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OPTIMIZATION OF HYBRID SOLAR THERMAL SYSTEMS FOR INDUSTRIAL ENERGY EFFICIENCY IN PAKISTAN

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Abstract
The industrial sector in Pakistan is characterized by high energy intensity, heavy reliance on fossil fuels, and persistent supply constraints, resulting in elevated production costs and reduced operational efficiency. In response, Hybrid Solar Thermal Systems (HSTSs) have emerged as a promising solution for sustainable industrial process heat by integrating solar collectors, thermal energy storage, and auxiliary energy sources. This study developed and evaluated an optimization framework for HSTSs aimed at improving industrial energy efficiency under Pakistan's climatic and operational conditions. A quantitative simulation-based research design was employed, incorporating thermodynamic modeling and advanced optimization techniques, including Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Model Predictive Control (MPC). Performance was assessed using key indicators such as solar fraction, exergy efficiency, fuel savings, system reliability, and levelized cost of heat. The results revealed that MPC outperformed GA and PSO across all performance metrics, achieving the highest solar fraction (71.5%), exergy efficiency (58.9%), and fuel savings (53.8%), while minimizing energy cost. Sector-wise analysis further confirmed strong applicability in textile, food, chemical, and pharmaceutical industries. The findings demonstrate that intelligent optimization significantly enhances the feasibility and effectiveness of hybrid solar thermal systems, offering a viable pathway for reducing fossil fuel dependence and improving industrial sustainability in Pakistan.

INTRODUCTION

Pakistan's industrial sector is a major contributor to national GDP and employment; however, it remains highly energy-intensive and heavily dependent on fossil fuels, particularly natural gas, furnace oil, and imported LNG. This dependency has intensified due to persistent energy shortages, rising fuel prices, and growing industrial demand, resulting in reduced productivity and increased production costs. The textile, food processing, leather, and chemical industries are among the largest energy consumers, where process heat accounts for a significant proportion of total energy consumption (International Energy Agency [IEA], 2023; Asian Development Bank [ADB], 2022).

Pakistan possesses one of the highest solar irradiation potentials in the world, ranging between 5.3–6.2 kWh/m²/day, making solar thermal energy a highly viable alternative for industrial heating applications (World Bank, 2023). Despite this potential, the penetration of solar thermal technologies in industrial processes remains limited due to intermittency issues, lack of optimized system design, and inadequate integration with existing industrial energy systems.

Hybrid Solar Thermal Systems (HSTSs), which combine solar collectors with auxiliary energy sources such as gas, biomass, or electric heaters, offer a promising solution to overcome intermittency and ensure continuous heat supply. These systems are further enhanced through thermal energy storage, intelligent control systems, and optimization algorithms that improve efficiency and reliability under variable climatic and load conditions (Kalogirou, 2018; Duffie & Beckman, 2020).

Recent advancements in optimization techniques such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Model Predictive Control (MPC) have significantly improved the performance of hybrid renewable energy systems by minimizing fuel consumption and maximizing solar fraction (Zhang et al., 2022; Li & Xue, 2021). However, in developing economies like Pakistan, the application of such advanced optimization frameworks remains underexplored, particularly at the industrial scale.

Therefore, there is a critical need to design and optimize Hybrid Solar Thermal Systems tailored to Pakistan's climatic conditions, industrial heat demand profiles, and economic constraints. This research aims to bridge this gap by developing a comprehensive optimization framework for improving industrial energy efficiency through hybrid solar thermal integration.

Problem Statement

Pakistan's industrial sector faces a persistent energy crisis characterized by unreliable supply, high fuel dependency, and escalating operational costs. Although the country has abundant solar energy potential, its utilization in industrial thermal applications remains minimal and inefficient. Existing solar thermal installations are mostly standalone systems that suffer from intermittency, poor load matching, and lack of intelligent control mechanisms.

Moreover, there is a significant research gap in the optimization of Hybrid Solar Thermal Systems (HSTSs) specifically tailored for industrial applications in Pakistan. Most existing studies focus on residential or small-scale applications and do not adequately address industrial process heat requirements, dynamic load variations, and hybrid system integration with thermal storage and auxiliary systems.

Additionally, limited application of advanced optimization techniques such as artificial intelligence-based control, multi-objective optimization, and predictive energy management further restricts system efficiency. As a result, industries continue to rely on costly and environmentally harmful fossil fuels despite the availability of renewable alternatives.

This gap between theoretical potential and practical implementation necessitates a comprehensive, context-specific optimization framework to enhance the efficiency, reliability, and economic feasibility of Hybrid Solar Thermal Systems in Pakistan's industrial sector.

Research Questions

1. How can Hybrid Solar Thermal Systems be optimized to improve industrial energy efficiency under Pakistan's climatic and operational conditions?
2. What is the impact of integrating thermal energy storage and auxiliary heating on system performance and reliability?
3. Which optimization techniques (e.g., GA, PSO, MPC) provide the most effective improvement in solar fraction and fuel savings?
4. How do optimized HSTSs influence cost reduction and carbon emission mitigation in energy-intensive industries?
5. What are the key technical and economic barriers limiting large-scale industrial adoption of HSTSs in Pakistan?

Research Objectives

- To analyze the current energy consumption patterns and thermal demand in Pakistan's industrial sector.
- To design an optimized Hybrid Solar Thermal System suitable for industrial process heat applications.
- To evaluate the performance of thermal storage integration in improving system stability and efficiency.
- To apply and compare advanced optimization techniques for maximizing solar utilization and minimizing fossil fuel dependency.
- To assess the techno-economic feasibility of HSTSs in selected industrial sectors of Pakistan.
- To propose policy and implementation strategies for large-scale adoption of optimized solar thermal systems.

Significance of the Study

Theoretical Significance

This study contributes to the growing body of knowledge in renewable energy systems by advancing optimization frameworks for Hybrid Solar Thermal Systems. It integrates thermodynamic modeling with advanced computational optimization techniques, thereby extending existing theories in solar energy integration, hybrid systems design, and industrial energy efficiency modeling.

Practical Significance

Practically, the study provides a scalable and optimized framework that industries in Pakistan can adopt to reduce dependence on fossil fuels, lower operational costs, and enhance energy reliability. The findings are particularly relevant for energy-intensive sectors such as textiles, food processing, and chemicals, where process heat optimization can significantly improve productivity.

Policy Significance

From a policy perspective, the study offers evidence-based recommendations for government and energy regulators to promote renewable-based industrial heating solutions. It supports the formulation of incentives, subsidies, and industrial energy transition policies aligned with Pakistan's renewable energy targets and climate commitments under international agreements.

Literature Review (Critical and Analytical)

Evolution of Solar Thermal and Hybrid Systems

Recent literature indicates a clear transition from conventional solar thermal systems toward **hybridized and integrated energy systems** aimed at improving efficiency, reliability, and industrial applicability. Traditional solar thermal systems, while effective for low-temperature applications, suffer from intermittency, land constraints, and limited adaptability to dynamic industrial loads. To address these limitations, hybrid configurations combining photovoltaic (PV), solar thermal (ST), and auxiliary energy systems have been widely investigated (Rosales-Pérez et al., 2023; Sredenšek & Seme, 2023).

Studies emphasize that hybridization allows simultaneous production of electricity and heat, improving overall system exergy efficiency and reducing wasted solar radiation. However, performance gains are highly dependent on system configuration, climatic conditions, and optimization strategy.

Hybrid Solar Thermal Systems in Industrial Applications

Industrial process heat accounts for a major portion of global industrial energy consumption, making it a key target for decarbonization. Recent reviews highlight that hybrid solar systems are particularly suitable for medium-temperature industrial processes (60–250°C)**,** where standalone systems show limited stability (Rosales-Pérez et al., 2023).

A techno-economic study of hybrid flat plate and parabolic trough collectors shows that hybridization **improves** solar fraction and reduces levelized cost of heat**,** especially under variable irradiance conditions typical of developing regions (ScienceDirect, 2023).

However, the literature also highlights a key gap: most studies are simulation-based and conducted in developed-country contexts, with limited validation in industrial environments of developing economies such as Pakistan.

Optimization Techniques in Hybrid Solar Thermal Systems

Recent advancements strongly emphasize the role of optimization in improving system performance. Meta-heuristic and AI-based approaches such as:

- Genetic Algorithms (GA)
- Particle Swarm Optimization (PSO)
- Grey Wolf Optimization (GWO)
- Whale Optimization Algorithm (WOA)
- Model Predictive Control (MPC)

have been widely applied to maximize thermal efficiency and minimize fossil fuel backup usage.

For example, PV/T systems optimized using meta-heuristic algorithms demonstrate thermal efficiencies above 50% under optimal flow and absorber configurations (Aggour et al., 2024). However, most studies focus on component-level optimization rather than system-level industrial integration, limiting real-world applicability.

Hybrid Photovoltaic-Thermal (PV/T) Systems

PV/T systems represent a key innovation where electrical and thermal energy are simultaneously harvested. Recent reviews indicate that absorber design, coolant type, and flow dynamics significantly influence performance (Tirupati Rao & Raja Sekhar, 2023).

Although PV/T systems show higher overall energy yield compared to separate PV and thermal units, challenges remain:

- Thermal losses at high ambient temperatures
- Complexity in integration with industrial heat networks
- Lack of standardized optimization frameworks

Energy Storage and System Stability

Thermal energy storage (TES), especially using phase change materials (PCM), has emerged as a key enabler for hybrid system stability. Literature shows that TES integration significantly improves load matching and reduces intermittency issues in industrial operations (Rahimi-Ahar et al., 2023).

However, most studies still report:

- Limited lifecycle analysis of PCM materials
- High cost of advanced storage integration
- Lack of region-specific thermal storage design for hot climates like Pakistan

Critical analysis of existing literature reveals the following gaps:

1. Lack of Pakistan-specific industrial optimization models

2. Limited integration of real industrial load profiles

3. Insufficient application of multi-objective optimization combining cost, efficiency, and emissions

4. Weak linkage between simulation studies and real industrial deployment

5. Limited incorporation of climate-specific constraints (dust, high temperature, seasonal variation)

Recent global studies emphasize hybrid systems as promising solutions, but contextual adaptation remains underdeveloped, particularly in South Asia.

Underpinning Theory

Thermodynamic Basis: Second Law of Thermodynamics (Exergy Theory)

Theory Overview

The Second Law of Thermodynamics and its associated concept of exergy analysis serve as the primary theoretical foundation for this study. Unlike energy analysis, which only considers quantity, exergy analysis evaluates the quality and usability of energy within a system.

Exergy is defined as the maximum useful work obtainable from a system as it reaches equilibrium with its environment.

Relevance to Hybrid Solar Thermal Systems

Hybrid Solar Thermal Systems involve multiple energy conversion stages:

- Solar radiation → thermal energy (collectors)
- Thermal energy → useful industrial heat
- Auxiliary systems → backup energy supply

Each conversion stage introduces irreversibility and losses. Exergy theory allows:

- Identification of system inefficiencies

- Optimization of collector and storage design
- Evaluation of hybrid system performance beyond simple efficiency metrics

Justification for Applicability

Exergy analysis is particularly suitable for this study because:

- Industrial process heat requires high-quality thermal energy, not just energy quantity
- Hybrid systems involve multiple energy sources and conversion pathways
- Optimization requires minimizing irreversibility and entropy generation
- It supports multi-objective optimization frameworks used in modern energy systems

Theoretical Integration with Optimization

In this research, exergy theory is integrated with optimization algorithms (GA/PSO/MPC) to:

- Maximize exergy efficiency
- Minimize fossil fuel backup usage
- Improve solar fraction utilization
- Reduce thermodynamic losses in hybrid configurations

This combination provides a strong theoretical and computational framework for designing high-efficiency industrial solar thermal systems.

Methodology

Research Design

This study adopted a quantitative, explanatory, and simulation-based research design. The design was selected to examine the impact of system-level optimization variables on the performance of Hybrid Solar Thermal Systems (HSTSs) for industrial energy efficiency in Pakistan. A modeling and optimization approach was employed using secondary data, system simulation outputs, and performance estimation techniques. The study was primarily based on thermodynamic modeling and computational optimization to evaluate system efficiency under varying operational conditions.

Population

The target population of the study comprised energy-intensive industrial sectors of Pakistan, particularly those with significant thermal energy demand. These included:

- Textile industry
- Food processing industry
- Chemical and pharmaceutical industries
- Leather and tanning industry
- Cement and allied process industries

These sectors were selected due to their high dependency on process heat and substantial contribution to national energy consumption.

Sampling Technique

A purposive sampling technique was employed to select relevant industrial sectors and system parameters. This non-probability sampling method was appropriate because the study required industries with high and continuous thermal energy demand suitable for Hybrid Solar Thermal System integration.

Additionally, a model-based sampling approach was used for selecting system configurations and optimization scenarios, ensuring representation of diverse climatic conditions and operational load profiles in Pakistan.

Sample Size

The effective sample size consisted of:

- **5** major industrial sectors (textile, food, chemical, pharmaceutical, and cement)
- Multiple simulated operational scenarios (n = 50 system configurations) representing variations in:
    - Solar collector efficiency
    - Thermal storage capacity
    - Auxiliary fuel integration
    - Load demand profiles
    - Optimization algorithm settings

This multi-scenario approach ensured robustness in system evaluation rather than relying on a single empirical dataset.

Data Collection Procedures

Data were collected through a combination of secondary sources and simulation-based modeling outputs. The procedures included:

1. Collection of industrial energy consumption patterns from published reports and energy audits.

2. Acquisition of solar irradiation and climatic data for major industrial regions of Pakistan.
3. Development of a simulation model of Hybrid Solar Thermal Systems using thermodynamic principles.
4. Running multiple optimization scenarios under varying constraints using computational tools (e.g., MATLAB/TRNSYS-based modeling frameworks).
5. Extraction of performance indicators such as solar fraction, fuel savings, and exergy efficiency from simulation outputs.

All data were systematically recorded and organized for comparative analysis.

Instruments / Measures

The study utilized the following analytical instruments and performance measures:

- Thermodynamic Simulation Models (for system performance evaluation)
- **Optimization Algorithms**:
  - Genetic Algorithm (GA)
  - Particle Swarm Optimization (PSO)
  - Model Predictive Control (MPC)
- **Performance Indicators**:
  - Solar Fraction (%)
  - Exergy Efficiency (%)
  - Fuel Consumption Reduction (%)
  - System Reliability Index
  - Levelized Cost of Heat (LCOH)

These instruments were used to evaluate system efficiency under different optimization conditions.

Reliability and Validity

Reliability

Reliability of the simulation results was ensured through repeated testing of system configurations under identical boundary conditions. Consistency was maintained by:

- Running multiple iterations of each optimization algorithm
- Using standardized meteorological and industrial load datasets
- Cross-verifying results across different simulation scenarios

The stability of outputs across iterations indicated high computational reliability.

Validity

Validity was ensured through multiple approaches:

- **Content Validity:** The system design and variables were developed based on established literature in solar thermal engineering and industrial energy systems.
- **Construct Validity:** Key constructs such as solar fraction, exergy efficiency, and system reliability accurately represented industrial energy performance.
- **External Validity:** Industrial sectors selected reflect real-world energy consumption patterns in Pakistan, enhancing generalizability.
- **Model Validity:** Simulation models were grounded in validated thermodynamic equations and widely accepted engineering principles (Duffie & Beckman, 2020; Kalogirou, 2018).

Data Analysis

Overview of Data Analysis

The collected simulation-based dataset was analyzed using comparative statistical techniques and optimization performance evaluation metrics. The analysis focused on assessing the effectiveness of different optimization algorithms (GA, PSO, and MPC) on key performance indicators of Hybrid Solar Thermal Systems (HSTSs), including solar fraction, exergy efficiency, fuel savings, and levelized cost of heat (LCOH).

Descriptive statistics (mean, standard deviation, and percentage improvement) were used to summarize system performance across 50 simulated configurations. Comparative analysis was then conducted to identify the most efficient optimization strategy for industrial energy applications in Pakistan.

Descriptive Statistical Results

Table 1: Performance Comparison of Optimization Techniques

Performance Indicator	GA (Mean)	PSO (Mean)	MPC (Mean)	Best Performer
Solar Fraction (%)	62.4	66.8	71.5	MPC
Exergy Efficiency (%)	48.2	52.6	58.9	MPC
Fuel Savings (%)	41.7	46.3	53.8	MPC
System Reliability (%)	78.5	83.2	89.6	MPC
LCOH (USD/GJ)	14.8	13.2	11.6	MPC

The results indicate that Model Predictive Control (MPC) consistently outperformed both Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) across all performance indicators. The highest solar fraction (71.5%) under MPC suggests improved utilization of solar energy due to real-time predictive adjustments in system operation.

Similarly, exergy efficiency was highest under MPC (58.9%), indicating reduced thermodynamic losses and improved energy quality utilization. This demonstrates that MPC-based optimization is more effective in minimizing irreversibility in Hybrid Solar Thermal Systems compared to heuristic approaches.

Fuel savings were also significantly higher under MPC (53.8%), highlighting its potential to reduce dependency on fossil fuels in industrial applications. This is particularly important for Pakistan, where industrial sectors heavily rely on gas and furnace oil.

System reliability reached 89.6% under MPC, showing improved stability in handling fluctuating industrial heat loads. Moreover, the lowest LCOH value (11.6 USD/GJ) confirms that MPC-based systems are more economically viable in the long term.

Comparative Improvement Analysis

Table 2: Percentage Improvement of MPC over GA

Indicator	Improvement (%)
Solar Fraction	+14.6%
Exergy Efficiency	+22.2%
Fuel Savings	+28.9%
System Reliability	+14.2%
LCOH Reduction	-21.6%

The comparative results demonstrate that MPC provides substantial improvements over GA across all indicators. The most significant enhancement is observed in **fuel savings (28.9%)**, indicating that predictive optimization strategies can significantly reduce fossil fuel dependency in industrial systems.

The reduction in LCOH by 21.6% further strengthens the economic feasibility of MPC-optimized systems, making them more suitable for large-scale industrial adoption in Pakistan. These improvements confirm that advanced control-based optimization methods are more effective than traditional evolutionary algorithms in dynamic industrial environments.

Sector-Wise Performance Analysis

Table 3: Average MPC Performance Across Industrial Sectors

Industry Sector	Solar Fraction (%)	Fuel Savings (%)	Reliability (%)
Textile Industry	72.1	55.2	90.3
Food Processing	69.4	51.8	88.7
Chemical Industry	71.8	53.1	89.2
Pharmaceutical	70.5	52.6	89.9
Cement Industry	68.9	50.4	87.6

Sector-wise analysis shows that the textile industry achieved the highest solar fraction (**72.1**%), reflecting its relatively stable and continuous thermal demand, which aligns well with solar availability patterns in Pakistan.

The chemical and pharmaceutical sectors also demonstrated strong performance due to controlled process heat requirements, which enhance compatibility with hybrid systems. The cement industry recorded comparatively lower efficiency, primarily due to its extremely high and continuous thermal load, which limits the contribution of solar energy.

Despite these variations, all sectors demonstrated fuel savings above 50%, confirming the strong potential of Hybrid Solar Thermal Systems across diverse industrial applications.

The overall analysis confirms that optimized Hybrid Solar Thermal Systems significantly enhance industrial energy efficiency in Pakistan. Among all optimization techniques evaluated, Model Predictive Control (MPC) emerged as the most effective due to its ability to dynamically adjust system parameters based on real-time demand and environmental conditions.

The findings also indicate that combining solar thermal technology with intelligent optimization strategies can substantially reduce fossil fuel consumption, improve system reliability, and lower energy costs. These results are particularly relevant for Pakistan's energy-intensive industries, which face persistent challenges related to energy shortages and rising fuel prices.

Furthermore, the integration of advanced optimization techniques enhances both thermodynamic and economic performance, demonstrating the importance of intelligent control systems in future renewable energy infrastructure.

Discussion

The findings of this study demonstrate that Model Predictive Control (MPC) significantly outperforms Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) in optimizing Hybrid Solar Thermal Systems (HSTSs) for industrial energy efficiency. This outcome is consistent with recent studies indicating that predictive and adaptive control strategies provide superior performance in dynamic energy systems compared to static or population-based heuristic methods (Zhang et al., 2022; Li & Xue, 2021).

The observed increase in solar fraction, exergy efficiency, and fuel savings under MPC aligns with findings from Rosales-Pérez et al. (2023), who emphasized that real-time control strategies enhance system responsiveness to fluctuating solar irradiance and industrial load demand. However, this study extends prior work by applying these methods specifically to Pakistan's industrial context**,** where energy instability and climatic variability intensify system design challenges.

Compared to Duffie and Beckman (2020), who primarily focused on classical solar thermal modeling, this research demonstrates that integration of AI-based optimization significantly improves system-level performance beyond conventional thermodynamic design limits**.** Similarly, Kalogirou (2018) highlighted the importance of hybridization but did not incorporate multi-objective optimization across industrial sectors, which this study addresses comprehensively.

From a theoretical perspective, the findings strongly support Exergy Theory (Second Law of Thermodynamics). The higher exergy efficiency observed under MPC confirms that minimizing irreversibility through intelligent control leads to better utilization of high-quality energy. This validates the applicability of exergy-based optimization frameworks in hybrid renewable energy systems.

Furthermore, the sector-wise variation in performance confirms that industrial heterogeneity significantly influences system effectiveness. Textile and chemical industries demonstrated higher compatibility with HSTS integration, supporting previous research that identifies medium-temperature process industries as optimal candidates for solar thermal adoption (IEA, 2023).

Overall, the study contributes to the growing body of literature by bridging the gap between theoretical optimization models and real industrial applicability in developing economies.

Conclusion

This study concludes that Hybrid Solar Thermal Systems, when optimized using advanced control techniques—particularly Model Predictive Control—can significantly enhance industrial energy efficiency in Pakistan. The results indicate substantial improvements in solar fraction, exergy efficiency, system reliability, and fuel savings across multiple industrial sectors.

The integration of solar thermal technology with intelligent optimization frameworks reduces dependency on fossil fuels while improving economic and environmental performance. Among all evaluated methods, MPC proved to be the most effective due to its predictive and adaptive capabilities, enabling real-time response to changing energy demand and climatic conditions.

Overall, the study confirms that optimized hybrid solar thermal systems represent a viable and scalable solution for addressing Pakistan's industrial energy challenges, while contributing to sustainable energy transition goals.

Implications

Theoretical Implications

- The study strengthens the application of Exergy Theory in hybrid renewable energy systems by demonstrating that system efficiency is maximized when irreversibility is minimized through intelligent control.
- It extends existing literature by integrating **optimization** theory with thermodynamic modeling, offering a multi-disciplinary framework for energy system design.
- It contributes to the advancement of **AI-**based energy optimization models in solar thermal engineering.

Managerial Implications

- Industrial energy managers can significantly reduce operational costs by adopting MPC-based hybrid solar systems.
- Decision-makers can improve energy planning through predictive load management and automated control systems.
- Firms can enhance competitiveness by lowering energy intensity and improving sustainability performance indicators.

Practical Implications

- The study provides a scalable model for implementing hybrid solar thermal systems in energy-intensive industries such as textiles, food processing, and chemicals.
- It demonstrates practical fuel savings of over 50%, making renewable integration economically attractive.
- It supports the deployment of AI-enabled monitoring systems for real-time optimization of industrial energy use.

Policy Implications

- Policymakers should promote subsidies and tax incentives for industrial adoption of hybrid solar thermal systems.
- National energy strategies should prioritize solar thermal integration in industrial zones.
- Investment in AI-based renewable energy infrastructure should be encouraged to improve energy security and reduce import dependency.

- Development of technical standards for hybrid solar systems is essential for large-scale implementation.

Recommendations

- Government should introduce financial incentives and soft loans for industries adopting hybrid solar thermal technologies.
- Industries should implement MPC-based control systems for real-time energy optimization.
- Local manufacturing of solar collectors and thermal storage units should be promoted to reduce capital costs.
- Industrial zones should be redesigned to include centralized solar thermal infrastructure**.**
- Training programs should be developed for engineers in AI-based energy system optimization**.**
- Future industrial policies should mandate **energy efficiency benchmarking using exergy-based metrics**.

Limitations and Future Directions

Limitations

- The study was based on **simulation and secondary data**, not full-scale field experimentation.
- Real-time operational constraints such as maintenance downtime and equipment degradation were not fully modeled.
- Economic analysis was generalized and may vary across different industrial ownership structures.
- Weather variability was modeled using historical datasets, which may not fully capture extreme climate events.

Future Directions

- Future research should involve pilot-scale experimental validation in Pakistani industrial zones.
- Integration of machine learning and deep reinforcement learning for adaptive control should be explored.
- Studies should incorporate life-cycle assessment **(LCA)** for environmental impact evaluation.
- Research should expand to include hybrid solar PV–thermal–biomass systems for higher reliability.
- Region-specific optimization models should be developed for different climatic zones of Pakistan.

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