JJMIE

Volume 19, Number 3, Sep. 2025
ISSN 1995-6665
Pages 531– 546
https://doi.org/10.59038/jjmie/190306
Editor-in-Chief: Prof. Ali M. Jawarneh

Jordan Journal of Mechanical and Industrial Engineering

Integrated Approach for Energy Conservation and Efficiency Enhancement of Cooling and Air Conditions in Industrial Operations: A Sustainable Design for Yemen

Wael Bakil Ali Hashed[1], Jagadeesh Pasupuleti[1], Johnny Koh Siaw Paw[1], Mokhtar Ali Amrani[2,3]

[1] *College of Engineering, Universiti Tenaga Nasional (UNITEN), Putrajaya Campus, 43000 Kajang, Selangor, Malaysia.*
[2] *Faculty of Engineering and Information Technology, Taiz University, Taiz, 6803, Yemen.*
[3] *Faculty of Engineering and Computing, University of Science & Technology, Aden, Yemen.*

Received 13 Apr 2025 *Accepted 30 Jul 2025*

Abstract

This study proposes a framework for an integrated and sustainable photovoltaic (PV)-based system, which aims at improving energy saving in cooling and air conditioning technologies, enhancing industrial productivity, and minimizing grid electricity dependency. The core goal of this study was to achieve efficient energy consumption by integrating PV systems with a thermal storage system (TES), high-temperatures cooling solutions, and a variable refrigerant flow (VRF). The PVsyst software was employed for analyzing the optimum tilt angle of the PV system in Taiz Al-Huban, Yemen, to be at 17.5°. The results showed a reduction in annual energy consumption by 24.79 % when PV is combined with VRF and TES, meeting industrial cooling demands, significantly reducing energy use, and lowering carbon emissions. An additional innovation of this system lies in the design of an efficient cooling system to control PV arrays' temperatures at the required levels, sustaining higher efficiency and generalizing it for varied climatic conditions. Another contribution of this study is the economic feasibility analysis, conducted using both Yemeni and global cost parameters, with an extremely short payback period for the Yemeni context at 2.4 years, underscoring the system's effectiveness in industrial applications. Furthermore, a literature gap analysis identified a clear need for continued research into the integration of advanced cooling technologies with PV systems in industrial settings. The proposed sustainable system agrees with the massive efforts required to bring Yemen's energy sector to a safe level, ensuring an uninterrupted power supply, competitive prices, and environmental cleanliness.

Keywords: Energy conservation, industrial operations, photovoltaic systems, cooling systems, PVsyst simulation, RE, CO_2 emissions, Energy storage.

Abbreviation

BIPV	Building-Integrated Photovoltaic
DCSs	District Cooling Systems
MPPT	Maximum Power Point Tracking
PR	Performance Ratio
PV/T	Photovoltaic/Thermal
AC	Air Conditioning
HVAC	Heating, ventilation and air conditioning
PV	Photovoltaic
PVsyst	Software
RE	Renewable Energy
TES	Thermal Energy Storage
VRF	Variable Refrigerant Flow
PCM	Phase Change Materials

* Corresponding author e-mail: Eng.waelbakil@gmail.com.

1. Introduction

The industrial sector is perhaps the most vital compartment for nations' economy, stability, and residents' welfare. However, this sector faces numerous challenges. Energy management and environmental pollution present significant challenges. Globally, the industrial sector accounts for roughly 50% of annual energy consumption, with a significant portion dedicated to heating, cooling, and electricity generation [1]. Cooling and refrigeration systems, particularly in hot and humid regions, contribute significantly to energy demand, comprising about 17% of total electricity use and approximately 8% of global greenhouse gas emissions [2]. Within buildings, air conditioning and cooling systems account for 50–60% of total electricity consumption on average. This percentage can reach up to 80% in extremely hot climates, such as in GCC countries [3], highlighting their critical role in energy expenditure [4]. The increasing reliance on conventional cooling technologies has led to rising energy consumption and operational costs, necessitating sustainable alternatives [5]. Notably, the industrial use of cooling systems extends beyond air conditioning to include various production processes. These systems consume a large fraction of total energy, which directly impacts the cost of the final product or service.

Researchers and decision-makers have shifted their focus to predicting sustainable energy solutions, especially HVAC systems that consume significant energy in this vital sector. Finding alternatives based on pure or hybrid RE sources is a feasible option for reducing reliance on traditional energy sources and lowering production costs. In other words, integrating RE technologies into HVAC systems presents a viable strategy for enhancing efficiency, reducing CO_2 emissions, and promoting environmental sustainability [6]. Among these technologies, PV systems have gained prominence due to their potential to reduce grid dependence and optimize industrial cooling efficiency [7]. Studies indicate that PV-powered cooling systems significantly lower energy costs while enhancing overall system performance [8].

It is not a challenging problem in industrial processes only; cooling and heating operations in buildings are perhaps the largest consumers of energy worldwide. The energy consumption for cooling purposes in GCC countries, for example, represents a substantial portion of buildings' total energy, reaching up to 80% of total electricity bills, primarily in summer [9,10].

In Yemen, the electricity infrastructure has greatly deteriorated due to a decade of political instability caused by the ongoing civil war. The country currently lacks a public electricity grid, while the cost of an electricity unit is nearly 4 times higher than the global average. This situation places greater pressure on the industrial sector, discourages investment opportunities, and raises the cost of products and services.

Yemen's political instability poses significant risks to the implementation of energy supply chains, leading to increased energy costs. The ongoing civil war has resulted in fragmented governance and deteriorating infrastructure, which complicates energy provision and exacerbates supply chain vulnerabilities [11,12]. Political risks - including bureaucratic inefficiencies and frequent project delays - further hinder oil and gas operations, driving up operational costs and uncertainty for companies in the sector [13]. Additionally, the interplay between conflict and climate change exacerbates resource scarcity, intensifying competition and instability, which can disrupt energy supply chains and inflate prices [14]. The negative correlation between political instability and economic growth underscores the broader economic implications, as instability deters investment and disrupts trade, further straining energy costs in a country already facing humanitarian crises [12,15].

Given the above motivation, this study gains substantial importance in exploring the integration of PV systems into industrial cooling and air conditioning operations, employing effective thermal storage systemsto ensure continuous power generation without interruption. It utilizes PVsyst software for system analysis and optimization. The findings are expected to contribute to the broader efforts toward sustainable energy utilization and the reduction of environmental impacts in the industrial sector.

2. Literature Review

This section discusses literature review studies related to efficient strategies employed for energy conservation and efficiency enhancement in industrial cooling and air conditioning systems, studies that implemented PVsyst in the energy conservation process, and research gaps in literature. Solar PV integrated with cooling and air conditioning systems is a promising research direction targeting the reduction of energy consumption and environmental risks [16,17,18,19,20]. Recent innovations in PV systems, such as integrating TES and VRF technologies, Spotlight on sustainable cooling solutions for residential, commercial, and industrial uses.

Despite its intermittent nature, harnessing solar energy is the most feasible option for large energy-demand systems. Providing continuous power based on solar energy is impractical unless an effective storage system is employed for night operation. Therefore, numerous research articles have focused on designing integrated energy systems that are safe, reliable, and non-intermittent. It was reported that substantial enhancement to industrial cooling systems' efficiencies can be achieved through implementing a pre-cooling system with innovative technologies, including evaporative cooling, adsorption cooling, and desiccant cooling [21]. These approaches utilize natural cooling processes and RE sources to minimize reliance on conventional air conditioning systems. Additionally,VRF design has demonstrated high energy savings by regulating refrigerant flow to different cooling zones, ensuring efficient temperature control without excessive energy consumption [22]. Similarly, the use of TES systems, which are designed to store surplus energy during off-peak hours and utilize it during periods of high demand, has also been highlighted as an effective strategy for industrial cooling [23].

The integration of PV systems with innovative cooling systems optimizes energy efficiency and aligns with sustainable development objectives [24]. Some recent studies have focused on enhancing the efficiency of standalone PV systems through maximizing power point tracking [24,25]. The acceleration in cost reduction and the absence of emissions have placed solar PV systems in a very competitive position among various forms of RE [25]. The augmentation of air jet impingement by applying transverse airflow has been proven to enhance thermal flows with position settings, such as jet directionality and separation, achieving consistent cooling and mechanical quality [26]. On the same note, innovation in HVAC systems, energy management systems, and environmentally friendly refrigeration fluids have led to energy use reduction by 40%. In other words, an increase in industrial systems' efficiency could be achieved [27]. In addition, the implementation of new fan control techniques in refrigeration systems has reduced energy consumption by 25.2%, indicating potential for enhancing energy efficiency in industrial applications [28].

In addition, district cooling systems (DCSs) provide flexibility and optimization of renewable electricity use, which improves the operating cost of DCSs by a reduction of 15.4% [29]. There are other green technologies in solar thermal for cooling that reduce the pressure on electric utilities [30]. Overall, integration of ice TES with PV systems and other compatible technologies can achieve a reduction in energy costs up to 33% and underline the feasibility of such integrated solutions [31]. By harmonizing traditional cooling innovations with RE sources, industrial companies can achieve remarkable improvements in cooling efficiency, energy conservation, cost reduction, and environmental sustainability.

Table 1 presents the findings of the reviewed studies, focusing on their energy advancement subsystems, as compared to the proposed design in this study. This work contributes to extant literature by presenting a comprehensive approach, discussing practical issues in the implementation of TES and VRF systems, and employing PVsyst for modeling. It is noteworthy that the use of the integrated system has been demonstrated through questions regarding energy flows, to which the novel answers and the exact nature of the simulation results apply to real life.

Despite extensive research on solar integration and demand management, several gaps remain, particularly in the context of HVAC systems. The existing literature has few results on the implementation of solar energy in HVAC systems only. Research is urgently required to understand the feasibility of harnessing solar energy for conditioning HVAC systems, minimizing reliance on the grid, and improving energy consumption [38]. Additionally, the impact of climatic conditions on solar HVAC performance remains underexplored, necessitating further studies to assess temperature variations, humidity levels, and seasonal influences to enhance system dependability [39]. Further research is needed on advanced control strategies for optimizing HVAC operations based on real-time solar power availability and demand cycles. This includes the development of smart algorithms for battery charging, discharging processes, and automated HVAC regulation to maximize efficiency [40].

Economic studies on solar-powered HVAC systems are also scarce, with limited analysis of payback periods, cost optimization, and long-term financial impacts beyond initial investment savings [41]. The interaction between solar HVAC systems and power grids remains another underexplored area, particularly in terms of grid stability, reliability, and demand response programs. There is a need to investigate the potential of solar-powered HVAC systems in balancing the grid, reducing peak loads, and integrating with smart grid technologies [42]. Nevertheless, these are the literature gaps that need to be filled to unlock the full potential of solar energy in Yemen's power grid, especially regarding the identified HVAC system.

Table 1. Comparison of the relevant literature review articles with the current study.

Study	Objective	Findings	Merits	Limitations	Current Study
[32]	To evaluate the efficiency of hybrid PV/T systems in low-energy houses.	Improved efficiency by 20%, combining solar collection and thermal management for energy generation.	Enhances overall system efficiency by utilizing both electrical and thermal energy.	Limited to heating applications and not extended to cooling systems.	Extends to cooling applications
[33]	To assess the energy savings of solar collectors are integrated into building facades.	Reduced energy consumption by up to 30% by lowering heating/cooling loads.	Integrates seamlessly into building structures, saving space, and improving aesthetics.	Focuses primarily on residential buildings with minimal insights into industrial cooling applications.	Includes TES and cooling integration
[34]	To develop accurate solar power forecasting models for large-scale PV systems.	Emphasized accurate irradiance forecasting to optimize PV performance; hybrid modeling approaches improve prediction accuracy.	Enhances PV system reliability and accuracy with advanced irradiance transposition models.	Primarily focused on forecasting models without integration of TES or cooling systems.	integration of TES or cooling systems.
[35]	To evaluate the effectiveness of TES using Glauber's salt in ventilation systems.	Reduced energy costs by 25% during peak cooling hours, demonstrating TES effectiveness.	Shows significant cost reductions and effective thermal management using innovative materials.	Limited scalability and applications for large-scale industrial cooling.	Appling TES to VRF cooling design
[36]	To analyze wind effects on hybrid PV/T systems.	Electrical efficiency improved by 10% due to wind-cooling effects.	Demonstrates the potential for passive cooling techniques to enhance PV performance.	Lacks integration of TES and energy storage for continuous cooling applications.	Provides detailed TES modeling
[37]	To analyze energy and structural benefits of BIPV systems.	BIPV systems increased energy yield by 15%, enhancing building energy efficiency.	Optimizes energy generation while saving space and contributing to building insulation.	Limited to urban environments and lacks focus on integration with cooling technologies.	Integrates PV, TES, and cooling

A feasibility study of hybrid-based solar energy solutions in Yemen reveals significant potential for addressing the country's energy shortage through renewable sources. Research indicates that hybrid systems combining PV, wind, and diesel technologies can achieve substantial reductions in both costs and carbon emissions. For instance, a hybrid PV/wind/diesel system demonstrated a 61.95% reduction in net present cost (NPC) and a 97.44% decrease in CO_2 emissions [43]. Additionally, off-grid systems utilizing PV and wind energy alone can achieve 100% CO_2 reduction and a 30% decrease in the cost of energy (COE) [44]. The design of microgrid systems tailored for remote areas has shown promising results in Yemen, with configurations achieving low unmet loads and high RE potential [45]. Furthermore, standalone PV systems installed in Yemen have proven economically viable, offering lower electricity costs compared to diesel generators [46]. Overall, these studies underscore the viability of hybrid solar energy solutions as a sustainable path for electrifying Yemen's rural and underserved communities [47].

To this, the investment in PV solar farm projects in Yemen becomes more economically feasible due to (1) the ultimately high price of the sold electricity unit in the country (four times its global price), (2) the annual atmospheric temperature range of 10 - 37 °C with an annual average of 25 °C, and (3) the deteriorated electricity infrastructure in the country.

PVsyst software is widely used for modeling and optimizing PV-integrated cooling systems, providing detailed shading analysis, energy yield estimations, and performance comparisons [48]. This assists in optimizing the energy return and conducive solar reinforcement in the electricity network [49,50].

Another novelty of the present work can be elucidated from the unique integration made. Of course, there are still gaps despite the significant progress in integrating PV systems with thermal storage and cooling technologies. These gaps can be explained in terms of: (1) mitigation of energy losses experienced during charge and discharge processes of TES, (2) analyzing system performance under various climate and utilization settings, and (3) investigating the potential of new materials for TES and integrated PV/T solutions for enhanced thermal conductance and energy storage capacity. This work attempts to bridge these gaps in the context of Yemen, an environment of interrupted electricity supply and extremely high electricity costs, four times the average global cost.

3. Methodology

This study proposed an integrated design for energy conservation and efficiency enhancement for industrial cooling processes. It investigated the integration of PV system to power cooling and air-conditioning technologies within an industrial context. The methodology involves the utilization of PVsyst V8.0.6 software to simulate the performance of a fixed-tilted PV system.

PVsyst V8.0.6 is professional software for designing, simulating, and analyzing (PV) systems, suitable for grid-connected, stand-alone, and pumping applications. It features extensive meteorological and component databases, advanced system sizing tools, flexible multi-orientation support, and precise 3D shading modeling. The software provides detailed energy yield simulations with comprehensive loss analysis, helping optimize system performance. Additionally, enhanced documentation and an improved user interface make it more accessible and efficient for PV professionals [51,52,53]. **Figure 1** illustrates the methodology structure design, which forms four key phases: design, simulation, implementation, and finally evaluation and improvement. The following is a detailed explanation of each phase, starting with the design phase.

3.1. Design Phase

The design phase followed a systematic and structured approach, beginning with the selection of industrial sites that demonstrated significant cooling requirements. Specifically, Al-Huban district in Taiz city, Yemen, was chosen as the study area (13°63’48.0”N, 44°11’36.0”E) situated approximately 250km to the south of the Capital city of Sana’a. The selected industrial site is characterized by its occupation as small and medium industries and suitable solar radiation for gaining the maximum output from the PV system, since Taiz has a hot, semi-arid climate, with highs ranging from 24-32°C and lows from 11-20°C, with an average daily sunshine of 11-13 hours [54,55], making it a suitable location for solar integration.

Research variables were carefully selected to obtain accurate and reliable conclusions and recommendations. Solar radiation, temperature, and humidity at different locations were collected from authentic sites, including Meteonorm [56]. Further data on the energy consumption of the industrial facility has been scrutinized to determine the amount of cooling required during the specific peak period. It helps the analysis give critical features that can be used to align the system to the nature of the site.

After deciding on the site and data, the PV system design was provided by PVsyst. The generated system was carefully planned to estimate an annual energy yield of 1,060 MWh, with the overall aim to meet the cooling energy requirements. This design implements high-efficiency monocrystalline PV modules of 1025 that feature high power conversion efficiency, good light performance, high durability, and stable operation at high temperatures, in compliance with the PV purchase and installation, which comprises 500 kW for the current system of 500W PV modules each. The PV array has been designed to consist of 41 strings, each with 25 modules; hence, the total area of the modules is 2434 m².

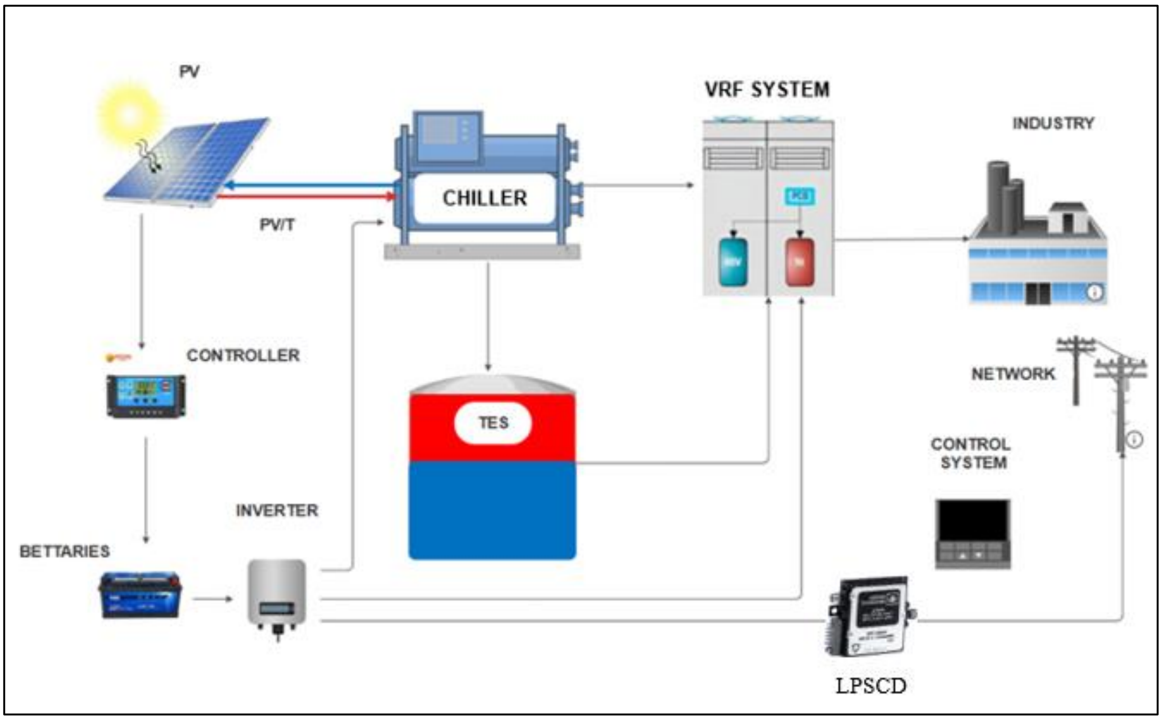

Figure 1. Model of integrated PV system with VRF, TES, and advanced cooling system, a proposed model for this research study.

To ensure that these modules could withstand the weather patterns of the understudy region, they were developed by the manufacturer's agent to be compatible with the regional climate. Moreover, there were two SUN2000-330KTL-H1 inverters, with a total of 500 kW; These converters were compatible with an MPPT function for efficient energy conversion. In addition to the PV system, an energy storage system with high energy capacity was incorporated to improve energy reliability and safety, through 7 Lithium-ion LFP batteries (Magna-UTL-373DC). These batteries have a nominal voltage of 1331V and a nominal capacity of 2030 Ah; hence, they offer the total stored energy of 2521.4 kilowatt-hours. The design was further enhanced based on key factors, such as tilt angle, layout plan, and shading study.

To improve energy density, a proprietary cooling system was implemented to sustain the temperatures of the PV panels at 30 °C; hence, minimizing the losses and the system's overall degradation. In this specific case, the PV/T hybrid cooling system circulates water to cool the PV panels, causing the temperature to drop from 35°C to 30°C. The TES tank was designed with a storage capacity of 80 T/m³, which is built of reinforced concrete in which chilled water being stored on it at a temperature of 7 °C could be released as per the requirements. The chiller has been designed to provide a cooling capacity of 30 TR, as per the standard requirement in the market. On the other hand, the VRF system, as shown in **Figure 1**, distributes the cooling output of the system across the industrial areas. The distribution channels rely on smart sensors to regulate cooling based on demand. Overall, this enhanced cooling system greatly improves energy efficiency and performance of the system.

3.2. Simulation Phase

Once the system design was completed, the next step was to perform a detailed performance simulation using PVsyst to analyze the viability and effectiveness of the integrated solar and cooling systems. Several important simulation tests were conducted at this stage. (1) The photovoltaic system's electrical power production was simulated using Meteonorm meteorological data, including solar radiation, temperature, and wind speed, along with approved design parameters to ensure the results were accurate and consistent with real-world conditions. (2) An in-depth analysis of the relationship between cooling demand and solar power generation was conducted to assess the system's ability to meet cooling needs throughout the year, with a focus on peak periods and times of reduced energy production. (3) The performance of the integrated cooling systems was tested through multiple simulations under various operating conditions. The cooling efficiency, energy consumption, and savings of the TES and VRT systems were evaluated separately and then combined, comparing them with conventional energy sources. This provided a comprehensive understanding of the benefits of integration and its impact on reducing overall consumption. (4) A comprehensive scenario analysis was conducted to assess the impact of changes in solar radiation levels, temperatures, and peak load periods on system performance, helping to identify potential strengths and weaknesses and improve design flexibility. (5) The environmental benefits of the integrated system were evaluated through simulations of potential carbon emissions, highlighting the extent to which the system reduces the carbon footprint compared to conventional solutions and supports the environmental sustainability of the project.

3.3. Implementation Phase

At this stage, critical items such as the PV panels, inverters, and other cooling systems required for the facility were situated as planned. Each component was connected and found to function as expected. After that, measures were implemented to permit firms to track energy production, cooling efficiency, and the entire system's performance. Temperature, relative humidity, energy consumption in the building, and solar energy production were monitored using sensors and data loggers.

The final aspect of this process was performing data analysis to evaluate the system's performance and identify where improvement could be made. The purpose of this analysis was as follows: (1) to ensure that system configurations are well enhanced, (2) to achieve improvement of control strategies in the energy consumption and climate control of the inside environment, (3) to ensure that the entire system was running to the best of its capacity, and (4) to reduce the risks of implementing an inefficient system.

Different aspects of the building design, such as the orientation of the panel units, shading coefficient, and cooling system, among others, were checked to enhance system efficiencies. Optimal control methodologies were developed and implemented in the design of the cooling systems for the proposed system through feedback mechanisms that consider the availability and feasibility of solar power and the demand over a given interval.

3.4. Evaluation and Improvement

Finally, the aggregate results of the data analysis were compared with other relevant data and then reported. The report constitutes operational records, operational costs, performance-based conclusions, and suggestions for other similar projects. Furthermore, the findings of these studies could be disseminated into the relevant stakeholders, industrial partners, and other experts in the field to promote the continuous advancement of cold systems in industrial processes.

The working principle of the proposed system is elucidated here. The system initiates with building PV panels that convert direct sunlight into electricity during daylight, which is then used to power various equipment, such as chillers, batteries for energy storage, and the VRF system. Eventually, cooling and storage processes are controlled through a chiller and a TES system. The chiller is used to generate chilled water when utility electricity or battery power is available in excess or during off-peak periods. This is either fed to the VRF system or stored in the TES tank, which is designed with the aid of stratification to enhance thermal effectiveness, with colder water stored at the base and warm water stored at the top. On the other hand, during periods of peak generation or when PV electricity is insufficient, the TES tank supplies chilled water to the VRF system while the chiller is switched off, reducing energy consumption and achieving maximum efficiency.

The VRF system controls and provides cooling to various industrial areas, based on their requirements. Chilled water generated either from the chiller, or the TES tank was utilized, depending on the availability of energy and the need. That is because the chilled water inside the TES tank is pumped to supply the VRF in a closed circuit until its temperature is reduced. Once that happens, the sensors inside the TES send a signal to the chiller to supply chilled water to the VRF and TES tank.

The surplus power from the PV system is stored in batteries, which will supplement power at night or when the sun is no longer shining due to cloudy conditions. That is to facilitate the operation of essential loads. The model integrates with the electrical grid, exporting surplus electricity to generate potential revenue through a line phase shift control device (LPSCD), while utilizing grid power as a backup during extended periods of insufficient RE availability. To enhance efficiency, a PV/T hybrid cooling system was implemented to circulate water and dissipate excess heat from the PV panels, effectively lowering their operating temperature from 35°C to an optimal 30°C, which significantly improves energy conversion efficiency. The entire system is managed by an advanced control system that ensures seamless integration and coordination between components, enabling efficient and uninterrupted operation.

To conclude, the above section described the research variables, approach, systems' components, software, working principles, and improved variables. In the coming section, the results will be presented and manipulated, and conclusions will be drawn.

4. Results

This section presents the outcomes of the proposed integrated solar system in terms of efficiency enhancement, energy saving, economic feasibility, and environmental gain. It discusses the optimum solar variables suitable for each location, such as optimum tilt angle, latitude of the place, solar insolation intensity, climatic changes, and annual rainfall, among others.

4.1. optimum tilt angle

Multiple simulations were conducted to determine the optimal tilt angle for maximizing annual system electricity generation. Tilt angles are often roughly estimated based on the latitude of the location, where the average tilt angle is close to the location's latitude, which is about 15° for the studied location. However, an exact estimation is compulsory for optimum design. **Figure 2** illustrates the relationship between tilt angle orientation (in degrees) and annual system electricity generation (in MWh), showing a nonlinear trend where electricity generation increases with the tilt angle up to a certain point before declining.

Figure 2 shows a plot of data analyzed from Al-Huban, Taiz, using PVsyst software. To determine the optimum tilt angle of PV panels, the tilt angle varied from 0° to 30° with 5° intervals to maximize energy output throughout the year. The results showed that a tilt angle of 17.5° exhibited the maximum annual energy gain at 1060 MWh, despite high values of energy harvested throughout a large range of tilt angles. The large energy values generated at the optimum tilt angle of 17.5° are plausibly due to Yemen's geographic location within the solar belt. Accordingly, the present study’s system design will consider a tilt angle of 17.5° for further calculations.

Many location-based and seasonal variables affect the optimal tilt angle for solar panels. Its optimum value varies significantly based on geographic location, particularly the latitude and annual rainfall levels. Additionally, various seasonal factors, such as solar irradiation intensity and day length, impact the optimal tilt angle. The design system must consider all these variables seriously to ensure maximum energy generation. In other words, this study suggests adjusting solar panel tilt angle quarterly rather than relying on annual averages.

These findings indicated the critical role of tilt angle optimization in maximizing the efficiency and performance of solar PV systems, particularly in regions with similar climatic conditions. Optimizing panel orientation is an essential process for enhancing energy generation, long-term sustainability, and economic viability in solar energy applications.

Table 2 presents the design system data derived from simulated data collected from Meteonorm [56] and historical energy consumption data using PVsyst. These results indicate the potential impact of integrating solar PV systems with advanced cooling technologies in Al-Huban, Yemen. It also provides valuable insights into the feasibility and benefits of such an integrated system design.

Table 2. Specifications and parameters of the proposed solar energy system.

Parameter	Value
PV System Size	500KW
Cooling System	Variable Refrigerant Flow (VRF) and Thermal Energy Storage (TES) systems.
Meteorological Data Source:	Meteonorm.
Tilt Angle	17.5°
Global on Collector Plane	2438 kWh/m²
Transportation Factor FT	1.04
Loss with Respect to Optimum	0.0%
Annual Energy Production	1060 MWh
Cooling System Consumption	841 MWh
Key parameters	
Module Type	Monocrystalline silicon.
Inverter Type	High-efficiency central inverters.
System Configuration	Optimal tilt and azimuth angles, minimal shading.

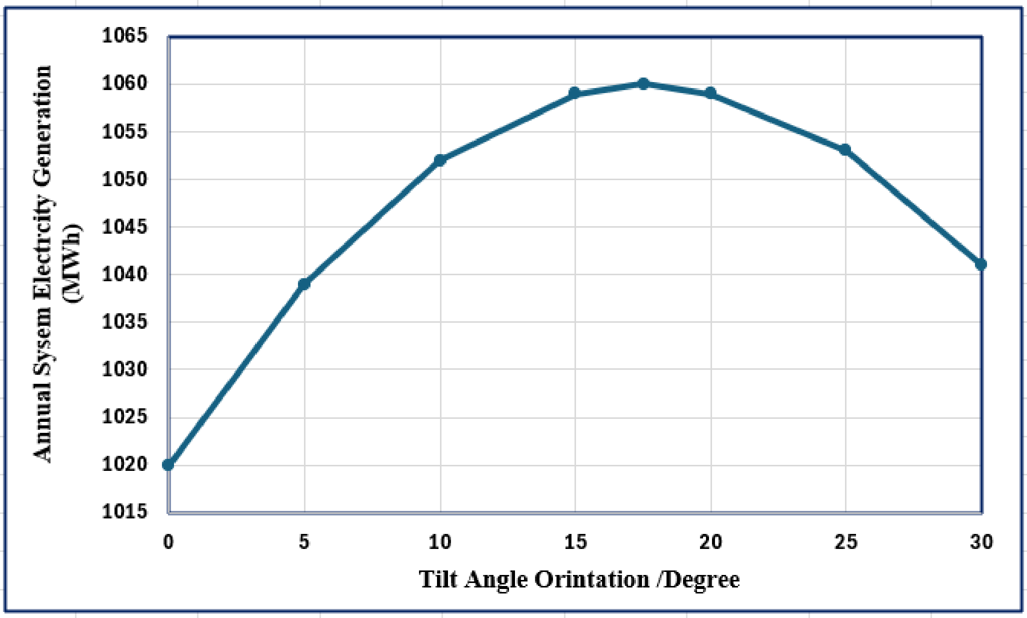

Figure 2. A plot showing the optimum tilt angle orientation for maximizing energy output according to the selected site. The analysis was perofrmed using PVsyst software

4.2. Energy conservation and efficiency enhancement

The data entered to the PVsyst, which includes system capacity, tilt angle, inverter properties, solar radiation and climate data, VRF characteristics, TES characteristics, cooling system features, and other energy values are described in the methodology section and are input for the system. In the next step, the simulation PVsyst manipulates these data to obtain the results and draw the required graphs.

Based on the above initial data, the PVsyst computation outcomes for Taiz Al-Huban reveal positive energy performance under an integrated 500 KW PV system and enhanced cooling techniques. The findings presented in **Figure 3** provide a comprehensive analysis of seasonal variations in solar energy availability and cooling demand, underscoring the effectiveness of integrating effective storage systems.

The chiller operates with a water flow rate of 18-20 m^3/h, outlet temperature of 7°C, and an inlet temperature of 12°C. Furthermore, its dynamic range is for inlet temperature ±2 °C and outlet temperature ±1 °C. That is to facilitate effective thermal regulation for both the VRF & TES apparatus. The analysis highlights the significant benefits of VRF and TES systems in improving energy efficiency and reducing cooling energy consumption.

Figure 3(a) illustrates the impact of incorporating the VRF into the solar system; it provides flexible control of cooling distribution according to need, resulting in an average energy savings of 8.89%. Its performance is enhanced during high-temperature months, optimizing cooling efficiency, though its impact is lower during transitional months due to reduced cooling demand. The results shown in **Figure 3(b)** demonstrate greater energy savings up to 15.91%, plausibly due to the incorporation of the TES system, which stores excess energy and improves overall system performance. Nonetheless, variations in charge and discharge cycles lead to minor changes throughout the year, although the overall savings are maintained at a constant level.

The results of **Figure 3(c)** indicate that energy savings of 24.79% are gained, particularly during the summer months when cooling consumption is high. It also helps in managing the peak demand and contributes to saving a considerable amount of costs associated with the load factor. Moreover, the use of the combined system supports the utilization of RE sources, especially in solar energy production.

Similarly, **Figure 3(d)** further shows the energy consumption pattern in terms of MWh. It also shows that by implementing TES and VRF, appreciable amounts of energy are conserved. That is because a decrease in monthly cooling demand is observed, as the average demand is approximately 46 MWh in November, December, January, and February due to climate change and the decrease in temperature during this period. Then the temperature begins to rise in March and April, and with it the cooling need increases by an average of 62 MWh per month until it reaches its peak in May, June, July, and August with an average of 97 MWh per month. After that, climate change begins, and the temperature begins to decrease in September and October, with an average of 80 MWh during the month.

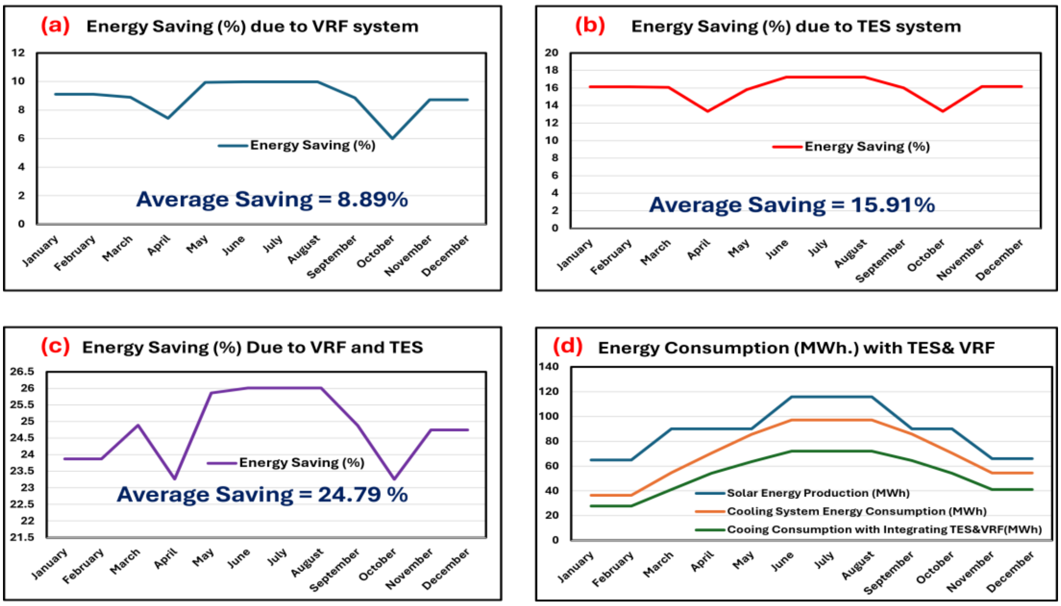

Figure 3. Graphs show the amount of energy saved due to the present system. i.e. monthly solar energy production vs. cooling energy consumption with and without the integrated system.

In conclusion, the integration of VRF and TES into solar PV systems provides effective cooling solutions, accompanied by reduced energy consumption and operation costs. These features make this approach most suitable for locations with high cooling demand and irregular solar power supply, where a combination of efficient energy storage solutions could achieve long-term energy management, peak cooling loads, and overall system performance. Moreover, the availability of excess energy demonstrates the potential of grid export techniques and underlines the effectiveness of sustainable and energy-efficient cooling technology in industrial needs.

4.3. Performance Ratio and Loss Analysis

The performance ratio (PR) of the analyzed PV system was measured at 85.1%, indicating efficient energy conversion (**Table 3**). PR is a key parameter for assessing the overall efficiency of the PV system in harnessing solar energy to generate usable electricity, considering losses. A higher PR reflects fewer energy losses and serves as an important benchmark for evaluating system performance and identifying potential areas for optimization.

The losses detailed in **Table 3** show that module quality, mismatch, DC and AC wiring, shading, and thermal effects are all within acceptable limits. However, the system experiences a 14.9% deviation from optimal conditions, primarily due to temperature-related losses (-7.0%), mismatch losses in modules and strings (-2.1%), battery losses (-2%), and ohmic wiring losses (-1.3%). Despite these losses, the overall PR remains favorable, reinforcing the system's reliability and operational efficiency. Furthermore, the findings confirm that the PV system operates with high efficiency, with an 85.1% performance ratio that reflects its effective energy conversion capability. While losses remain within manageable limits, targeted optimizations could further reduce inefficiencies, paving the way for a more robust and sustainable PV system.

Table 3. Performance ratio and loss analysis calculation of the proposed PV-based solar system.

Loss Component	Value (%)
IAM factor on global	-1.6
PV loss due to irradiance level	-0.2
PV loss due to temperature	-7.0
Module quality loss	+0.7
Mismatch loss (modules and strings)	-2.1
Ohmic wiring loss	-1.3
Inverter Loss during operation	-1.4
Batteries loss	-2
Loss with Respect to Optimum	0.0
Performance Ratio (PR)	85.1

5. Economic and environmental feasibility analysis

The economic feasibility of the proposed system is evaluated by calculating the Return on Investment (ROI) based on key financial parameters. An initial investment of $993,532 is required, as shown in **Table 4**, with an annual production capacity of 1,060 MWh. At an electricity price of $0.40 per kWh, the annual revenue is estimated at $412,000. Using the ROI formula:

$$ROI = \frac{(Annual\ Revenue - Operational\ Cost)}{Initial\ Investement} \times 100\%$$

The calculation estimated the annual operational cost at $12000; the initial ROI is calculated at 41.5%. Over a project lifespan of 30 years, with a 1% annual degradation in energy production, the total ROI is projected to reach approximately 980%, meaning the investment earns more than 11 times its initial cost. The payback period, which is the time needed to achieve a ROI of 100%, is estimated at around 2.4 years. Overall, by the end of the 30-year period, the total revenue generated by the project is expected to be $11,036,720, demonstrating strong financial viability and long-term profitability.

In an alternative scenario, at the international electricity average cost of $0.10 per kWh, the annual revenue would be $94,000. In this case, the initial ROI would be just 9.46%, and the total ROI over 30 years would decrease to approximately 146.5%. The payback period would be longer, at about 11.1 years. Despite this, the total revenue over the 30-year period would still reach $2,758,000, indicating a feasible but less profitable investment compared to the higher electricity price scenario in Yemen. Overall, implementing the proposed integrated system is economically viable, regardless of the initial average cost of electricity. The very low operational costs and clean, RE sources are additional advantages of this system.

Table 4. Economic viability parameters and main findings of the proposed system

Parameters	Yemen average cost ($0.40/kWh)	International average cost ($0.10/kWh)
Initial Investment	$993,532	$993,532
Annual Production Capacity	1,060 MWh	1,060 MWh
Electricity Price	$0.40 per kWh	$0.10 per kWh
Annual Revenue	$412,000	$94,000
Annual Operational cost	$12000	$12000
Initial ROI	41.5%	9.46%
Annual Degradation	1%	1%
Total ROI (30 years)	980%	146.5%
Payback Period	2.4 years	11.1years
Cumulative Revenue (30 years)	$11,036,720	$2,758,000

Generating electricity using fossil fuels releases various air pollution elements; CO_2 emission is the major concern in the process [25]. Replacing power system generation with the proposed PV system could contribute much to our planet. Generally, the value of CO_2 saved is taken in the range of 0.4-0.9 kg/kWh, based on the alternative source and power plant size. This study benchmarked the grid emission factor at 0.64 kg CO_2/1 kWh, aligning well with Álvarez et al.' study [57]. Accordingly, for an annual energy production of 1,060 MWh, the total CO_2 emissions offset, 678.4 tons, contributing to substantial greenhouse gas mitigation.

Additionally, over its 30-year operational lifespan, the system achieves a net CO_2 reduction of 16,734.4 tons, effectively reducing emissions that conventional power sources would otherwise generate, where this value was calculated after analyzing the avoided emissions from solar energy system operation, estimated at approximately 20,350 tons, minus the emissions resulting from installation and maintenance, which amount to approximately 922 tons over the entire system lifecycle. The effect of the natural deterioration rate of solar panels, averaging 1% per year, was also considered, directly impacting the future production value and the total avoided emissions over the long term.

Over the past 30 years, CO_2 emissions from industrial sites have remained a significant concern, with the industry accounting for approximately 40% of global emissions, primarily due to energy-intensive processes that are based on fossil fuels [58]. Despite improvements in energy efficiency, total emissions have continued to rise, driven by increased production demands, which are projected to double by 2050 [58]. Existing solutions, such as the integration of RE, smart management practices, and advanced quantification strategies, have been proposed to mitigate these emissions effectively [59,60]. For instance, the implementation of energy-efficient technologies could potentially reduce emissions significantly by 2030 [4]. Additionally, innovative approaches for aging facilities, including vent-to-flare conversions and carbon sequestration, could achieve up to 95% emissions reduction over time [61]. These strategies highlight the urgent need for a comprehensive, multifaceted approach to achieve substantial reductions in industrial CO_2 emissions.

6. System Performance:

The performance of the integrated PV system is assessed through key parameters, including the daily input/output diagram, the relationship between array temperature and effective irradiance, and system output power distribution (**Figure 4**). These metrics offer valuable insights into the system's efficiency and effectiveness in energy conservation within industrial settings.

Based on the daily input/output data, the daily activity characterized energy generation and consumption, with high solar generation coinciding with the cooling system's high demands. It enables efficient management of energy resources to match the highest energy use with the maximum solar generation. Furthermore, the distribution of the array temperature to the effective irradiance shows that high irradiance causes high temperatures in the array. This leads to an increase in temperature, which affects the system's efficiency due to thermal losses and thus the importance of cooling. For efficiency, it is suggested that integrating the water circulating and cooling system of PV panels, together with the cooling tower, enables a reduction in the solar panels' working temperature from 35°C to 30°C, thereby boosting efficiency in converting solar energy. In this way, the proposed approach of maintaining system operating temperatures at a level that reduces thermal losses will create a higher level of system efficiency.

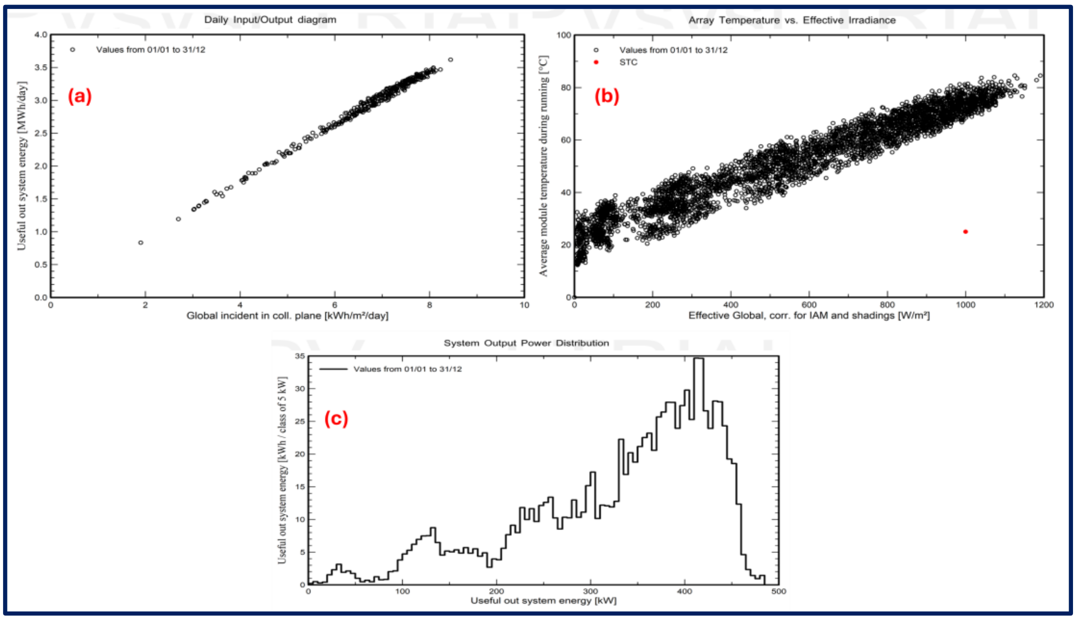

Figure 4. System performance analysis graphs using PVsyst software, (a) daily energy input/output diagram, (b) array temperature vs. effective irradiance, and (c) system output power distribution.

Furthermore, the system output power distribution graph emphasizes the reliability and consistency of the PV system, demonstrating a well-balanced energy output across various times of the day. This stability is essential for industrial operations, ensuring a continuous and efficient power supply. The findings from this study align with previous research conducted in similar climatic conditions. The PVsyst simulation results for the Taiz Al-Huban region, using a fixed tilt angle of 17.5°, are consistent with studies on industrial energy conservation through PV integration.

The observed 14.9% reduction in performance efficiency due to environmental factors, such as irradiance levels and thermal losses **(Figure 4),** aligns with findings by studies from the literature [62], which identified similar challenges in comparable geographic settings, This study emphasizes the importance of effective cooling technologies in mitigating thermal losses and enhancing PV system efficiency. These cooling technologies thus help minimize energy loss in arrays and improve the system's performance in the quest for energy-efficient technologies [63,64]. Particularly, a PV/T hybrid cooling system is incorporated in this study to manage temperatures of the arrays, ensuring that excess heat losses or reduced conversion efficiencies are absent. Besides, it reduces thermal losses, while increasing the efficiency and the reliability of the PV system and hence the sustainability of techsolar as an independent energy source.

These findings are compatible with power distribution and system output in other research studies [65], which noted that fixed-tilt PV systems installed in industrial facilities sustain a consistent electricity generation throughout the day. This reliability is further enhanced when practiced alongside other superior energy management techniques, such as VRF & TES systems [66]. The PV arrays, when operated under varying irradiance conditions, produce output profiles that conform to the typical load profiles of many industries, thus enhancing energy utilization [67, 68]. To conclude, integrating PV/T hybrid cooling, VRF, and TES systems enhances the effectiveness of PV systems at industrial facilities, creating an efficient energy system.

7. Discussion

The use of PV systems in the cooling and air conditioning industries plays a crucial role in promoting energy conservation, sustainability, and efficiency. The PVsyst simulation results indicate an annual energy production of 1,059.89 MWh, with 841 MWh utilized for industrial operations, contributing to a solar fraction of 42.79%.The integration of PV, VRF, and TES has sustained the total annual energy consumption by 25.2%. Specifically, the TES system alone achieved 16% savings, which aligns well with previous research on energy-efficient strategies, showing energy use reductions of 8-20% across various applications [69,70,71,72,73,29]. Similarly, the VRF system achieved a 9% reduction, which is compatible with other recent studies [74, 75]. In numbers, VRF lowers cooling energy demand by 59.50% (630.75 MWh) and achieves energy savings of 19.83% (210.25 MWh).

Additionally, the system produced a 40.49% (429.25 MWh) surplus, indicating opportunities for grid integration, energy storage expansion, or supplementary industrial applications. The performance ratio (PR) of the analyzed PV system is measured at 85.1%. This key finding is consistent with the results of the study of Truong et al., of 83% [76], and Zdyb & Sobczyński of 88% [77]. The system's stable energy output, as observed in the output power distribution graph, underscores its ability to serve as a reliable and RE source. By replacing fossil-fuel-based electricity, the system achieves a net CO_2 reduction of 16,734.4 Tons of CO_2 over its lifetime, reinforcing its role in lowering industrial carbon emissions and other applications [78,79].

Alongside the abovementioned implications, the daily input/output diagram **(Figure 6)** shows a pronounced correlation between system performance and irradiance levels. The output indicated that the maximum energy generation occurs at local noon, which conforms with the former analysis of Nobre et al. [80], who studied PV systems in tropical climates like Penang (Malaysia), and noted that maximum energy yield happened between 10 AM and 2 PM.

These behaviors are critical for maximizing energy use in industrial operations, particularly when accompanied by cooling systems that generally consume high energy during the warmer times throughout the day [81]. It is well stated that industries can greatly decrease their dependence on grid electricity and improve energy efficiency by aligning the energy output from the PV system with the highest cooling demands [82, 83]. Moreover, the output power distribution graph suggests better performance, validating that minor shifts in irradiance do not greatly affect the PV system's ability, offering sufficient output for industrial cooling purposes [84].

This is further confirmed by the efficiency loss, which was estimated by PVsyst simulation to be 10% on average when the temperature of the PV modules is relatively high. This is supported by Jo et al. [85] and Hamid et al. [86], who inferred that PV array temperature influences the efficiency of energy conversion, while high temperatures decrease the efficiency by 15%. However, these losses could be prevented by using different heat management techniques in the systems. On the other hand, Kumar et al. [87] confirmed the application of phase change in an industrial cooling system. It manages the temperatures of the PV arrays [88,89]. Moreover, water-cooling mechanisms engineered into the PV systems help dissipate excess heat, bringing water temperature to the range of 30-35°C, which provides efficient heat exchange and does not affect the efficiency of the panels. Additional advancements in ventilation systems play a role in preventing heat accumulation within a confined environment, thus maintaining the optimum operating temperatures for PV panels.

A way of enhancing the efficiency of industrial cooling is to use PV/T hybrid cooling with TES. It is established that utilizing both conventional and RE systems results in a system efficiency enhancement of 10–15% compared to integrated PV systems [32]. In addition, flexibility is guaranteed during peak loads, grid access, and operation costs are minimized [86]. TES is useful in averting high energy demand points, a factor supported by research done on energy storage in the integration of RE [90,34]. The PVsyst simulation results indicated that the use of PV/T hybrid cooling is inclined to reduce thermal loss and consequently enhance overall system performance. These compatible strategies reduce thermal losses, improve energy proficiency, and thereby result in a remarkable decrease in carbon emissions [91,92]. Like the approach in this study, Dutra and de Souza-Santos [93] explored innovative RE integration strategies, further reinforcing the potential of advanced cooling solutions in mitigating greenhouse gas emissions and PV system sustainability.

The findings further confirm that the fixed-tilt PV system operates at optimal energy efficiency, as observed in integrated systems installed in energy-efficient structures. The water-cooling mechanism contributes to better heat dissipation, and research has also indicated an increase in PV efficiency. TES provides a buffer during peak energy demand, a feature corroborated by studies on energy storage in renewable integration [90,34]. The PVsyst simulation supports this, showing that the system successfully replaces 20,349.8 TCO_2 in emissions over its lifetime, further reinforcing its environmental benefits.

Even though the current simulation results are satisfactory, there is always potential for improvement. Optimization of the system may include the use of higher efficiency modules, robust inverter settings, and computation of shading losses. Thus, further research on systems that integrate solar PV with other forms of renewables, for example, wind or biomass, could offer a healthier and more stable configuration of the appliances.

The application of PV systems in conflict-affected regions of Yemen faces significant scalability challenges due to a combination of infrastructural, political, and economic factors. The ongoing conflict has exacerbated an already dire energy crisis, with many areas lacking basic electricity services, as evidenced by the fact that 58% of healthcare facilities remain without power [94]. The pre-existing low electrification rate, coupled with high energy losses and inefficient service delivery models, complicates the integration of RE sources like PV [95,96] Additionally, the political instability and financial constraints hinder investment in renewable projects, while the lack of institutional capacity further impedes the development of decentralized energy solutions, which are crucial for remote and conflict-impacted areas [96,97]. Thus, while PV technology holds potential, its scalability is severely limited by these multifaceted challenges.

Also, the PV cooling systems face problems such as poor performance in extreme weather conditions and reduced battery life over time. To improve efficiency, panels can be selforientated to track the sun and increase energy production. It's also preferable to replace the water used for cooling with less evaporative liquids to improve cooling efficiency and maintain system stability. These solutions contribute to increasing the efficiency and reliability of solar energy systems and enhancing their sustainability in various operating environments.

8. Conclusions

This study highlights the benefits of integrating solar PV systems with advanced cooling, energy storage technologies (TES), and variable refrigerant flow (VRF) for industrial applications. The PVsyst simulation results confirmed that the proposed system significantly enhances energy efficiency, reduces operational costs, and lowers carbon emissions.

The PVsyst simulation analysis tested various tilt angles in the range of 0° – 30° and predicted that the optimum tilt angle for the Yemeni climate is at 17.5°.The system was exclusively designed for air conditioning purposes at an industrial factory in Al-Huban, Taiz, Yemen. The proposed system is designed to meet Yemen's geographical and geopolitical environment, where the average unit price of electricity is $0.40/ kWh, four times the global average. Furthermore, the proposed system is equipped with cooling systems suitable for hot weather conditions in other Yemeni regions and beyond.

The proposed system was planned with 500 kW of PV solar panels; all arranged in arrays with a fixed tilt angle of 17.5°. The system assumes 6 sunny hours/day, which then proposes to generate 1,060 MWh/year. Interestingly, the integration of PV-VRF-TES has resulted in a reduction in total annual energy consumption of 24.79%, lowering cooling energy demand to 59.50% (630.75 MWh), and achieving energy savings of 19.83% (210.25 MWh). Additionally, the system produced a 40.49% (429.25 MWh) surplus, indicating opportunities for grid integration, energy storage expansion, or supplementary industrial applications.

The economic feasibility analysis confirms that the proposed PV system is a highly viable investment, especially in regions with high electricity costs, such as Yemen. With an initial investment of $993,532 and an annual energy output of 1,060 MWh, the system achieves a rapid payback period of 2.4 years and a substantial ROI of 980% over 30 years at an electricity price of $0.40 per kWh. Again, the system's economic feasibility is based on the global average electricity price of $0.10 per kWh, which is still financially feasible, with a payback period is 11.1 years, and the total ROI is 146.5%. It is equally obvious that its utilization of RE and near-zero operational costs also contribute to its sustainable business model and improved feasibility, whatever the type of electricity price structure in place.

The proposed PV system brings extra economic benefits and is also environmentally friendly and reduces carbon dioxide emissions. The system has made a significant contribution in combating climate change with an annual offset of 678.4 tons and reducing 16,734.4 tons within the next three decades. The use of RE also provides long-term ecological benefits to the environment and hence can be considered as a long-term resource for generation of electricity instead of using fossil fuels.

It is not a financial issue only; the integration of VRF and TES improves energy distribution, load flexibility, and RE integration, while the PV/T hybrid cooling approach effectively mitigates thermal losses as well as improves system performance. These innovations increase industrial energy resilience, ensuring greater reliability, and sustainability in energy management.

The proposed sustainable system agrees with the massive efforts required to bring Yemen's energy sector to a safe level, ensuring an uninterrupted power supply, competitive prices, and environmental cleanliness. Future research should focus on optimizing control algorithms to further enhance system efficiency, along with comprehensive cost-benefit analyses to assess the economic feasibility of expanded energy storage solutions. By refining energy management strategies, these advancements will contribute to the development of a more resilient, cost-effective, and environmentally sustainable industrial energy infrastructure.

References

[1] D. A. Dixit, "the Role of Renewable Energy in Achieving Sustainable Development Goals: a Global Perspective on G20 Nations," *Futur. Trends Manag. Vol. 3 B. 3*, no. November, pp. 91–96, 2024, doi: 10.58532/v3bhma3p2ch3.

[2] A. Kavya and S. Yadav, "Comprehensive Evaluation of the Environmental Footprint Across Energy Sources: Toward Sustainable Solutions," 2023, doi: 10.20944/preprints202312.1241.v1.

[3] D. B. M. Indraganti, "An adaptive relationship of thermal comfort for the Gulf Cooperation Council Countries The case of offices in Qatar," *Energy Build.*, vol. 159, pp. 201–212, 2018, [Online]. Available: https://doi.org/10.1016/j.enbuild.2017.10.087.

[4] K. Kaygusuz, "Energy efficiency and renewable energy sources for industrial sector," *Energy Serv. Fundam. Financ.*, pp. 213–238, 2021.

[5] J. A. G. S. Punchihewa, K. U. C., Abeynayake, A. A. D. I., Weerasinghe, T. S., Wijewardane, A., Amarasinghe, S., & Jayasekara, "Applicability of Eco-friendly Solar Adsorption Refrigeration Systems to reduce the energy consumption in industrial refrigeration applications," *Moratuwa Eng. Res. Conf.*, pp. 225–230, 2023.

[6] M. Rossi, C. Favi, M. Germani, and M. Omicioli, "Comparative life cycle assessment of refrigeration systems for food cooling: eco-design actions towards machines with natural refrigerants," *Int. J. Sustain. Eng.*, vol. 14, no. 6, pp. 1623–1646, 2021, doi: 10.1080/19397038.2021.1970274.

[7] E. R. Suryaman, N. N., & Noordianto, "ANALISA HASIL UJI KOMPRESOR SISTEM REFRIGERASI MENGGUNAKAN INVERTER," *J-ENSITEC*, vol. 10, no. 01, pp. 966–971, 2023.

[8] K. Kaushik and V. Naik, "An Energy Consumption Dataset for Ductless-split Cooling Systems to Train Large Models," *BuildSys 2023 - Proc. the10th ACM Int. Conf. Syst. Energy-Efficient Build. Cities, Transp.*, pp. 216–219, 2023, doi: 10.1145/3600100.3623721.

[9] M. Bayram, I. S., Al-Qahtani, M., Saffouri, F., & Koç, "Estimating-the-Cost-of-Summer-Cooling-in-Bahrain." In 2017 9th IEEE-GCC Conference and Exhibition (GCCCE), pp. 1–9, 2017.

[10] M. Narayanan, R., Anazi, A. A. A., Pippia, R., & Rasul, "Design Optimization of Solar Desiccant Cooling System for the Climatic Condition of Kuwait." In AIP Conference Proceedings, 2022.

[11] A. Al-Eryani, "The Political Economy of Energy Security in Wartime Yemen. Middle East Law and Governance," *Middle East Law Gov.*, 2024, [Online]. Available: https://doi.org/10.1163/18763375-20241480

[12] B. S. Watol, "The Post-2011 Yemen Internationalized Civil War: It's National, Regional and Global Implications," *European Journal of Arts, Humanities and Social Sciences*, vol. 1, no. 4. pp. 3–25, 2024. doi: 10.59324/ejahss.2024.1(4).01.

[13] I. M. M. Aboelkheir, "Review of Literature on Political Risks to the Operations of Large Oil & Gas Companies and Their Mitigation in Yemen," *Cogniz. J.*, vol. 2, no. 4, pp. 7–23, 2022, [Online]. Available: https://doi.org/10.47760/cognizance.2022.v02i04.002

[14] R. Poornima, B. G., & Ramesh, "Yemen's Survival Quandary: The Compounding Effects of Conflict and Climate Obstruction," vol. 18, pp. 264–279, 2023, [Online]. Available: https://doi.org/10.1177/15423166231197807

[15] N. Alomaisi, "Political Instability and Economic Growth in the State of Yemen Analysis Study," *Journal of Public Administration and Governance*, vol. 10, no. 2. p. 233, 2020. doi: 10.5296/jpag.v10i2.16311.

[16] M. A. Rasuli and S. Torii, "A review on solar air conditioning systems," *J. Sustain. Energy Revolut.*, vol. 4, no. 1, pp. 1–13, 2024, doi: 10.37357/1068/jser/4.1.01.

[17] F. Ahmed, Y. E., Maghami, M. R., Pasupuleti, J., Danook, S. H., & Basim Ismail, "Overview of Recent Solar Photovoltaic Cooling System Approach.," *Technologies*, vol. 12, no. 9, 2024.

[18] F. Ayadi, O., Rinchi, B., & Alsaleem, "Experimental Evaluation of a Solar-Powered Air Conditioner," *Sol. Energy*, vol. 272, p. 112466, 2024.

[19] F. Ghaith, T. Siddiqui, and M. Nour, "Design of Solar-Powered Cooling Systems Using Concentrating Photovoltaic/Thermal Systems for Residential Applications," *Energies*, vol. 17, no. 18, 2024, doi: 10.3390/en17184558.

[20] T. Ibrahim, M. Abou Akrouch, F. Hachem, M. Ramadan, H. S. Ramadan, and M. Khaled, "Cooling Techniques for Enhanced Efficiency of Photovoltaic Panels—Comparative Analysis with Environmental and Economic Insights," *Energies*, vol. 17, no. 3, 2024, doi: 10.3390/en17030713.

[21] K. I. Ohenhen, P. E., Chidolue, O., Umoh, A. A., Ngozichukwu, B., Fafure, A. V., Ilojianya, V. I., & Ibekwe, "Sustainable cooling solutions for electronics: A comprehensive review: Investigating the latest techniques and materials, their effectiveness in mechanical applications, and associated environmental benefits," *World J. Adv. Res. Rev.*, vol. 21, no. 1, pp. 957–972, 2024, doi: 10.30574/wjarr.2024.21.1.0111.

[22] S. S. C. G. Senarathna, D. S. N., Waidyasekara, K. G. A. S., & Vidana, "Efficiency and adaptability: a study on variable refrigerant flow (VRF) air conditioning systems in Sri Lanka," *Prop. Manag.*, 2024.

[23] H. I. M. M. T. H. M. Ali, T. U. Rehman, M. Arıcı, Z. Said, B. Duraković, "Advances in thermal energy storage: Fundamentals and applications," *Prog. Energy Combust. Sci.*, vol. 100, p. 101109, 2024.

[24] A. I. and M. Zribi, "Maximum power point tracking of a standalone photovoltaic system using electromagnetic field optimization algorithm," *Int. J. Energy Environ. Eng.*, vol. 14, no. 4, pp. 961–971, 2023, [Online]. Available: doi: 10.1007/s40095-023-00560-6.

[25] A. Godlonton, C. M. Borain, A. J. Isafiade, K. Möller, and T. Chitsiga, "Synthesis and Optimisation of an Integrated Renewable Energy and Greenhouse Network," *Process Integr. Optim. Sustain.*, vol. 8, no. 3, pp. 791–811, 2024, doi: 10.1007/s41660-023-00386-z.

[26] G. D. Eddine, R. Stéphane, A. Nadine, S. Alain, and L. Damien, "Optimizing Thermal Management with Regulated Jet Impingement Boiling Cooling and Transverse Airflow: A Parametric Analysis," *Proc. 9th World Congr. Momentum, Heat Mass Transf.*, 2024, doi: 10.11159/enfht24.273.

[27] L. C. DAS, A. S. M. MOHIUL ISLAM, S. AKTAR, and F. SULTANA, "Climate Change Challenges in Bangladesh," *Int. J. Big Data Min. Glob. Warm.*, vol. 06, no. 01, 2024, doi: 10.1142/s263053482430001x.

[28] M. Koşan, M., Dilber, Y., Erten, S., Bahar, E. M., Erdoğmuş, F. N., Aktaş, M., & Öder, "Investigation of the effects of fan control technique on energy consumption in industrial refrigerated display cabinet: An experimental study," *Proc. Inst. Mech. Eng. Part E J. Process Mech. Eng.*, vol. 238, no. 1, pp. 227–239, 2024.

[29] C. Dai, W., Xia, W., Li, B., Goh, H., Zhang, Z., Wen, F., & Ding, "Increase the integration of renewable energy using flexibility of source-network-load-storage in district cooling system.," *J. Clean. Prod.*, vol. 144, p. 140682, 2024.

[30] H. SINGH, H., & SINGH, "RECENT TRENDS IN SOLAR THERMAL COOLING TECHNOLOGIES," *i-Manager's J. Mech. Eng.*, vol. 14, no. 2, 2024.

[31] O. Y. Odufuwa, K. Kusakana, B. P. Numbi, and L. K. Tartibu, "Optimal energy management of grid-connected PV for HVAC cooling with ice thermal storage system," *J. Energy Storage*, vol. 77, no. November 2023, p. 109844, 2024, doi: 10.1016/j.est.2023.109844.

[32] S. Shapoval *et al.*, "Ecological and energy aspects of using the combined solar collectors for low-energy houses," *Chem. Chem. Technol.*, vol. 11, no. 4, pp. 503–508, 2017, doi: 10.23939/chcht11.04.503.

[33] V. Zhelykh, I. Venhryn, K. Kozak, and S. Shapoval, "Solar collectors integrated into transparent facades," *Prod. Eng. Arch.*, vol. 26, no. 3, pp. 84–87, 2020, doi: 10.30657/pea.2020.26.17.

[34] K. Roy, A., Ramanan, A., Kumar, B., Abraham, C. A., Hammer, A., Barykina, E., ... & Balaraman, "Development of a day-ahead solar power forecasting model chain for a 250 MW PV park in India," *Int. J. Energy Environ. Eng.*, vol. 14, no. 4, pp. 973–989, 2023, doi: 10.1007/s40095-023-00560-6.

[35] Y. Ulewicz, M., Zhelykh, V., Kozak, K., Furdas, "Application of thermosiphon solar collectors for ventilation of premises," *Lect. Notes Civ. Eng.*, vol. 47, pp. 180–187, 2020, [Online]. Available: doi: 10.1007/978-3-030-27011-7_23.

[36] B. Venhryn, I., Shapoval, S., Zhelykh, V., Gulai, "Experimental Studies of Energy Efficiency of a Thermal Photovoltaic Hybrid Solar Collector Under the Influence of Wind Flow," *Lect. Notes Civ. Eng.*, vol. 290, pp. 424–431, 2023, [Online]. Available: https://doi.org/10.1007/978-3-031-14141-6_43

[37] B. Shapoval, S., Zhelykh, V., Pryimak, O., & Gulai, "Integrated Solar Collectors in External Protection for Energy-Efficient Buildings," *Lect. Notes Civ. Eng.*, vol. 438, pp. 392–398, 2024, [Online]. Available: doi: 10.1007/978-3-031-44955-0_39.

[38] M. P. Shah and P. Kaur, *Biomass Energy for Sustainable Development*, no. March. 2024. doi: 10.1201/9781003406501.

[39] A. P. G. R. G. Barone, A. Buonomano, C. Forzano, G. F. Giuzio, "A comprehensive review on solar to thermal energy conversion and storage using phase change materials," *J. Energy Storage*, vol. 72, p. 108280, 2023.

[40] G. Barone, G., Buonomano, A., Forzano, C., Giuzio, G. F., Palombo, A., & Russo, "A new thermal comfort model based on physiological parameters for the smart design and control of energy-efficient HVAC systems," *Renew. Sustain. Energy Rev.*, vol. 173, p. 113015, 2023.

[41] B. Delač, B. Pavković, and V. Glažar, "Economic and Energetic Assessment and Comparison of Solar Heating and Cooling Systems," *Energies*, vol. 16, no. 3, 2023, doi: 10.3390/en16031241.

[42] M. Khalid, "Smart grids and renewable energy systems: Perspectives and grid integration challenges," *Energy Strateg. Rev.*, vol. 51, no. January, p. 101299, 2024, doi: 10.1016/j.esr.2024.101299.

[43] S. Mubaarak *et al.*, "Potential techno-economic feasibility of hybrid energy systems for electrifying various consumers in Yemen," *Sustainability (Switzerland)*, vol. 13, no. 1. pp. 1–24, 2021. doi: 10.3390/su13010228.

[44] A. M. Ajlan, A., Tan, C. W., & Abdilahi, "Assessment of environmental and economic perspectives for renewable-based hybrid power system in Yemen," *Renew. Sustain. Energy Rev.*, vol. 75, no. 75, pp. 559–570, 2017, [Online]. Available: https://doi.org/10.1016/J.RSER.2016.11.024

[45] M. A. Albasheri, M. A. H. Mujammal, O. Bouchhida, Y. Soufi, and A. Cherifi, "Affordable Clean Energy Through Optimized Hybrid Microgrid Design in Yemen." 2024. [Online]. Available: https://www.researchsquare.com/article/rs-5707101/v1

[46] R. Saeed, Y. A., Muqbel, M. A., & Al-Rebati, "Techno-Economical Analysis of Solar PV Systems for Electrification of Workers' Buildings at Al-Wahdah Cement Factory–Yemen.," 2023, [Online]. Available: https://doi.org/10.1109/esmarta59349.2023.10293333

[47] A. Hadwan, M., & Alkholidi, "Solar power energy solutions for Yemeni rural villages and desert communities," *Renew. Sustain. Energy Rev.*, vol. 57, pp. 838–849, 2016, [Online]. Available: https://doi.org/10.1016/J.RSER.2015.12.125

[48] PVsyst, "PVsyst: Photovoltaic Software for Professionals." Accessed: Jul. 23, 2024. [Online]. Available: https://www.pvsyst.com

[49] A. Maalouf, T. Okoroafor, Z. Jehl, V. Babu, and S. Resalati, "A comprehensive review on life cycle assessment of commercial and emerging thin-film solar cell systems," *Renew. Sustain. Energy Rev.*, vol. 186, no. August, p. 113652, 2023, doi: 10.1016/j.rser.2023.113652.

[50] T. A. N. M. M. Ray, M. F. Kabir, M. Raihan, A. B. M. Noushad Bhuiyan, "Performance evaluation of monocrystalline and polycrystalline-based solar cell," *Int. J. Energy Environ. Eng.*, vol. 14, no. 4, pp. 949–960, 2023, [Online]. Available: doi: 10.1007/s40095-023-00560-6.

[51] A. Kaddour, L. Benmebrouk, S. A. Bekkouche, B. Benyoucef, S. Bezari, and R. Khenniche, "Improvement of the Stand-Alone PV System Performance by PVSYST Software," *Proc. 2019 7th Int. Renew. Sustain. Energy Conf. IRSEC 2019*, 2019, doi: 10.1109/IRSEC48032.2019.9078290.

[52] M. B. and H. K. Channi, "Analysis and design of solar PV system using PVSYST software," *Mater. Today Proc.*, vol. 48, pp. 1332–1338, 2022.

[53] M. Ahmad, F. F., Abdelsalam, M., Hamid, A. K., Ghenai, C., Obaid, W., & Bettayeb, "Experimental Validation of PVSYST Simulation for Fix Oriented and Azimuth Tracking Solar PV System," *Model. Simul. Intell. Comput. Proc. MoSICom2020*, pp. 227–235, 2020.

[54] Sunheron, "Weather and Climate in Taʿizz, Yemen," Sunheron." Accessed: Jul. 29, 2025. [Online]. Available: https://www.sunheron.com/cities/yemen/taizz-weather-climate/

[55] W. Atlas, "Taʿizz, Yemen - Climate data," Weather Atlas. Accessed: Jul. 29, 2025. [Online]. Available: https://www.weather-atlas.com/en/yemen/taizz-climate

[56] Meteonorm, "Meteonorm: The Global Meteorological Database." [Online]. Available: https://meteonorm.com/

[57] R. Álvarez, M., Cuello, N., & Berigüete, "Determination of the Grid CO_2 Emission Factor for the Electrical System of the Dominican Republic," *Soc. Sci. Res. Netw.*, 2013, [Online]. Available: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2399961

[58] P. S. Brown, T., & Fennell, "Reducing CO_2 emissions from heavy industry: a review of technologies and considerations for policy makers," 2012.

[59] J. Huang and X. Tao, "Bridging Gaps in Carbon Emission Assessment: Optimization Strategies for Industrial Parks," *E3S Web of Conferences*, vol. 580. 2024. doi: 10.1051/e3sconf/202458002015.

[60] H. Feng, D., Xu, W., Gao, X., Yang, Y., Feng, S., Yang, X., & Li, "Carbon Emission Prediction and the Reduction Pathway in Industrial Parks: A Scenario Analysis Based on the Integration of the LEAP Model with LMDI

Decomposition," *Energies*, 2023, [Online]. Available: https://doi.org/10.3390/en16217356

[61] "Towards Realising Net Zero Carbon Emissions for Sustainability of Existing and Aging Offshore Facilities," 2022, [Online]. Available: https://doi.org/10.4043/31408-ms

[62] S. F. Ahmed *et al.*, "Integration of phase change materials in improving the performance of heating, cooling, and clean energy storage systems: An overview," *J. Clean. Prod.*, vol. 364, 2022, doi: 10.1016/j.jclepro.2022.132639.

[63] A. P. G. R. G. Barone, A. Buonomano, C. Forzano, G. F. Giuzio, "A sub-system design comparison of renewable energy based multi-generation systems: A key review along with illustrative energetic and exergetic analyses of a geothermal energy based system.," *Sustain. Cities Soc*, vol. 82, p. 103893, 2022.

[64] J. Tarragona, C. Fernández, L. F. Cabeza, and A. de Gracia, "Model predictive control applied to a heating system with PV panels and thermal energy storage," *Build. Simul. Conf. Proc.*, vol. 4, pp. 2836–2843, 2020, doi: 10.26868/25222708. 2019.210319.

[65] D. P. P. J. Y. M. A. Zahid, M. de Assis Rabelo, H. Yousuf, Y. Kim, "Anti-reflective coating and cooling technique for innovative photovoltaic system in tropical region," *J. Power Sources*, vol. 564, p. 232812, 2023.

[66] M. Ahmad, M. Zeeshan, and J. A. Khan, "Life cycle multi-objective (geospatial, techno-economic, and environmental) feasibility and potential assessment of utility scale photovoltaic power plants," *Energy Convers. Manag.*, vol. 291, pp. 1–49, 2023, doi: 10.1016/j.enconman.2023.117260.

[67] A. Alahmer and S. Ajib, "Solar cooling technologies: State of art and perspectives," *Energy Convers. Manag.*, vol. 214, no. May, 2020, doi: 10.1016/j.enconman.2020.112896.

[68] P. Dwivedi, K. Sudhakar, A. Soni, E. Solomin, and I. Kirpichnikova, "Advanced cooling techniques of P.V. modules: A state of art," *Case Stud. Therm. Eng.*, vol. 21, no. December 2019, p. 100674, 2020, doi: 10.1016/j.csite.2020. 100674.

[69] M. Al-Atari, Z., Shipman, R., & Gillott, "Optimisation of Integrated Heat Pump and Thermal Energy Storage Systems in Active Buildings for Community Heat Decarbonisation," *Energies*, 2024.

[70] E. Abdollahi, S. A., Faramarzi, S., Ranjbar, S. F., Hashemi, K., Majidi, H. R., & Gholamian, "An Innovative Energy Storage System Based on Phase Change Material and Solar Energy Integrated With an Air Handling Unit to Produce Heating and Cooling," *Energy Storage*, vol. 6, no. 6, 2024.

[71] A. I. Biyanto, T. R., Alhikami, A. F., Nugroho, G., Bayuaji, R., Firmanto, H., Waluyo, J., & Sonhaji, "Thermal energy storage optimization in shopping center buildings," *J. Eng. Technol. Sci.*, vol. 47, no. 5, pp. 549–567, 2015.

[72] B. Yau, Y. H., & Rismanchi, "A review on cool thermal storage technologies and operating strategies," *Renew. Sustain. energy Rev.*, vol. 16, no. 1, pp. 787-797.2012 ,.

[73] Y. Wang, Y., Wang, X., & Zhang, "Leveraging thermal storage to cut the electricity bill for datacenter cooling," *Proc. 4th Work. Power-Aware Comput. Syst.*, 2011.

[74] D. K. Patel, K., Jain, P. K., & Koli, "A Review of a HVAC With VRF System," 2015.

[75] Y. H. Lee, J. H., & Song, "Annual effect of the VRF control algorithm in response to the TOU rate plan," *Sustainability*, vol. 15, no. 10, p. 7751, 2023.

[76] D. Zdyb, A., & Sobczyński, "AnAssessment of a Photovoltaic System's Performance Based on the Measurements of Electric Parameters under Changing External Conditions," *Energies*, vol. 17, no. 9, p. 2197, 2024.

[77] P.-L. Truong, L. P., Bui, V.-T., & Le, "A methodology for performance evaluation and system loss analysis of photovoltaic power plants: case studies in Vietnam," *Int. J. Power Electron. Drive Syst.*, vol. 14, no. 4, p. 2674, 2024.

[78] M. M. Abdullahi *et al.*, "A review of building integrated photovoltaic: Case study of tropical climatic regions," *Int. J. Power Electron. Drive Syst.*, vol. 12, no. 1, pp. 474–488, 2021, doi: 10.11591/ijpeds.v12.i1.pp474-488.

[79] R. Azwardi, A., Andaiyani, S., & Pertiwi, "Renewable Energy Consumption, Trade Openess, and Climate Change in Asia Emerging Market Countries," *J. Renew. Energy Environ.*, vol. 11, no. 2, pp. 132–137, 2024.

[80] A. M. Nobre, S. Karthik, W. Y. Liew, R. Baker, R. Malhotra, and A. Khor, "Performance Evaluation of a Fleet of Photovoltaic Systems Across India and Southeast Asia," *Conf. Rec. IEEE Photovolt. Spec. Conf.*, pp. 1372–1376, 2019, doi: 10.1109/PVSC40753.2019.8981226.

[81] K. Kunaifi, A. Reinders, S. Lindig, M. Jaeger, and D. Moser, "Operational performance and degradation of PV systems consisting of six technologies in three climates," *Appl. Sci.*, vol. 10, no. 16, 2020, doi: 10.3390/APP10165412.

[82] G. Osma-Pinto and G. Ordóñez-Plata, "Dynamic thermal modelling for the prediction of the operating temperature of a PV panel with an integrated cooling system," *Renew. Energy*, vol. 152, pp. 1041–1054, 2020, doi: 10.1016/j.renene. 2020.01.132.

[83] M. Sharaf, M. S. Yousef, and A. S. Huzayyin, "Review of cooling techniques used to enhance the efficiency of photovoltaic power systems," *Environ. Sci. Pollut. Res.*, vol. 29, no. 18, pp. 26131–26159, 2022, doi: 10.1007/s11356-022-18719-9.

[84] H. Ş. A. J. P. M. S. K. Pathak, P. O. Sharma, V. Goel, S. Bhattacharyya, "A detailed review on the performance of photovoltaic/thermal system using various cooling methods," *Sustain. Energy Technol. Assess.*, vol. 51, p. 101844, 2022.

[85] S. Jo, H. H., Kang, Y., Yang, S., Kim, Y. U., Yun, B. Y., Chang, J. D., & Kim, "Application and evaluation of phase change materials for improving photovoltaic power generation efficiency and roof overheating reduction," *Renew. Energy*, vol. 195, pp. 1412–1425, 2022, doi: 10.1016/j.renene.2022.06.119.

[86] A. K. Hamid, N. T. Mbungu, A. Elnady, R. C. Bansal, A. A. Ismail, and M. A. AlShabi, "A systematic review of grid-connected photovoltaic and photovoltaic/thermal systems: Benefits, challenges and mitigation," *Energy Environ.*, vol. 34, no. 7, pp. 2775–2814, 2023, doi: 10.1177/ 0958305X221117617.

[87] F. Kumar, N. M., Yadav, S. K., Chopra, S. S., Bajpai, U., Gupta, R. P., Padmanaban, S., & Blaabjerg, "Operational performance of on-grid solar photovoltaic system integrated into pre-fabricated portable cabin buildings in warm and temperate climates," *Energy Sustain. Dev.*, vol. 57, no. June, pp. 109–118, 2020, doi: 10.1016/j.esd.2020.05.008.

[88] H. Kim, H., Oh, J., Hong, J., Choi, H., Kim, H., & Lee, "Design optimization of finned multi-tube PCM heat exchanger for enhancing EV energy performance," *Appl. Therm. Eng.*, vol. 124477, 2024.

[89] S. Ahmadzadehtalatapeh, M., & Khaki, "Application of Phase Change Material (PCM) for Cooling Load Reduction in Lightweight and Heavyweight Buildings: Case Study of a High Cooling Load Region of Iran," *J. Renew. Energy Environ.*, vol. 5, no. 2, pp. 31–40, 2018.

[90] V. Zhelykh, M. Ulewicz, K. Kozak, O. Savchenko, and M. Kasynets, "Analysis of the Influence of the Heat-Absorbing Surface of an Air-Cooled Solar Collector on Its Thermal and Mechanical Properties," *Syst. Saf. Hum. - Tech. Facil. - Environ.*, vol. 1, no. 1, pp. 481–489, 2019, doi: 10.2478/czoto-2019-0062.

[91] R. Chandel, S. S. Chandel, and A. Khosla, "Modelling and experimental investigation of cooling of field-operating PV panels using thermoelectric devices for enhanced power generation by industrial solar plants," *Next Energy*, vol. 5,

no. July, p. 100162, 2024, doi: 10.1016/j.nxener.2024.100162.

[92] M. A. Fakhrulddin, E. F. Abbas, and J. A. Yagoob, "Assessment of thermal performance of PV/T collectors under different enhancement methods: A review study," *AIP Conf. Proc.*, vol. 2862, no. 1, 2023, doi: 10.1063/5.0171450.

[93] A. O. D. and M. L. de Souza-Santos, "Mitigation of greenhouse gas emissions from power generation through cofiring coal and raw glycerol: a theoretical feasibility study," *Int. J. Energy Environ. Eng.*, vol. 14, no. 4, pp. 905–920, 2023, doi: doi: 10.1007/s40095-023-00560-6.

[94] P. Al-akori, A., Ansari, D., Cader, C., Brahim, W., & Blechinger, "Conflict, health, and electricity: An empirical assessment of the electrification of healthcare facilities in Yemen," *Energy Res. Soc. Sci.*, vol. 95, p. 102905, 2023, [Online]. Available: https://doi.org/10.1016/j.erss.2022.102905

[95] E. M. Huenteler, J., Khanna, A., Badiei, S., Matsuo, T., Maier, E., & Fernstrom, "Republic of Yemen - Restoring and expanding energy access : power sector reengagement note," 2017, [Online]. Available: https://documents.worldbank.org/curated/en/655811496412539032/Republic-of-Yemen-Restoring-and-expanding-energy-access-power-sector-reengagement-note

[96] E. E.-D. Al-Barashi, M. M., Ibrahim, D. K., & Abo El-Zahab, "Evaluating The Energy System in Yemen," vol. 16, no. 1, 2016.

[97] S. Rawea, A., & Urooj, "Strategies, current status, problems of energy and perspectives of Yemen's renewable energy solutions," . *Renew. Sustain. Energy Rev.*, vol. 82, pp. 1655–1663, 2018, [Online]. Available: https://doi.org/10.1016/J.RSER.2017.07.015