real-time control and precise monitoring at a high rate for individual PV panels. Automated EL testing significantly reduced inspection costs. Demonstrated edge computing capabilities for partial-shading anomaly detection. Potential for cost-effective implementation in PV farms.
2.	A. K Yadav et al. 2024, [60]	Design of Novel IoT-Based Solar Powered PV Pumping Systems for Agricultural Applications in Diverse Climatic Zones of India	To develop a solar-powered IoT-based irrigation system tailored for diverse Indian climatic zones, improving efficiency and water management in agriculture.	Developed an automated irrigation system using soil moisture sensors, GSM modules, and Arduino programming. System performance analysed across five climatic zones (hot, cold, humid, etc.) in locations like Jaisalmer and Bangalore.	Performance ratio ranged from 0.514 to 0.739. Pump efficiencies were 57.10% (temperate) to 58.60% (hot/humid zones). Farmers' survey revealed 80% approval. System losses varied from 0.27 to 0.37 kWh/kWp/day. Bangalore showed minimum performance ratio, while Jaisalmer showed maximum.
3.	M. K. Pitchai et al. 2024, [61]	IoT-enabled EMS for Grid-Connected Solar PV-fed DC Residential Buildings with Hybrid HBA-DCGNN Approach	To minimize electricity costs in grid-connected solar PV-fed DC residential buildings while ensuring comfort and appliance functionality.	Proposed a hybrid HBA-DCGNN approach combining Honey Badger Algorithm for power flow optimization and DCGNN for predicting solar PV generation and demand. Evaluated the approach in MATLAB and compared with RFA, SOA, and WHO.	Reduced electricity costs to **$1.12**, outperforming RFA ($1.17), SOA ($1.24), and WHO ($1.30). Optimized appliance scheduling and energy storage system management while maintaining indoor comfort and efficient PV power utilization.

4.	C. K. Rao et al. 2024, [62]	A Literature Review on IoT-Based Intelligent Smart Energy Management Systems for PV Power Generation	To examine techniques and approaches in IoT-enabled intelligent energy management for PV power generation systems.	A detailed review of techniques and IoT-based energy management systems, with an emphasis on two-way communication and real-time monitoring. Future directions for energy management were discussed.	IoT-enabled Intelligent Smart Energy Management Systems (ISEMS) enable real-time monitoring and power management, achieving up to 25% energy savings through better resource utilization. Future scope includes advanced energy storage technologies and grid integration.
5.	A.S. Samosir et al. 2021, [63]	IoT-Based Solar Energy Monitoring System	To monitor and optimize PV panel efficiency remotely	IoT sensors integrated into PV panels with real-time monitoring via a web interface	Improved system efficiency by identifying power losses
6.	C. Villalobos et al. 2023, [64]	IoT for Hot Spot Detection in Photovoltaic Modules	Detecting hot spots to improve safety and efficiency of PV modules	AI and IoT systems with temperature and current sensors	Hot spot detection enabled better maintenance and reduced energy loss
7.	Sundaram et al.	Development of IoT-Based PV Power Plant Monitoring	Real-time data analysis for solar power plants	IoT architecture with cloud storage and data analytics	Reduced downtime and enhanced predictive maintenance
8.	A. Senthilnathan et al. 2022, [65]	Fuzzy Logic Controlled 3 Port DC to DC Cuk Converter with IoT-Based PV Panel Monitoring System	To develop a 3-port DC-DC Cuk converter for solar PV and fuel cell integration with IoT-based monitoring for EVs.	Used fuzzy logic for MPPT control, integrating IoT sensors (Node MCU ESP8266, Arduino ATMega2560) with Thinkspeak for graphical monitoring; implemented on MATLAB/SIMULINK and validated in hardware.	Improved MPPT response, reduced voltage ripple, and enhanced suitability for EV applications. IoT module achieved 98% data accuracy and fast data processing (~30 seconds). Suitable for remote monitoring.
9.	M. Uzair et al. 2021, [66]	A Low-Cost, Real-Time Rooftop IoT-Based Photovoltaic (PV) System for Energy Management and Home Automation	To develop a highly efficient, low-cost IoT-based rooftop PV system that enables monitoring, control, and automation of utilities for improved energy usage.	Proposed an IoT-enabled PV system for monitoring and controlling utilities. Simulated the system's performance under scenarios with and without automation and conducted surveys to evaluate user perspectives.	Outperforms manual systems by automating load control via IoT, achieving higher energy utilization and efficiency. Reduces reliance on the grid, minimizing peak hour power demands, and cuts electricity bills. Proves scalability for large-scale applications.
10.	R. Samkria et al. 2021 [67]	Automatic PV Grid Fault Detection System with IoT and LabVIEW as Data Logger	To develop an IoT and LabVIEW-based automatic system for PV grid fault detection, monitoring, and remote control.	A 3 × 3 PV array system was used with Atmega328 for reconfiguration between SP and TCT configurations under PSC. LabVIEW environment was employed for monitoring and RF modem for data transmission. Fault status was visualized on the Blynk IoT app.	Voltage sensors identified shading and fault-induced drops in PV module performance, with system voltage reduced by up to 35% during partial shading. SP to TCT reconfiguration improved system efficiency by 12%-18%. Remote IoT-based monitoring achieved 98% fault detection accuracy.

6. Use of IoT in solar heaters

The integration of the Internet of Things (IoT) in solar heaters represents a cutting-edge application that enhances the efficiency and functionality of these renewable energy systems. Remote monitoring and control of all processes related to solar heaters using IoT technologies IoT–Enabled sensors can be used to collect real-time data on environmental conditions, sunlight intensity, and temperature. This data is sent to a central system that identifies intelligent decisions to optimize the solar heating system. By constantly tracking weather, adjustments can be made in order to absorb and use as much energy as possible.

IoT further allows for remote connectivity, so users can access and control their solar heaters through mobile devices or computers. It allows setting it up remotely, which contributes even more to convenience, and, should the need arise, allows adapting it to the environment in real-time. With the incorporation of Internet of Things technologies, solar heaters have evolved to offer advantages such as increased effectiveness, remote management, and predictive maintenance, helping power optimally sustainable and smart heating practices.

Chandrasekaran et al. [68] studied the performance of IoT based smart solar heater. This advanced solar heater senses the quality of water inters in the setup by testing the pH value of water, which helps to improve the setup performance. Other sensors help to provide the water level and temperature inside the setup. The sensor values are analyzed by the IoT cloud, which then issues instructions to the control unit of the intelligent solar system. The efficiency of the IoT-enabled solar water heating system is particularly high, making it suitable for smart homes and Industry 4.0 applications. Block diagram of an IoT-based solar heater monitoring system is shown on Figure 11.

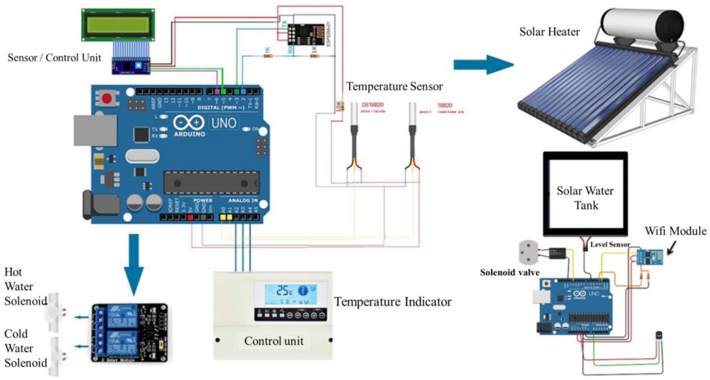

Figure 11. Block diagram of an IoT-based solar heater monitoring system [68]

Cardona et al. [69] fabricated a domestic water heater controlled by an IoT system. IoT technology assists in detecting water leakage, changes in efficiency, and various surface temperatures of the water heater. This automatically controlled water heater provides values with the help of a machine learning algorithm, and a Wi-Fi connection enables a remote-control system. The block diagram of IoT based solar heater is shown in Figure 12. Some previous work on IoT based solar water heater/evacuated tube collector is listed in Table 4.

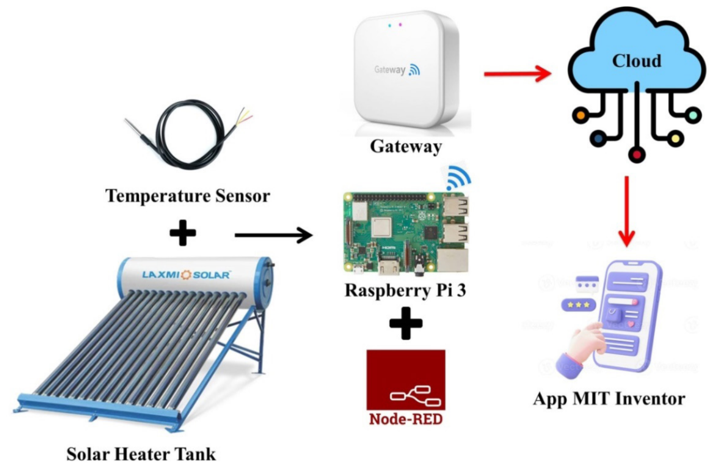

Figure 12. Block diagram of IoT based solar heater [69]

Table 4. Previous work on IoT based solar water heater system

Author(s)	Study Title	Key Focus/Objective	Methodology	Key Findings
Wen-Tai Li et al. 2021, [70]	Energy Efficiency Improvement of Solar Water Heating Systems – An IoT-Based Commissioning Methodology	To investigate and improve the energy efficiency of a solar water heating system in a hospital building in Singapore.	An IoT-based monitoring system was used to collect data on environmental and operational parameters. A comprehensive energy audit and experimental control strategies were employed for performance improvement.	- Identified inefficiencies in three subsystems: circulation system (high heat loss), solar thermal system (low solar energy extraction), and heat pump (high workload). - Proposed control strategies reduced electricity consumption by 32.9% without affecting user experience. - Experimental results validated improvements in heat loss, solar energy extraction, and workload reduction.
G. Chandrasekaran et al. 2023, [68]	IoT Enabled Smart Solar Water Heater System Using Real-Time ThingSpeak IoT Platform	To reduce cold water wastage, optimize water heater temperature, and enhance solar water heater efficiency using IoT.	Designed an IoT-enabled system with sensors for tank level, temperature, and pH. Used ThingSpeak IoT platform for data collection, analysis, and remote control.	- Reduced cold water wastage by redirecting it to the water tank. - Achieved high efficiency for smart homes and Industry 4.0. - Continuous monitoring ensured better performance analysis. - Proposed integration of edge computing for improved functionality.
E. Rosiana et al. 2022, [71]	Automatic Temperature Controller on IoT-Based Solar Water Heater	To develop an automatic temperature control system for a solar water heater, reducing energy and time waste.	Used a DS18B20 temperature sensor with a WeMo's D1 R2 microcontroller to manage water temperature, with IoT-enabled remote control via the Blynk platform.	- Achieved water temperatures of 50.25°C (10 L), 46°C (20 L), and 43.12°C (30 L). - Stability of 35°C water (30 L tank) lasted 1 hour, 19 minutes, and 51 seconds. - Sensor accuracy was 95.38%. - Automated relay control successfully maintained set point temperatures.

M. El-saggan et al. 2024, [72]	Performance Testing of an Innovative Integrated Zenithal Daylight Guide with Solar Water Heater Under Real-Weather Conditions	To develop and test a combined Zenithal Daylight Guide (ZDG) and Solar Water Heater (SWH) system for efficient energy use and cost reduction under extreme climates.	Experimental analysis of thermal and lighting performance in Aswan, Egypt, across different seasons. Integrated ZDG/SWH system with serpentine collector tested for thermal efficiency, illumination, and cost savings under real-weather conditions.	- Achieved maximum water temperature of 70°C and peak instantaneous efficiency of 37%. - Maximum daily thermal efficiency: 31.5%. - Average indoor illumination: 2470 lux, enabling 5 hours of natural lighting. - Cost savings: $90 annually, with a payback period of 2.38 years. - Daily stored heat: 1884 W.
S. A. Bari et al. 2022, [73]	Enhancement of Thermal Power Plant Performance through Solar-Assisted Feed Water Heaters: An Innovative Repowering Approach	To enhance the performance of a 200 MW thermal power plant using solar-powered heat exchangers for feed water heating via 14 case studies.	Analysis of a regenerative Rankine cycle with solar-assisted feed water heaters. Simulations in Engineering Equation Solver (EES) covering 14 scenarios.	- Maximum energy efficiency of 43.69% and power output of 261 MW achieved (Case 13). - Triple extractions yield the best improvement in efficiency and output. - Case 12 shows optimal feasibility under varying parameters.
A. Araújo and V. Pereira 2017, [74]	Solar Thermal Modeling for Rapid Estimation of Auxiliary Energy Requirements in Domestic Hot Water Production: On-Off Flow Rate Control	To develop a simplified mathematical model for solar domestic hot water systems with on-off flow rate control.	A mathematical approach using yearly climate data and hourly time steps to evaluate solar fraction (F) and auxiliary energy (SQA), avoiding complex iterative techniques. Dependency on collector area, flow rate, and storage volume analyzed.	- Solar fraction (F) increases rapidly with collector area (A) initially but levels off at high A. - Solar fraction rises with storage volume (VS) but becomes constant at high VS. - Proper insulation reduces F losses by 3%. - Simplified model achieves <2% error with hourly steps.

The integration of IoT in solar desalination, drying, PV panels, and heaters shows a shift in renewable energy use. Implementing real-time monitoring, predictive maintenance, and remote control enhance the efficiency and reliability.. From intelligent solar stills to IoT-enabled solar dryers, the findings show the transformative impact of IoT on optimizing operations and lowering maintenance costs in solar techniques.

7. Mathematical relations for calculation of efficiency of different solar thermal system

Solar thermal systems require simple metrics for comparing their effectiveness in converting sunlight into useful thermal energy. These formulas consider how much solar energy goes in and how much useful thermal energy comes out. In doing so, they also take into account factors such as the amount of sunlight available, outside temperature, heat losses and the system design. Understanding these equations is useful in identifying performance problems, optimizing resource usage and employing energy more efficiently. This type of analysis is crucial for developing solar thermal systems that are efficient, reliable and sustainable over the long-term.

7.1. Thermal efficiency of a solar collector/water heater

The efficiency of a solar collector is a measure of how effectively it converts solar radiation into useful heat energy. It is calculated by dividing the useful heat gain by the total solar energy received. Efficiency is affected by absorber material, heat losses, and operating conditions. It is an important parameter for evaluating the performance of a solar thermal system [75].

$$\eta = \frac{\dot{m} \times c_p \times (T_{out} - T_{in})}{I_{sr} \times A} \quad (1)$$

$\dot{m}$: Mass flow rate of the heat transfer fluid (kg/s)

c_p : Specific heat capacity of the fluid (J/kg·K)

T_{out} : Outlet temperature of the fluid (K)

T_{in} : Inlet temperature of the fluid (K)

A: Collector area (m^2)

I_{sr}: Solar irradiance (W/m^2)

Heat Transfer Rate in Solar Water Heater [76]Iraq. The study utilized T*SOL software focused on three different solar collector systems: Thermital, Eraslan, and Apricus, chosen based on their type of collector loop (open loop or closed loop:

$$Q = \dot{m} \times c_p \times (T_{out} - T_{in}) \quad (2)$$

7.2. Heat loss in a flat plate collector

In case of flat plate collector, heat will be lost from absorb plate to surrounding through conduction, convection and radiation. These losses depend on insulation quality, ambient temperature, wind speed, and materials emissivity. In this way, the thermal efficiency of the collector and the energy conversion performance of the whole system is improved by minimizing heat losses [77].

$$\eta_{fpc} = \frac{Q_{ue}}{A_{fpc} I_{sr}} \quad (3)$$

Where,

Q_{ue} : Useful energy,

A_{fpc} : Collector surface area,

I_{sr}: Solar radiation

Useful energy can be calculate as the given relation:

$$Q_{ue} = \dot{m}C_p\,(T_{wo} - T_{wi}) \tag{4}$$

$\dot{m}$: Fluid mass flow rate

C_p : Water specific heat

T_{wo} : Outlet temperature of water

T_{wi} : Inlet temperature of water

7.3. Electrical efficiency of PV panel (η_{PV})

The electrical efficiency of a PV panel represents the ratio of electrical energy produced to the incident solar energy on the panel's surface. It is influenced by factors such as material properties, temperature, and light intensity. Higher efficiency is achieved by minimizing resistive losses, optimizing cell design, and employing advanced technologies like anti-reflective coatings and multi-junction cells [78][79].

$$\eta_{PV} = \frac{P_{electrical}}{I_{sr} \times A} \tag{5}$$

Where

$P_{electrical}$= PV power output (W)

I_{sr} = Solar radiation incident on the PV surface (W/m^2)

A = Area of the PV surface (m^2)

7.4. Thermal efficiency of PV panel ($\eta_{Thermal}$)

The thermal efficiency of a PV panel refers to its ability to manage heat while converting solar energy into electricity. Excessive heat can reduce the electrical output due to temperature-dependent efficiency losses. Proper thermal management, such as using cooling systems or heat-dissipating materials, is essential to maintain optimal performance and enhance the panel's overall energy efficiency.

$$\eta_{Thermal} = \frac{Q_t}{I_{sr} \times A} \tag{6}$$

Where

Q_t = Collected heat, it can be obtained by the following equation

$$Q_t = \dot{m}C_p\,(T_o - T_i)$$

$\dot{m}$: Mass flow rate of fluid

C_p : Specific heat of water

T_o Water temperature at outlet

T_i Water temperature at inlet

7.4.1. Overall efficiency can be rewritten as

Multiple studies have demonstrated the overall efficiency of PVT systems using Equation (7) as a reference [80]. This efficiency denoted as η_o is fundamentally represented as the combined contribution of both thermal and electrical efficiencies.

$$\eta_o = \eta_{PV} + \eta_{Thermal} \tag{7}$$

Electrical power and thermal energy are two separate forms of energy; the former is a high-grade source as it results from the conversion of thermal energy. However, to get a more accurate evaluation of the total performance of a PVT system, Huang [81] proposed energy saving efficiency (η_f), which is mathematically given as follows in Equation (8).

$$\eta_f = \eta_{Thermal} + \frac{\eta_{PV}}{\eta_{Power}} \tag{8}$$

In this context, η_{Power} represents the efficiency of electricity generation in a conventional power plant, which is typically assumed to be 0.38 for calculation purposes.

7.5. Efficiency of solar still with heat exchanger:

The efficiency of a solar still with a heat exchanger reflects its ability to enhance freshwater production by transferring additional heat to the evaporation process. The heat exchanger improves thermal performance by utilizing waste heat or preheating feedwater, reducing energy losses. This integration significantly boosts evaporation rates, making the system more effective for water purification applications [82].

$$\eta_{Thermal} = \frac{m_{distillate} \times L_v}{I_{sr} \times A} \tag{9}$$

Where,

$m_{distillate}$ = Mass of distilled water

L_v = Latent heat of vaporization of water, J/kg

The improved efficiency can be represented by the following formula, which accounts for the heat recovered by the heat exchanger:

$$\eta_{solar\ still\ with\ HX} = \frac{m_{distillate} \times L_v + Q_{recovered}}{I_{sr} \times A} \tag{10}$$

Where,

$Q_{recovered}$:Amount of heat recovered by the heat exchanger

7.6. The efficiency of a solar dryer:

The efficiency of a solar dryer is calculated as the ratio of useful energy output (in terms of the energy used to remove moisture from the material) to the total solar energy input received by the dryer. This can be expressed with the following formula [83].

$$\eta_{solar\ dryer} = \frac{m_{water} \times L_v}{I_{sr} \times A \times t} \tag{11}$$

Where,

m_{water}: Mass of the water removed during the drying process (in kg).

L_v: Latent heat of vaporization of water (typically around J/kg) [84,85].

I_{sr}: The average solar irradiance incident on the dryer (in W/m²).

A : Effective area of the solar collector or the dryer surface (in m²).

t : drying time (in seconds).

Table 5 compares the various cloud platforms used in the application of Internet of Things based on some of the key performance indicators and illustrates their features and suitability to specific applications. Latency, packet loss, throughput, update interval, storage capacity, and security protocols of every platform Adafruit IO, AWS, Blynk, ThingSpeak, and Ubidots are evaluated. Platforms vary widely in latency, which is paramount to real-time applications. The most responsive is Blynk, and the AWS is the most average in latency. The percentage of packet loss and throughput rate is used to show reliability; only Adafruit IO and Ubidots do not achieve 100% throughput, although they may experience low or no packet loss. All other platforms ensure data consistency. Their processing efficiency in terms of data processing is also demonstrated by the update intervals, which further distinguish them. As an example, Adafruit IO and Ubidots allow instant updates, whereas ThingSpeak delays the batch feed updates by 10 seconds.

Storage capacity and duration are important differentiators in the case of IoT applications that use a lot of data. Whereas solutions such as Adafruit IO focus on short-term data storage, Ubidots and Blynk offer long-term storage capabilities that are suitable in long-term monitoring. The security mechanisms of all platforms are based on TLS 1.2, but their applications are further limited by variations in the strength of RSA encryption (2048 vs. 3072 bits) and additional integrations, such as the MATLAB support of ThingSpeak.

Table 5. Comparison of IoT cloud technologies: key metrics [87–90]

Metric	Adafruit IO	AWS	Blynk	Thing Speak	Ubidots
Total Samples	336	433	687	577	596
Packet Loss (%)	1.2	0.0	0.0	0.0	0.2
Maximum Latency (ms)	920	35977	822	2702	2891
Throughput (%)	98.81	100.0	100.0	100.0	99.83
Average Latency (ms)	178.6	25619	76.33	1255.46	1265.05
Update Interval	2 s	0.0 s	0.0 s	10 s	0.0 s
Minimum Latency (ms)	59	10160	56	849	819
User Friendliness	Excellent	Good	Excellent	Acceptable	Excellent
Storage Limit	1.5 GB, 1 Month	5.0 GB, No Limits	Unlimited, 3 Months	3M data/year	Unlimited, 2 Years
Security Protocol	TLS 1.2, RSA 3072	TLS 1.2, RSA 2048	TLS 1.2, RSA 3072	TLS 1.2, RSA 3072	TLS 1.2, RSA 3072
Platform Specifics	Direct control	Broad integration	Webhook support	MATLAB integrations	Custom platform

Advanced power management functions are made possible via the Smart Socket Module, which acts as a link between the SEM unit and linked appliances. Appliance control, connectivity, and energy data gathering and processing are some of these aspects [91,92]. As shown in Table 6, the article emphasizes the different functions of different parts of the smart socket, including data collection, processing, communication, and operational control.Users with approved credentials can use a web portal in this IoT-integrated configuration to remotely monitor power-related parameters over the internet. The efficiency, affordability, dependability, and general management of renewable energy supplies are all improved by this system design.

This system architecture enhances the management of renewable energy sources.

When installed on-site, smart meters create real-time communication networks that facilitate effective data storage and energy usage tracking. The integration of cloud-based apps into energy management systems inside smart grids which mostly rely on information technology for improved performance is investigated in this study [93].

Since networks are intimately connected to the grid through communication, reliable data systems are essential to guaranteeing dynamic control of electricity. The research delves into proactive cloud computing strategies for managing energy in IoT-enabled grids, illustrating how cloud technology facilitates energy distribution in smart grid systems (Table 6) [94].

Key findings include an in-depth understanding of cloud computing's role in electrical energy management, an analysis of its applications in the energy sector, and insights into the growing reliance on cloud-based power distribution in advanced energy systems [95,96].

Table 6. Demand response options and goals

Integrated System	DSM Method/Technique	Operation Mode	Control Type	Outcome	Ref.
Solar power and battery-based hybrid system	Predictive control program for demand response	Grid-connected	Centralized	Lowered electricity bills for users. Enhanced reliance on solar energy and battery storage.	Jaber M. et al., 2016 [97]
Wind-powered industrial microgrid with energy storage	Demand response scheme	Grid-connected	Centralized	Reduced carbon emissions from wind turbines by 88%. Additional 30% reduction due to DSM. Total energy costs cut by 73%.	Maple C. et al., 2017 [98]
Residential microgrid with solar panels, wind turbines, and storage	Linear programming-based demand response scheme	Grid-connected	Decentralized	Energy demand reduced by 16%. Consumption and CO2 emissions cut by 10%. Use of renewable supply reduced by 74%.	Colakovic C., and Hadzialic, M., 2018 [99]
Microgrid integrating solar, wind, diesel, batteries, and water system	Artificial neural network integrated with DSM	Grid-connected	Decentralized	Achieved a 3.06% reduction in operational costs.	Koshizuka N., and Sakamura K., 2010 [100]
Distributed PV systems in homes	Event-driven energy management algorithm	Grid-connected	Centralized	Preserved user comfort while reducing energy expenses.	Atlam H.F. et al., 2017 [101]
Smart grid with distributed renewable energy sources	Parallel optimization for demand response	Grid-connected	Centralized	Lowered both electricity bills and generation costs.	Zhou J. et al., 2017 [102]
Microgrid featuring radial feeders, wind turbines, solar panels, and fuel cells	Demand response strategy	Grid-connected	Centralized	Minimized peak load on grid connections. Optimized scheduling of battery and diesel generators.	Abate F. et al., 2018 [103]
Microgrid with renewable power and energy storage	Demand response mechanism	Isolated	Centralized	Optimized peak load distribution and power generation processes.	Mohale V. P. et al., 2015 [104]
Smart grid with high wind energy integration	Demand response initiative	Isolated	Centralized	Achieved 30% cost savings. Adjusted 56% of demand to optimize usage.	Rostami Z. et al., 2020 [105]
Grid with integrated energy storage	Demand response system	Grid-connected	Centralized	Reduced peak demand and decreased energy costs for customers.	Shahryari, K., and Anvari-Moghaddam A., 2017 [106]
Microgrid combining wind and solar power	Demand response framework	Grid-connected	Decentralized	Lowered operational expenses and reduced carbon emissions.	Sheikhi A. et al., 2015 [107]
Wind farm integrated into smart grid	Demand response model	Grid-connected	Centralized	Established efficient 24-hour balance between energy generation and usage.	Wu C., 2021 [108]
Isolated microgrid with solar panels, wind turbines, and batteries	Mixed-integer programming applied to demand response	Isolated	Decentralized	Decreased peak load by 17.2% and operational costs by 36.8%.	Saravanan D. and Lingeshwaran T., 2019 [109]
Smart grid incorporating photovoltaic systems	Demand response structure	Grid-connected	Decentralized	Enhanced and stabilized load factor over the course of a year.	Murdan A. P. and Caremben S. 2018 [110]

Table 7 illustrates some prior research on IoT applications in solar thermal systems, illustrating the range of methods and objectives. Among the main areas of focus are real-time monitoring, increasing efficiency, defect detection, and energy optimization. It highlights how integrated IoT devices with specialized sensors, cloud computing, and predictive algorithms may enhance operational control and system performance. Mobile app integration along with machine learning capabilities provides the ability to access data at any time and get predictions leading to predictive maintenance. In summary, IoT provide a great opportunities to conserve power, minimize also costs, enhance the reliability of systems to reverse the usage of fresh resources in any way for various solar thermal applications [86], it will totally revolutionize the landscape of renewable energy systems.

Table 7. Some previous work on IOT based solar thermal system

S. No.	Author's	Study Title	Key Focus/Objective	Methodology	Key Findings/Outcomes
1.	Shukla et al. 2017, [111]	IoT-Based Monitoring of Solar Thermal Systems	Remote monitoring and control of solar thermal systems	Developed sensor network connected to cloud platform	Real-time monitoring improved data accessibility and system efficiency
2.	Kumar & Singh, 2018, [112]	Smart Solar Water Heating System with IoT	Enhance efficiency of solar water heaters through IoT	Integrated sensors and a mobile app for remote monitoring	Improved temperature regulation and energy efficiency through IoT
3.	Lee et al., 2019, [113]	IoT-Based Solar Thermal Collector for Real-Time Data	Real-time data collection on solar collector performance	Sensor nodes connected to a cloud database	Enabled remote access to data, facilitating maintenance and optimizing energy harvesting
4.	Zhang & Wu, 2019, [114]	Integration of IoT in Solar Energy Systems	Review of IoT applications in solar energy	Literature review of IoT technologies for solar energy applications	IoT significantly enhances solar energy systems' efficiency and control
5.	Gonzalez et al. 2020, [115]	Smart Monitoring of Solar Thermal Plants Using IoT	Monitoring efficiency and fault detection in solar thermal plants	Sensors and cloud computing	Improved system reliability and fault prediction using real-time data
6.	Ramírez & González, 2021, [116]	Optimization of Solar Thermal Energy Management with IoT	Automated control of solar thermal energy to enhance energy management	IoT-enabled sensors with predictive algorithms	Enhanced energy management, reducing operational costs
7.	Wu Zhi-Sheng et al. 2021, [117]	IoT-Enhanced Solar Water Heater for Remote Performance Monitoring	Evaluation of IoT's impact on solar water heater performance	IoT sensors with mobile app interface	Enhanced remote control led to higher efficiency and reduced energy waste
8.	Chen et al. 2022, [118]	IoT and Machine Learning in Solar Thermal Systems	Application of IoT and ML in optimizing solar thermal systems	IoT sensors integrated with machine learning models	Machine learning improved predictive maintenance and operational efficiency
9.	Bansal & Kumar, 2022, [119]	IoT-Driven Energy Optimization in Solar Heating Systems	Energy optimization in solar heating through IoT-based control	IoT-based real-time data analytics	Significant energy savings achieved through continuous optimization
10.	Ivanov et al. 2023, [120]	Advancements in IoT-Integrated Renewable Energy Systems	IoT applications in renewable systems, focusing on solar thermal systems	Review of IoT technologies in renewable energy	IoT integration enhances system resilience, performance, and scalability for renewable applications

The table 8 provides an overview of various software tools utilized in research on IoT-integrated solar thermal systems. These software tools have a wide range of applications including simulation, modeling and even control and optimization. They help researchers advanced systems. As an example, MATLAB/Simulink and LabVIEW are well known for modeling and real- time data acquisition, therefore, they are very useful in the performance evaluation of IoT enabled solar water heaters and dryers.

IoT applications require the use of programming platforms like Python, Arduino IDE, and Raspberry Pi OS which are flexible in coding, data analysis, and even hardware interfacing. Such tools allow the researcher to embed machine learning algorithms and control strategies for greater system performance. At the same time, RETScreen and energy focused HOMER Pro helps perform feasibility and optimization studies of IoT integrated renewable systems. Energy-Plus, Open-Studio, and COMSOL Multiphysics are the more commonly used software for heat and energy modeling as well as multi- physics simulations because they allow for comprehensive system performance analysis under different system operational scenarios.

CFD tools like ANSYS Fluent assist in simulating fluid dynamics in components such as evacuated tube collectors, improving their design and efficiency[121,122].

IoT-specific platforms, such as Thing-Speak, AWS IoT, and Google Cloud IoT, simplify the storage, analysis, and visualization of sensor data, facilitating remote monitoring of solar systems. By leveraging these software solutions, researchers can address challenges in system design, control, and energy optimization, contributing significantly to advancements in IoT-integrated solar thermal technologies. These tools are indispensable for driving innovation and achieving sustainable energy solutions [123].

Table 8. Different software commonly used in research on IoT integrated solar thermal systems [121,122,124–129]

Software	Purpose/Applications in Research	Examples of Use in Solar Thermal Systems
MATLAB/Simulink	Simulation, modelling, control algorithms	Designing and testing IoT-based solar water heater control systems
LabVIEW	Real-time data acquisition and hardware interfacing	Monitoring temperature and flow rate in solar dryers
Python	Data analysis, IoT programming, machine learning	IoT-enabled optimization in solar PVT systems
Arduino IDE	Microcontroller programming for IoT systems	Control of sensors and actuators in solar still systems
Raspberry Pi OS	Programming and interfacing with IoT hardware	Developing a cloud-connected solar evacuated tube collector system
RETScreen	Renewable energy project feasibility analysis	Evaluating energy savings and performance of IoT-integrated solar systems
EnergyPlus	Building energy simulation	Assessing energy efficiency improvements using IoT in solar thermal systems
ThingSpeak	IoT data visualization and analysis	Monitoring real-time performance of solar thermal collectors
OpenStudio	Energy modeling and simulation	Optimization of solar thermal systems integrated with IoT controls
COMSOL Multiphysics	Multiphysics modeling and thermal analysis	Heat transfer analysis in IoT-enabled solar water heaters
Proteus	IoT hardware simulation and circuit design	Circuit design for IoT-based solar monitoring systems
HOMER Pro	Hybrid renewable system design and optimization	Designing IoT-integrated hybrid solar thermal systems
ANSYS Fluent	Computational fluid dynamics (CFD) analysis	Fluid flow simulation in IoT-controlled solar evacuated tube collectors
IoT Platforms (AWS IoT, Google Cloud IoT, Azure IoT)	Cloud storage and analytics of sensor data	Remote monitoring of solar systems via cloud

8. Analysis of communication technology upgrades in iot over the past decade

Table 9 offers a brief snapshot of major communication technologies that have shaped IoT development, comparing their standards, launch years, data rates, coverage ranges, and operating frequency bands to highlight how each technology supports different IoT need.

8.1. Early-stage technologies:

Wireless data transmission was made possible by early IoT communication technologies like Wi-Fi (1973) and Radio Frequency Identification (RFID), which were first established in 1970. RFID has a low range (~2m), yet it can function in a wide frequency range (0.125–5876 MHz). On the other hand, Wi-Fi, which is standardized under IEEE 802.11, is a basic wireless communication technique that provides much faster data rates and wider coverage. Similar to this, direct device contact was made possible by Machine-to-Machine (M2M) communication, which was first developed in 1973 and is essential for industrial automation and remote monitoring.

8.2. Advancements in wireless connectivity:

IoT communication in low-power and short-range was expanded with Bluetooth (1994) and Ultra-Wideband (2002). IEEE 802.15.1 Bluetooth was used in personal devices, as it operates with low data rates and minimal power. UWB is much faster (11-55Mbps) and more mid-range. This concept of large numbers of small sensors operating together at low power was extended with Wireless Sensor Networks in 2003, which created the possibilities of further scope of IoT applications.

8.3 Growth of mobile communication in IoT:

Long-Term Evolution (1991) and subsequently 5G (2019) provided a strong impetus to the development of IoT. The LTE has a maximum data rate of 100 Mbps at 400 to 1900 MHz, thus ensuring that IoT connections are quicker and more stable. IoT can now support smart cities, smart self-driving systems and real-time automation of industrial processes with 5G that provides the highest possible speed of up to 20Gbps and extensive coverage.

8.4 Specialized IoT protocols:

Other technologies such as 6LoWPAN (2006) and Z-Wave (2013) have enhanced the connectivity aspect of IoT devices where 6LoWPAN is built on IEEE 802.15.4 which enables low-power devices to effectively communicate in an IoT network. Z-Wave operates on the frequencies of 868908 MHz and is widely utilized in smart homes due to its availability of a reliable communication measure based on mesh networking. Near Field Communication (NFC) (2004) is a communication over very short range with a standard based on ISO 18092 which is used in contactless payment and secure authentication.

Table 9. Different communication technology upgrades in IoT over the past decade [62,130,139,140,131–138]

Technology	Protocol Standard	Year Introduced	Max Data Speed	Coverage Range	Frequency Band
Radio Frequency Identification (RFID)	ISO 18092	1970	Up to 100 kbps	Short-range (~2m)	0.125–5876 MHz
Wi-Fi (Wireless Fidelity)	IEEE 802.11	1973	Varies (up to Gbps)	Tens to hundreds of meters	1 GHz–6 GHz
Machine-to-Machine (M2M)	Multi-Protocol	1973	50–150 Mbps	5–20 meters	1–20 GHz
Long-Term Evolution (LTE)	3GPP	1991	100 Mbps	About 35 meters	400–1900 MHz
Bluetooth	IEEE 802.15.1	1994	720 kbps	Approx. 10 meters	2450 MHz
Ultra-Wideband (UWB)	IEEE 802.15.3	2002	11–55 Mbps	10–30 meters	2400 MHz
Wireless Sensor Networks (WSN)	IEEE 802.15.4	2003	250 kbps	Up to 30 meters	826, 915 MHz
Near Field Communication (NFC)	ISO 18092	2004	106–424 kbps	Less than 0.2 meters	13.56 MHz
6LoWPAN	IEEE 802.15.4	2006	250 kbps	Up to 30 meters	915 MHz
Z-Wave	Z-Wave Alliance	2013	100 kbps	Around 30 meters	868.42, 908.42 MHz
Fifth-Generation (5G) Networks	3GPP	2019	Up to 20 Gbps	Wide coverage	1 GHz–6 GHz

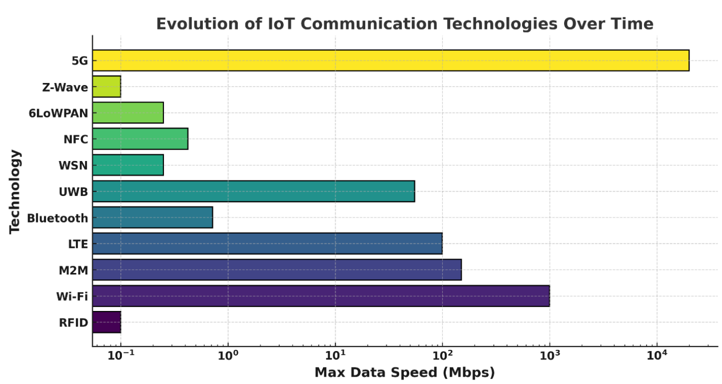

Figure 13. Evolution of IoT Communication Technologies over time [62,130,139,140,131–138]

The change in the connectivity in the IoT through Figure 13 reveals that in the past, the connectivity had a slow and limited range, whereas in the present, the network of connectivity is so fast and extensive. The initial systems such as RFID, Bluetooth, and WSN only enabled low-data, basic, and simple monitored activities such as sensing, monitoring, and tracking. With the increased demand of IoT, faster solutions emerged: Wi-Fi facilitated speed of up to Gbps to homes and industries, M2M enhanced automation of devices to each other, and LTE opened the IoT to cell networks with enhanced coverage. UWB and Z -Wave were new short-range technologies that brought more accuracy and reliability to home and location applications. The establishment of 5G, with speeds up to 20Gbps, can now be used in advanced applications like autonomous vehicles, smart cities or industrial automation. This general development indicates that the IoT has evolved to encompass small local networks to the high-speed and worldwide networks.

Table 10 presents a summary of the benefits of the IoT in enhancing solar thermal systems with real-time monitoring, optimal use of energy, automation, and predictive maintenance with the assistance of sensor networks, cloud-based platforms, and machine-learning techniques.

Table 10. Common Findings on IoT Integration in Solar Thermal Systems

S. No.	Author's	Methodology	Common Finding
1.	Shukla et al. 2017, [111], Lee et al., 2019, [113]	Developed sensor network connected to cloud platform	Real-time monitoring improves data accessibility and system efficiency
2.	Kumar & Singh, 2018, [112], Bansal & Kumar, 2022, [119]	IoT-based real-time data analytics	IoT enhances energy efficiency and optimization in solar thermal systems
3.	Ramírez & González, 2021, [116], Wu Zhi-Sheng et al. 2021, [117]	IoT-enabled sensors with predictive algorithms	Remote control and automation lead to better system performance and reduced energy waste
4.	Chen et al. 2022, [118], Gonzalez et al. 2020, [115]	IoT sensors integrated with machine learning models	IoT enables predictive maintenance and fault detection, improving system reliability
5.	Wu Zhi-Sheng et al. 2021, [117]	IoT sensors with mobile app interface	Enhanced remote control led to higher efficiency and reduced energy waste
6.	Ivanov et al. 2023, [120], Zhang & Wu, 2019, [114]	IoT applications in renewable systems, focusing on solar thermal systems	Cloud-based IoT solutions provide scalability and better management of solar energy
7.	M. T. Ágreda et al. 2024, [59], A.S. Samosir et al. 2021, [63]	Developed an IoT module with local processing, Wi-Fi/BLE communication, distributed algorithms, and active panel control. Included functions like I–V curve tracing, anomaly detection, and dark EL testing automation. Verified through simulations and experimental tests.	Real-time monitoring improves PV panel efficiency and power management.
8.	C. Villalobos et al. 2023, [64] R. Samkria et al. 2021 [67]	IoT sensors integrated into PV panels with real-time monitoring via a web interface	IoT-based predictive maintenance and fault detection enhance system reliability
9.	A. K Yadav et al. 2024, [60], M. Uzair et al. 2021, [66]	A prototype of an automated irrigation system was built based on soil-moisture sensors, GSM, and Arduino control and its functionality was experimented in five climatic zones such as Jaisalmer and Bangalore. At the same time, it was suggested to equip a pv system with IoT in order to monitor and remotely control electrical utilities, which would enhance the efficiency and reliability of the entire system.	IoT enables remote control and automation, optimizing energy utilization
10.	Alaa M. Odeh, Isam Ishaq, 2024, [48], Benghanem et al. 2021, [50]	Combined solar energy with IoT-based sensor networks to monitor system performance and water quality in real time	Hybrid solar desalination systems with IoT reduce energy consumption.

9. Results and discussion

IoT solar thermal systems have developed at a very high rate between 2010 and 2024 to be smarter, efficient, and easier to manage. They have now a better set of sensors, automation, cloud services, and artificial intelligence to enhance the use of energy, real-time monitoring, and predictive maintenance. Good developments are realized in Solar PVT units, solar water heaters and solar dryers. Such challenges as cybersecurity and high setup cost are still available, though the future work is directed towards AI control, blockchain security, and smart energy-trading systems carried out with the help of advanced software tools.

Figure 14 indicates the increase in the use of IoT in solar thermal systems between 2010 and 2024. Early research was on data collection and monitoring (20%), automated control (15%), which assisted in smooth running of systems and early detection of faults. Next, the emphasis was on energy efficiency (25%), in which the IoT enhanced heat capture and minimized losses. The introduction of AI and ML (10%) allowed making smarter predictions and optimizing the system. The reliability was also enhanced by predictive maintenance (10%) and smart-grid compatibility (15%), which facilitated grid integration. In general, the figure demonstrates a consistent trend of IoT transforming solar thermal systems into more intelligent, efficient and connected technology.[124,127]. Lastly, the creation of user-friendly platforms that enable customers to remotely monitor and control their solar thermal systems is highlighted in the User Interface & Remote Access category (5%).

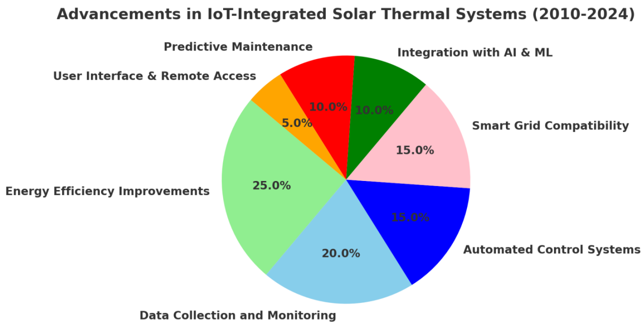

Figure 14. Distribution of advancements in IoT-Integrated Solar Thermal Systems from 2010 to 2024.

The main areas of emphasis for IoT-integrated solar thermal system developments between 2010 and 2024 are shown in Figure 15. 30% of the focus has been on sensor technology advancements, which have been essential for precise data collecting and system optimization. At 20%, system control algorithms have been just as crucial for intelligent and automated control to improve system responsiveness and efficiency. In order to manage massive datasets from IoT devices and enable insights and predictive analysis, data processing and storage (15%) is essential. Advanced computing powers, centralized data storage, and remote access are made possible via cloud integration (10%). Sustainable and environmentally friendly system designs are the emphasis of Environmental Impact Reduction (12%). User Accessibility Improvements (8%) is aimed at simplifying the work of IoT-based solar systems. Cost Reduction Strategies (5%)- The objective of these strategies is to reduce the overall system costs in order to increase the adoption of these technologies by more people. A combination of these advances in Figure 16 demonstrates a continuous evolution of the IoT-integrated infrastructure of solar thermal towards a more connected, efficient and user-friendly infrastructure.

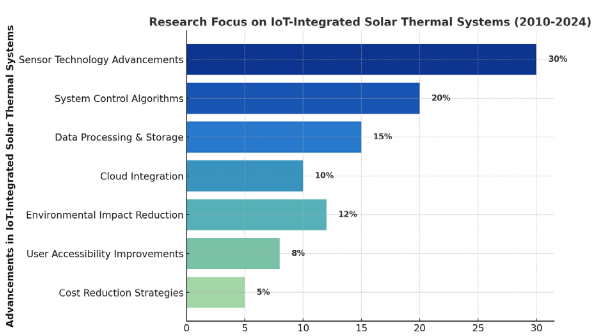

Figure 15. IoT-integrated solar thermal system advancements from 2010 to 2024

Figure 16 demonstrates the most rapid growth in solar PVT systems with a percentage increase of between 5 and 75 in 2010 to 2024, respectively outpacing the other IoT incorporated solar thermal systems including solar stills, dryers, evacuated tube collectors, water heaters and trackersn [141]. Figure 16 shows that solar PVT systems have the highest growth rate since they provide heat and electricity, thus IoT integration is of great advantage. Solar water heaters and solar trackers increase to approximately 60% by 2024 due to their cheap nature, simple construction, and automatic adjustment to enhance efficiency. Solar dryers (55%) and evacuated tube collectors (48%) continue to grow steadily as the IoT enhances temperature control and energy efficiency of operation. Solar stills have slower development, with the highest rate of about 50 percent, primarily because of difficulties in enhancing the efficiency of the distillation process. Overall, Figure 16 demonstrates that the number of studies related to the IoT-enabled solar thermal systems is evidently increasing due to the enhanced monitoring, control, and optimization of performance of all technologies.

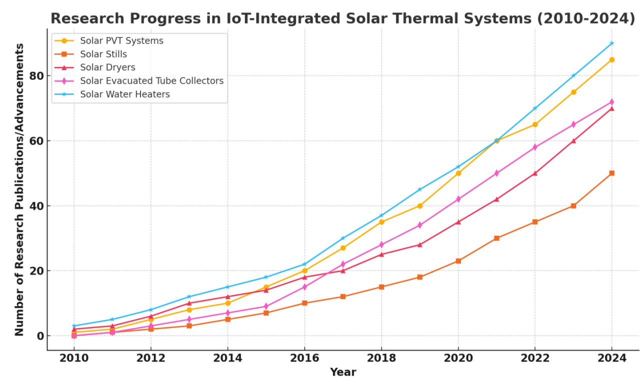

Figure 16. Research progress in various IoT-integrated solar thermal systems from 2010 to 2024

Figure 17 (Pie chart) shows the distribution of reviewed papers in the various solar technologies. A good proportion of the 142 papers reviewed, which constitutes a good percentage of the total papers reviewed, is on solar dryers. Similarly, 19 papers on PV panels are also published, highlighting the significance of this technology in the study of the sun. In papers 17 and 15, solar stills and solar water heaters are represented, respectively, and this shows a great interest in these types of technologies. The other articles, which are classified under the category, Others are more general or integrated solar energy issues. This distribution depicts the variety of solar energy research with a similar representation in some technologies. It is accompanied by overall trends in the field of renewable energy, and it shows the increased interest in the enhancement of systems, such as dryers, stills, and heaters. The analysis gives an idea of how the research trends have moved and how each of the technologies is important in contributing to the solutions to sustainable energy.

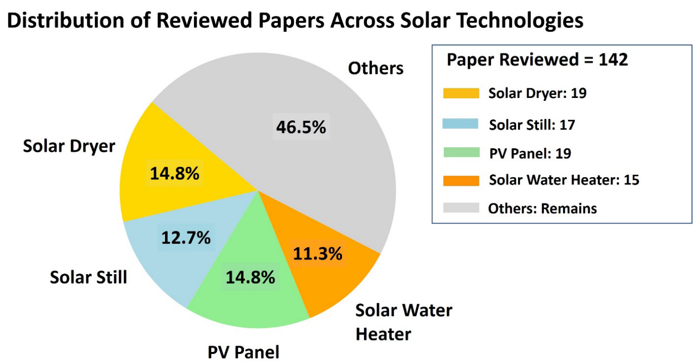

Figure. 17. The pie chart depicts the allocation of reviewed papers across different solar technologies discussed in the current manuscript

10. Effectiveness of iot adoption in solar thermal systems

Solar thermal system has become smarter, faster and more reliable with the IoT which allows real-time monitoring and automatic control. The sensors monitor the sunlight, temperature, and pressure, and these data are utilized in operating the system more effectively to boost energy production and decrease the total cost of energy. Predictive maintenance assists in identifying the problems at early stages, minimizing manual inspections, and enhancing the life of components. Remote diagnostics can fix issues wherever one is. IoT also enhances the storage and distribution of energy when it is linked to smart grids [142].

10.1. Application, strengths, weaknesses, and future potential of IOT-based solar thermal systems

Application: Solar stills, solar dryers, and smart solar water heaters have IoT-based solar thermal systems, which enhance heating, drying, and water purification. They are also used in remote monitoring, the construction of climate control, and industrial heating to contribute to the improvement of productivity, automation, and the whole management of energy.

Strengths: They are mainly defined by real time data-collection, intelligent system control, and predictive maintenance which reduces downtimes. Energy efficiency IoT is also enhanced with automation and solar dryers and heaters performance is also improved and can be integrated with smart grids to supply energy on a stable and demand basis.

Weaknesses: Nevertheless, the systems also have their vulnerabilities including cybersecurity threats, lack of interoperability with other platforms, and excessive expenses of installing sensors and communication modules. Lack of AI-based optimization and applicable fault-detection automation also decrease the reliability of the system.

Future Potential: The IoT based solar thermal systems have a great potential in future with the opportunities in AI based energy management, block chains-based security, open standard IoT platforms, low power devices and smart energy trading architecture that will facilitate peer to peer solar power exchange.

11. Conclusion

Its introduction into the solar thermal systems has substantially revolutionized the renewable energy sector because the Internet of Things (IoT) has enhanced the sun thermal systems to a new level in the aspects of real-time monitored systems, automation, predictive maintenance, and energy optimization. This paper has systematically discussed the future of IoT-based solar thermal technology between 2010 and 2024 with the critical developments, uses, strengths, weaknesses, and potential of the technology.

Key Findings:

- IoT-based solar drying is a more accurate and efficient drying method that reduces moisture control and drying efficiency by 15-25 percent in comparison to traditional drying methods.
- Hybrid solar stills with IoT generate freshwater output of 6.570 L/day, the efficiency goes up by 1525 per cent with real-time monitoring.
- IoT-based live PV tracking saves up to 25 percent of energy, minimizing the waste of power and efficiency of resources.
- Hybrid solar water heaters with daylight guides are used to provide maximum water temperature of 70 o C, thermal efficiency of 37, and daily stored heat of 1884 W.
- Simplified solar thermal modeling using IoT shows that less than 2% error is obtained in the optimization of the auxiliary energy needs, which advances energy planning and resources management.

Technological Advancements (2010-2024): IoT in solar thermal systems has developed in terms of sensor technology, systems control algorithms, data processing, cloud computing, and optimization based on AI. The use of Solar PVT systems has been increasing significantly between 5 percent in 2010 and 75 percent in 2024, which depict the growing contribution of the IoT in hybrid energy systems.

IoT Adoption Effectiveness: IoT-solar thermal systems have enhanced operational efficiency, energy management, and predictive maintenance, minimizing the downtime and resource optimization. IoT implementation has also helped in compatibility of smart grids to allow dynamic distribution and storage of energy.

IoT applications in the Solar Thermal Systems: IoT has been largely embraced in solar water heaters, solar dryers, solar stills, industrial heating, and building climate control, which will guarantee better automation, energy conservation, and cost optimization. The possibility of remote monitoring also promotes the efficiency of operations.

IoT-Based Solar Systems Strengths: The main benefits are the enhanced system intelligence, energy efficiency, process automation, predictive maintenance, and smart grid integration. The following factors make renewable energy applications to be sustainable and scalable.

Challenges and Limitations: The challenges are cybersecurity vulnerabilities, high implementation costs, interoperability, low levels of AI optimization, and inefficiency in fault detection. The need to address these barriers is essential to big scale adoption and smooth integration.

Potential Future and Research Prospects: The AI-based energy management, cryptographic security of data integrity, open-source IoT architecture to ensure interoperability, the development of low-power IoT-based devices, and smart energy trading to support decentralization of energy delivery are the directions of the future IoT-based solar thermal systems.

The IoT-based solar thermal solutions will transform the sustainable energy application and make it clever, efficient, and safe by solving the challenges and using the innovations of the future. The paper offers invaluable information to the researcher and practitioners in the industry, citing that more needs to be done in the field of AI, cybersecurity, and smart energy networks to ensure the IoT is fully utilized in solar energy.

12. Future scope

IoT and solar thermal systems integration will lead to efficiency and real-time monitoring and automation. Further studies can delve into the enhanced cloud platforms, AI implementations, and better mathematical models of performance optimization. The key to such challenges is industry-academia cooperation, which will result in massive deployment of the technology, its sustainability and energy efficiency in solar thermal processes such as as solar dryers, solar stills, solar water heaters, and PV panels.

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