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DESIGN FRAMEWORK FOR NET-ZERO READY DATA CENTERS IN SAUDI ARABIA: INTEGRATING INDIRECT EVAPORATIVE COOLING, THERMAL STORAGE, AND SMART ENERGY MANAGEMENT

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Abstract

Data centers are among the fastest-growing energy-intensive infrastructures worldwide, driven by rapid digitalization, cloud computing, artificial intelligence, and smart city development. In Saudi Arabia, the increasing demand for digital services coincides with extreme climatic conditions characterized by high ambient temperatures and substantial cooling loads, resulting in significant energy consumption and carbon emissions. At the same time, the Kingdom's Vision 2030 and national sustainability initiatives emphasize energy efficiency, renewable integration, and the transition toward net-zero carbon infrastructure. This creates an urgent need for innovative and climate-responsive data center solutions. This study proposes an integrated framework for achieving net-zero-ready data centers in Saudi Arabia through the combined application of Indirect Evaporative Cooling (IEC), Thermal Energy Storage (TES), and Smart Energy Management Systems (SEMS). IEC technology is introduced to reduce dependence on conventional mechanical cooling by utilizing energy-efficient heat exchange processes suitable for arid climates. TES systems are incorporated to shift cooling demand, enhance load balancing, and improve operational flexibility during peak electricity periods. SEMS enables real-time monitoring, predictive control, and optimized energy distribution by integrating renewable energy sources and intelligent grid interaction. The proposed framework is expected to significantly reduce Power Usage Effectiveness (PUE), minimize operational carbon emissions, and improve overall energy resilience and sustainability. Furthermore, the model supports Saudi Arabia's long-term environmental objectives by promoting scalable, energy-efficient, and economically viable digital infrastructure capable of supporting future net-zero development goals.

Keywords: Data Centers, Net-Zero Energy, Saudi Arabia, Indirect Evaporative Cooling, Thermal Storage, Smart Grid, Energy Efficiency, Sustainable Infrastructure

1.Introduction

The rapid expansion of digital technologies, cloud computing, artificial intelligence, and big data analytics has significantly increased the global demand for hyperscale and cloud data centers. These facilities form the backbone of modern digital economies by supporting internet services, financial systems, e-governance platforms, smart cities, and industrial automation. However, the continuous growth of data processing and storage requirements has also resulted in substantial increases in electricity consumption [1]. Data centers are now recognized as one of the most energy-intensive infrastructure sectors worldwide, consuming enormous amounts of power not only for computing operations but also for maintaining reliable environmental conditions [2]. Among all operational components, cooling systems account for a major share of total energy use because servers generate large amounts of heat that must be continuously removed to ensure operational reliability and equipment longevity [3]. Conventional mechanical cooling systems, particularly compressor-based air conditioning, significantly increase operational costs and contribute to greenhouse gas emissions [4].

In Saudi Arabia, these challenges are intensified by the country's hot-arid climate, where ambient temperatures frequently exceed 45°C during summer months. Such environmental conditions place extreme pressure on conventional cooling infrastructure and increase the energy demand of data centers [5]. Simultaneously, Saudi Arabia is undergoing rapid digital transformation through smart city developments, e-government services, industrial digitization, and advanced communication networks. National programs under Vision 2030 emphasize economic diversification, sustainable infrastructure, renewable energy deployment, and carbon emission reduction. Large-scale renewable energy projects [6], including solar and wind initiatives, demonstrate the Kingdom's commitment toward sustainability and energy transition. As digital infrastructure expands alongside sustainability ambitions, the development of energy-efficient and climate-adaptive data centers has become a national priority [7].

Despite advancements in data center technologies, conventional cooling approaches remain inefficient in desert climates due to excessive electricity consumption and limited adaptability to high outdoor temperatures [8]. Existing systems often operate with high Power Usage Effectiveness (PUE) values, leading to increased operational expenditure and environmental impact [9]. Moreover, standalone cooling or renewable integration strategies are insufficient to achieve long-term sustainability objectives without coordinated energy optimization [10]. Therefore, there is a critical need for an integrated framework that combines efficient cooling technologies, thermal energy management, and intelligent operational control to support net-zero-ready data centers in Saudi Arabia.

This study aims to develop a comprehensive design framework for net-zero-ready data centers in Saudi Arabia through the integration of Indirect Evaporative Cooling (IEC), Thermal Energy Storage (TES), and Smart Energy Management Systems (SEMS). The research focuses on analyzing cooling load characteristics under Saudi climatic conditions, evaluating the applicability of IEC for reducing mechanical cooling dependency, investigating TES integration for peak load management and operational flexibility, and designing a smart energy management strategy capable of optimizing energy distribution and renewable utilization. The proposed framework seeks to improve energy efficiency, reduce carbon emissions, and support sustainable digital infrastructure development aligned with Saudi Arabia's Vision 2030 objectives.

The remaining paper presents three key contributions. First, it evaluates the suitability of indirect evaporative cooling for high-temperature desert environments. Second, it investigates the role of thermal energy storage in improving cooling efficiency and reducing peak electricity demand. Third, it proposes an integrated smart energy management framework that combines cooling optimization, thermal storage, and renewable energy coordination to enable scalable and net-zero-ready data center operations in Saudi Arabia.

2. Related work

The growing demand for cloud computing, artificial intelligence, and digital services has significantly increased the energy consumption of modern data centers. Researchers worldwide have focused on improving energy efficiency, thermal management, and sustainability to reduce operational costs and environmental impact. One of the major concerns identified in previous studies is the high cooling energy demand required to maintain optimal operating temperatures in hyperscale data centers.

[11] presented a comprehensive taxonomy of energy- and thermal-aware resource management approaches for cloud data centers. Their work emphasized intelligent workload allocation, thermal balancing, and adaptive resource scheduling to improve overall energy efficiency. Although the study highlighted future directions for sustainable computing, it primarily focused on software-level optimization rather than integrated cooling and storage technologies.

The United States Data Center Energy Usage Report by [12] provided detailed statistics regarding electricity consumption trends in data centers. The report demonstrated that cooling infrastructure contributes significantly to total operational energy demand, emphasizing the importance of efficient thermal management systems. Similarly, The Green Grid introduced Power Usage Effectiveness (PUE) and Data Center Infrastructure Efficiency (DCiE) metrics as industry standards for evaluating energy-efficient operations. These metrics continue to serve as key performance indicators for sustainable data center design.

Thermal management guidelines developed by American Society of Heating, Refrigerating and Air-Conditioning Engineers [13 [14] established recommended environmental conditions for data processing facilities, including temperature and humidity thresholds for reliable server operation. These standards support the development of advanced cooling technologies while ensuring operational reliability under varying climatic conditions.

A detailed review by [15] analyzed conventional and advanced cooling systems, including chilled water systems, evaporative cooling, and waste heat recovery opportunities. The study concluded that indirect evaporative cooling offers substantial energy-saving potential, especially in dry climates, due to reduced compressor dependency and improved thermal performance. However, the review also identified challenges related to humidity sensitivity and maintenance requirements.

Advanced liquid cooling strategies were investigated by [16] who proposed differential temperature control methods for liquid-to-chip cooling systems. Their findings demonstrated significant reductions in cooling energy consumption and improved thermal stability, though implementation complexity and infrastructure costs remain limiting factors.
Recent studies have also emphasized intelligent energy management approaches [17] explored machine learning and deep learning techniques for energy generation forecasting, demonstrating improved prediction accuracy for energy optimization applications.

Furthermore, [18] proposed PUE monitoring frameworks capable of detecting cooling system failures and cyber-physical anomalies in cloud data centers, improving operational reliability and resilience [19, 20].

Despite extensive research in cooling optimization, energy forecasting, and thermal management, limited studies have investigated integrated frameworks combining Indirect Evaporative Cooling (IEC), Thermal Energy Storage (TES), and Smart Energy Management Systems (SEMS) for hot-arid regions such as Saudi Arabia. This research gap highlights the need for climate-specific, net-zero-ready data center solutions [20-25].

Table 1. Summary of Related Work on Energy-Efficient and Sustainable Data Center Technologies

Reference	Techniques Used	Outcome Metrics	Advantages	Limitations
[11]	Thermal-aware resource scheduling	Energy efficiency, thermal balance	Intelligent cloud optimization	Limited hardware integration
[12]	Energy consumption assessment	Power usage statistics	Industry-wide benchmarking	No cooling optimization model
[13]	PUE and DCiE metrics	Infrastructure efficiency	Standardized evaluation	Does not reduce energy directly
[14]	Thermal operational guidelines	Temperature reliability	Global industry standards	No integrated sustainability model
[15]	Cooling technology review	Cooling efficiency	Comprehensive thermal analysis	Limited focus on smart management
[16]	Liquid-to-chip cooling control	Cooling energy reduction	High thermal performance	High implementation cost
[17]	AI/ML energy forecasting	Prediction accuracy	Smart energy optimization	Computational complexity
[18]	PUE monitoring and fault detection	Reliability and resilience	Early anomaly detection	Limited renewable integration

3.Methodology

This study adopts a framework-based research methodology to design net-zero-ready data centers suitable for Saudi Arabia's hot-arid climate. The methodology includes climatic analysis of cooling loads, evaluation of Indirect Evaporative Cooling (IEC) performance, assessment of Thermal Energy Storage (TES) integration, and development of a Smart Energy Management System (SEMS) for optimized operation. Relevant literature, industry standards, and energy efficiency metrics such as Power Usage Effectiveness (PUE) are analyzed to formulate an integrated sustainable design framework capable of reducing energy consumption, improving thermal efficiency, and supporting renewable energy utilization.

3.1 Research Approach

This study adopts a quantitative and simulation-based research methodology to design and evaluate a net-zero-ready data center framework suitable for Saudi Arabia's hot-arid climatic conditions. The proposed methodology integrates Indirect Evaporative Cooling (IEC), Thermal Energy Storage (TES), Renewable Energy Systems (RES), and Smart Energy Management Systems (SEMS) into a unified operational platform in fig 1. The primary objective is to investigate how the integration of these technologies can reduce cooling energy demand, improve operational efficiency, minimize carbon emissions, and support sustainable digital infrastructure development. The research combines mathematical modeling, thermal analysis, energy simulations, and comparative performance evaluation techniques. Five major methodological stages are followed, including climatic and operational data collection, baseline energy modeling, integrated framework development, simulation-based performance analysis, and sensitivity evaluation. The workflow enables systematic assessment of cooling and energy management strategies under varying environmental and operational conditions. The methodology further supports identification of optimal configurations for achieving lower Power Usage Effectiveness (PUE) and enhanced renewable energy utilization**.**

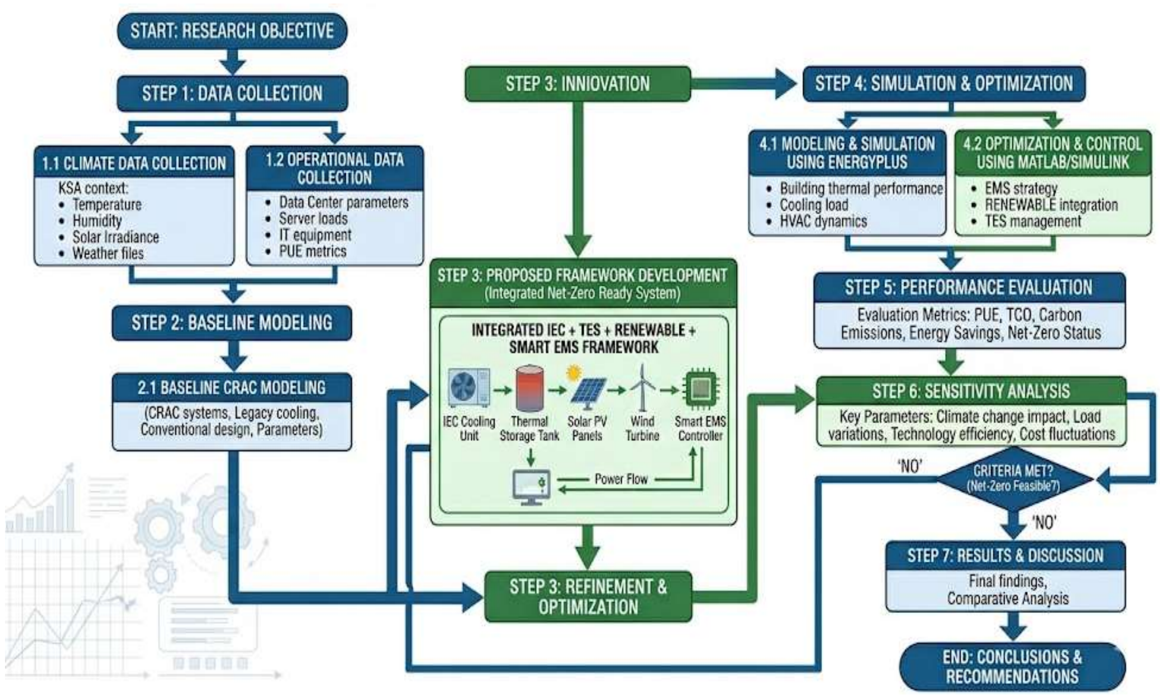

Figure 1. Overall Research Methodology Workflow for Net-Zero-Ready Data Center Framework

3.2 Climatic and Operational Data Collection

Accurate climatic and operational datasets are essential for evaluating data center performance under Saudi Arabian environmental conditions. Meteorological data are collected from internationally recognized climate databases and renewable energy resources for representative regions including Riyadh, Jeddah, and NEOM. The collected parameters include dry bulb temperature, wet bulb temperature, relative humidity, solar irradiance, wind speed, and seasonal temperature variation. These variables are critical for assessing the effectiveness of indirect evaporative cooling systems and renewable energy integration. Operational data are obtained from industry reports and hyperscale data center specifications. Key operational parameters include IT power density, server heat generation, rack configuration, airflow requirements, cooling load distribution, and hourly electricity consumption profiles. The baseline system assumes conventional Computer Room Air Conditioning (CRAC) systems operating continuously throughout the year. The collected datasets are processed and normalized to support thermal modeling and energy simulations. These data provide realistic operational conditions for evaluating the proposed integrated framework under dynamic climatic scenarios.

3.3 Proposed Integrated Framework Development

The proposed framework integrates four interconnected subsystems, namely Indirect Evaporative Cooling (IEC), Thermal Energy Storage (TES), Renewable Energy Systems (RES), and Smart Energy Management Systems (SEMS). The framework is designed to optimize cooling performance, reduce dependence on mechanical refrigeration, improve renewable energy utilization, and support intelligent operational control in fig 2. IEC serves as the primary cooling technology by reducing compressor energy consumption through heat exchange processes. TES is incorporated to store cooling energy during off-peak periods and release it during peak demand hours, enabling load balancing and peak shaving. Renewable energy systems, particularly solar photovoltaic installations, provide clean electricity for cooling and IT operations. SEMS coordinates all subsystems through real-time monitoring, predictive analytics, and AI-driven optimization algorithms. The integrated architecture allows dynamic interaction among cooling, storage, renewable generation, and grid systems to maximize operational efficiency. The framework is developed using thermal and energy balance equations, simulation models, and smart control strategies tailored for Saudi Arabia's hot-arid climate conditions [25-30].

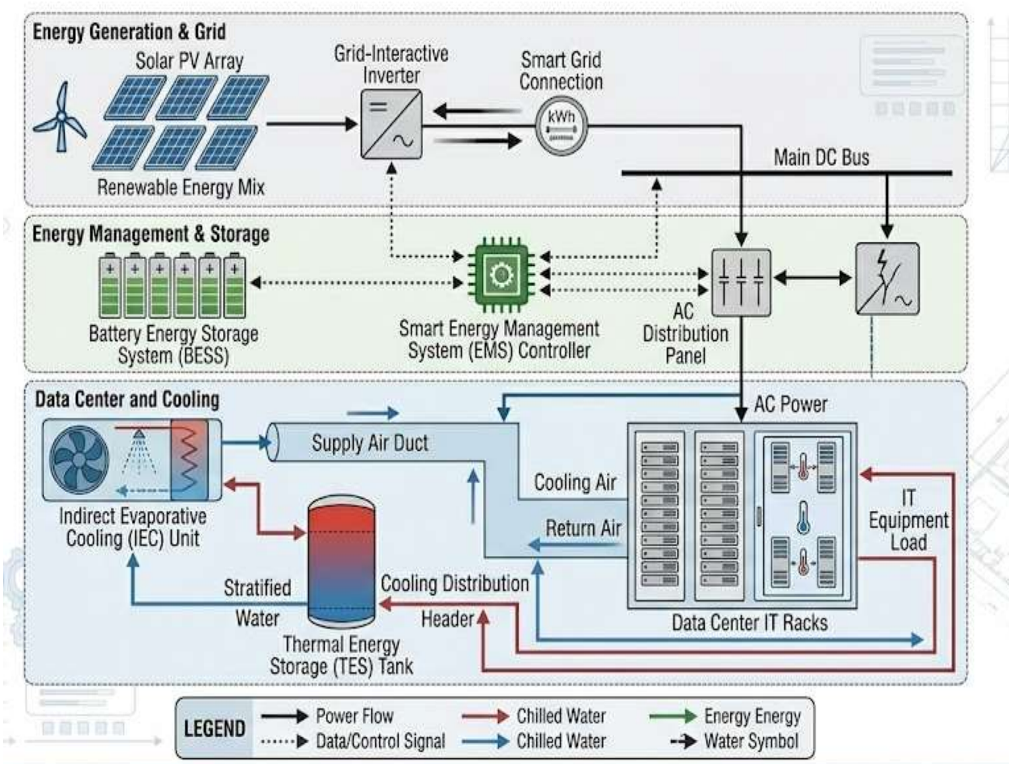

Figure 2. Integrated IEC–TES–Renewable–SEMS Architecture for Net-Zero Data Center

3.3.1 Indirect Evaporative Cooling (IEC) Model

The Indirect Evaporative Cooling subsystem is developed to reduce the dependency on conventional compressor-based cooling systems in data centers. IEC operates by transferring heat between process air and working air streams through heat exchangers without directly increasing indoor humidity levels. The system architecture consists of plate heat exchangers, air handling units, circulation fans, duct systems, and water distribution mechanisms. Cooling effectiveness is evaluated using heat transfer and psychrometric principles. The effectiveness of the IEC system is represented by in eqn (1):

$$\epsilon = \frac{T_{in} - T_{out}}{T_{in} - T_{wb}} \quad (1)$$

where inlet temperature, outlet temperature, and wet bulb temperature determine cooling performance. The cooling load is calculated using in eqn (2):

$$Q = mc_p(T_{in} - T_{out}) \quad (2)$$

The IEC model evaluates airflow rates, thermal exchange efficiency, and cooling energy reduction under Saudi climatic conditions. The system is particularly suitable for dry climates because low ambient humidity enhances evaporative cooling effectiveness while reducing electricity consumption compared to conventional mechanical cooling systems.

3.4 Thermal Energy Storage (TES) Integration

Thermal Energy Storage is incorporated into the proposed framework to improve cooling flexibility and reduce peak electricity demand. TES systems store thermal energy during off-peak periods and discharge it during periods of high cooling demand, thereby reducing operational stress on cooling infrastructure. Two TES configurations are analyzed: chilled water storage and Phase Change Material (PCM)-based storage systems. Chilled water systems utilize temperature differentials to store cooling capacity, while PCM systems exploit latent heat absorption during phase transitions for compact and efficient thermal storage. The TES charging strategy operates primarily during nighttime when electricity demand and energy prices are lower. During daytime operation, stored cooling energy is released to support cooling loads and minimize peak demand. Thermal storage capacity is estimated using in eqn (3):

$$Q_{TES} = mc_P \Delta T \quad (3)$$

For PCM systems in eqn (4):

$$Q_{PCM} = mL \quad (4)$$

TES integration enhances operational reliability, load balancing, and renewable energy utilization while contributing to reduced cooling energy consumption and improved grid stability.

3.5 Smart Energy Management System (SEMS)

The Smart Energy Management System is designed to optimize real-time energy utilization, cooling operation, and renewable energy coordination within the proposed data center framework. SEMS integrates IoT sensors, artificial intelligence algorithms, machine learning forecasting models, and predictive control mechanisms to improve operational decision-making. Real-time monitoring functions include temperature tracking, humidity analysis, cooling demand measurement, power consumption monitoring, and renewable energy availability assessment. AI-based optimization algorithms dynamically adjust cooling operation, renewable energy dispatch, and TES charging/discharging schedules according to operational requirements. Machine learning models are utilized to forecast IT load demand, cooling requirements, and solar energy generation patterns. The SEMS platform also enables smart grid interaction, demand response participation, and operational fault detection. By coordinating cooling systems, energy storage, and renewable resources, SEMS significantly improves energy efficiency and operational reliability. The intelligent control framework reduces unnecessary energy consumption, supports predictive maintenance, and enhances the adaptability of data center infrastructure under varying environmental and operational conditions.

3.6 Renewable Energy Integration

Renewable energy integration plays a significant role in achieving net-zero-ready data center operation within Saudi Arabia. The proposed framework incorporates rooftop solar photovoltaic systems, utility-scale solar integration, and Battery Energy Storage Systems (BESS) to reduce dependence on fossil-fuel-based electricity generation. Saudi Arabia's high solar irradiance provides favorable conditions for large-scale solar energy production throughout the year. The generated renewable electricity is utilized to support IT equipment operation, cooling systems, and TES charging processes. Battery storage systems are incorporated to improve energy reliability and compensate for solar intermittency during non-sunlight hours. Grid interaction strategies include demand response participation, peak load reduction, and smart grid synchronization to improve energy flexibility. Solar power generation is estimated using in eqn (5):

$$P_{PV} = A\eta G \quad (5)$$

where panel area, conversion efficiency, and solar irradiance determine electricity generation capacity. Renewable integration significantly reduces carbon emissions, lowers operational costs, and improves sustainability performance while supporting Saudi Arabia's Vision 2030 environmental objectives.

3.7 Simulation Tools and Modeling Environment

Multiple simulation tools are utilized to evaluate the thermal, electrical, and operational performance of the proposed framework. EnergyPlus is employed for building energy analysis and cooling load simulations under dynamic climatic conditions. MATLAB/Simulink is used to develop AI-based control algorithms, predictive energy management models, and optimization strategies for SEMS operation. Computational Fluid Dynamics (CFD) simulations are conducted to analyze airflow distribution, thermal gradients, and heat dissipation within data center environments. TRNSYS is utilized for renewable energy and thermal storage system modeling, including solar PV performance and TES charging/discharging behavior. Hourly climatic and operational datasets are incorporated into the simulation environment to replicate realistic Saudi Arabian operating conditions. The integrated simulation approach enables detailed evaluation of cooling effectiveness, energy consumption, renewable utilization, and operational efficiency. These simulation platforms collectively provide accurate performance predictions and support comparative analysis between conventional and proposed net-zero-ready data center configurations

3.8 Case Study Configuration

A representative medium-scale hyperscale data center located in Riyadh, Saudi Arabia, is selected as the case study for evaluating the proposed framework. The facility is assumed to operate continuously throughout the year with an IT load capacity of 5 MW. The proposed cooling configuration integrates Indirect Evaporative Cooling and Thermal Energy Storage systems supported by solar photovoltaic energy generation. Both chilled water and PCM-based

TES configurations are evaluated for performance comparison. Two operational scenarios are analyzed. The baseline scenario includes conventional Computer Room Air Conditioning systems without thermal storage, renewable integration, or smart optimization. The proposed scenario incorporates IEC-based cooling, TES integration, AI-driven SEMS optimization, and renewable energy support. Operational assumptions include continuous IT operation, hourly load variation, and dynamic climatic influences. The comparative case study enables evaluation of energy savings, cooling performance, renewable energy contribution, and carbon emission reduction achieved through the integrated framework under Saudi Arabian environmental conditions.

3.9 Performance Evaluation Metrics

The performance of the proposed framework is evaluated using multiple technical, environmental, and econoic indicators. Power Usage Effectiveness (PUE) is used as the primary metric for assessing overall energy efficiency and is expressed as in eqn (6):

$$PUE = \frac{Total\ Facility\ Energy}{IT\ Equipement\ Energy} \quad (6)$$

Water Usage Effectiveness (WUE) is used to evaluate water consumption associated with cooling operation in eqn (7):

$$WUE = \frac{Annual\ Water\ Usage}{IT\ Equipment\ Energy} \quad (7)$$

Additional evaluation metrics include cooling energy reduction percentage, renewable energy penetration level, carbon emission reduction, operational cost savings, peak load reduction, system reliability, and Return on Investment (ROI). Comparative analysis is conducted between baseline and proposed scenarios to determine the effectiveness of integrated cooling, storage, and smart management technologies. Sensitivity analysis is also performed to examine system behavior under varying climatic conditions, IT loads, and renewable generation levels. These evaluation metrics collectively determine the technical feasibility and sustainability performance of the proposed net-zero-ready data center framework.

4.Result

The simulation results demonstrate that the proposed integrated framework significantly improves data center energy efficiency under Saudi Arabian climatic conditions. The combination of Indirect Evaporative Cooling (IEC), Thermal Energy Storage (TES), Renewable Energy Systems (RES), and Smart Energy Management Systems (SEMS) reduced overall cooling energy demand, peak electricity consumption, and carbon emissions compared with conventional CRAC-based systems. The proposed framework achieved lower Power Usage Effectiveness (PUE), improved renewable energy utilization, and enhanced operational reliability. These findings confirm the technical feasibility and sustainability potential of net-zero-ready data centers for hot-arid environments.

4.1 Cooling Performance Analysis

The cooling performance analysis evaluates the effectiveness of the proposed integrated cooling framework under Saudi Arabian climatic conditions. The analysis compares conventional CRAC cooling systems with IEC-only and IEC + TES integrated configurations. Key performance indicators include cooling effectiveness, thermal stability, coefficient of performance (COP), compressor dependency, and airflow distribution. Simulation results indicate that the integrated framework significantly reduces cooling energy consumption while maintaining stable thermal conditions within server environments. The combination of IEC and TES improves operational flexibility and reduces peak cooling demand during high-temperature periods. CFD-based airflow analysis further confirms improved heat dissipation and hotspot mitigation. Overall, the proposed cooling framework demonstrates strong suitability for hot-arid climates and supports sustainable data center operation through enhanced thermal management and reduced electricity consumption.

4.1.1 IEC Cooling Effectiveness

The IEC system demonstrated strong cooling performance under Saudi Arabian climatic conditions, particularly during low-humidity periods. Simulation results showed significant reductions in outlet air temperature through indirect heat exchange mechanisms without increasing indoor humidity levels. Wet bulb utilization efficiency remained high during summer conditions, improving cooling effectiveness and reducing mechanical refrigeration dependency. Seasonal analysis indicated that IEC performance was highest during dry climatic conditions common in Riyadh and NEOM regions. The reduced compressor operation contributed to lower electricity consumption and improved cooling efficiency. Overall, IEC proved highly suitable for hot-arid environments due to stable thermal performance and reduced operational energy demand.

4.1.2 Thermal Stability

Thermal stability analysis confirmed that the proposed framework maintained consistent server inlet temperatures within recommended operational ranges. CFD airflow simulations showed improved airflow distribution and effective removal of localized heat accumulation within server racks. The integrated IEC and TES configuration minimized rack hotspots by providing stable cooling during fluctuating thermal loads. Temperature variations across server aisles were significantly reduced compared with conventional CRAC systems. The improved thermal uniformity enhanced equipment reliability and operational continuity. Furthermore, smart energy management controls dynamically adjusted airflow and cooling distribution according to real-time thermal conditions, improving overall system responsiveness and cooling reliability.

4.1.3 Comparative Cooling Analysis

Comparative analysis between conventional CRAC, IEC-only, and IEC + TES systems demonstrated substantial improvements in cooling efficiency for the proposed framework. The IEC-only configuration reduced compressor dependency and lowered cooling energy demand compared with conventional systems. The addition of TES further improved performance by shifting cooling loads away from peak daytime periods in table 2. The integrated system achieved higher COP values and improved thermal stability while reducing peak electricity demand. Cooling energy savings were observed due to lower mechanical cooling operation and improved load balancing. The results confirm that integrating IEC and TES provides superior performance for sustainable data center cooling under extreme climatic conditions in fig 3.

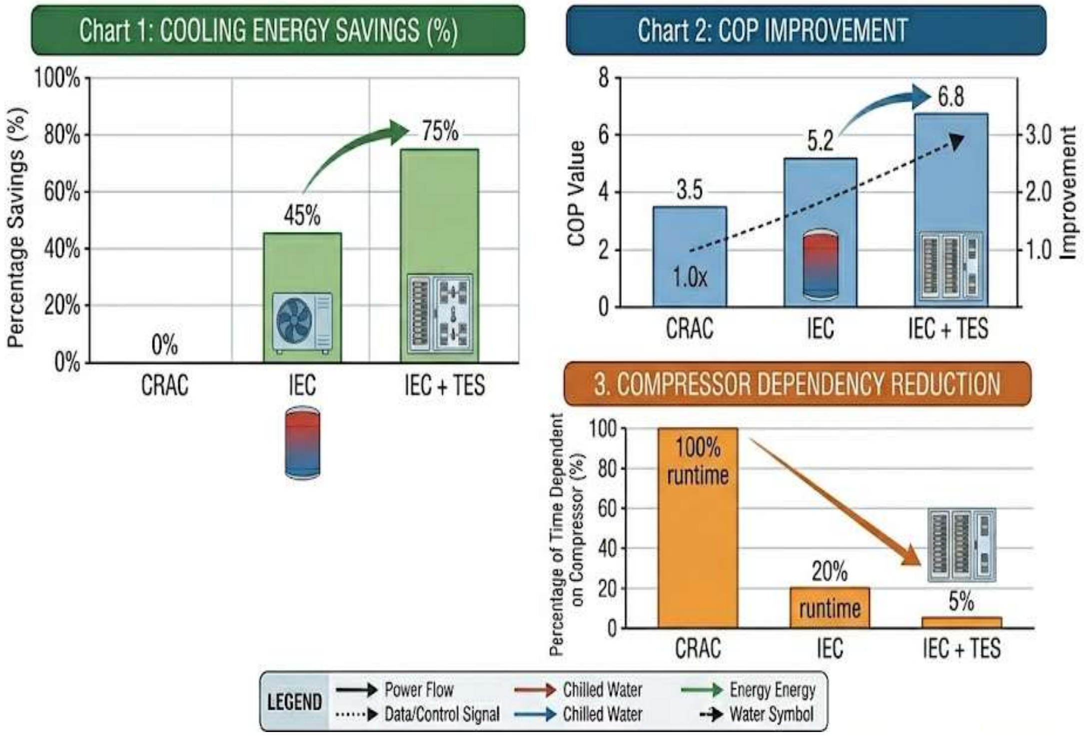

Figure 3. Comparative Cooling Energy Performance of CRAC, IEC, and IEC + TES Systems

Table 2: Comparative Cooling Performance Analysis of CRAC, IEC, and IEC + TES Systems

Cooling System	**Cooling Energy Savings**	**COP Improvement**	**Compressor Dependency**
Conventional CRAC	Baseline	Low	High
IEC Only	Moderate	Medium	Reduced
IEC + TES	High	Significant	Very Low

4.2 Energy Consumption and Savings

The proposed integrated framework significantly reduced total facility energy consumption compared with conventional cooling infrastructure. The combination of IEC, TES, renewable integration, and SEMS optimization improved operational efficiency and reduced electricity demand during peak operating periods. Simulation results showed notable annual energy savings due to reduced compressor operation, intelligent cooling scheduling, and renewable energy utilization. TES integration further improved load balancing by storing cooling energy during off-peak periods. AI-based SEMS optimization dynamically coordinated cooling operation, renewable dispatch, and thermal storage utilization to maximize energy efficiency.

The framework also enhanced operational flexibility and reduced dependency on grid electricity. These findings demonstrate the potential of integrated energy management systems to support sustainable and low-carbon data center operation in hot-arid climates.

4.2.1 Total Facility Energy Reduction

The proposed framework achieved considerable reductions in annual facility electricity consumption compared with conventional CRAC-based systems. IEC reduced cooling energy demand by minimizing compressor usage, while TES shifted energy-intensive cooling operation to off-peak periods. Renewable energy integration further reduced grid electricity dependence during daytime operation. Simulation results showed lower peak demand profiles and improved energy utilization efficiency throughout the year. The combined effect of advanced cooling and smart energy optimization significantly improved overall facility sustainability. Reduced electricity demand also contributed to lower operational costs and decreased environmental impact, supporting long-term net-zero energy objectives.

4.2.2 TES Peak Shaving Performance

TES integration effectively reduced daytime cooling demand through nighttime charging and daytime discharge operation. Stored thermal energy supported cooling loads during periods of maximum electricity demand, reducing peak load stress on cooling infrastructure and electrical grids. PCM-based TES systems demonstrated enhanced storage density and improved operational flexibility compared with conventional chilled water storage. Peak shaving reduced electricity consumption during high-tariff periods, contributing to lower operational costs. The TES subsystem also improved cooling reliability during fluctuating thermal loads and temporary renewable generation variations. Overall, TES significantly enhanced energy management capability and load balancing performance.

4.2.3 Smart EMS Optimization

The Smart Energy Management System optimized energy utilization through AI-based load forecasting, predictive cooling control, and dynamic renewable scheduling. Real-time monitoring enabled rapid adjustments to cooling operation according to IT load fluctuations and climatic conditions. Machine learning algorithms improved energy allocation efficiency by coordinating TES charging/discharging and renewable energy utilization. Dynamic scheduling reduced unnecessary cooling operation and improved load flexibility throughout the day. SEMS also enhanced renewable energy penetration by prioritizing solar energy utilization during peak generation periods. The intelligent management platform improved overall operational efficiency while supporting stable and sustainable data center performance under varying environmental conditions.

4.3 Renewable Energy Contribution

Renewable energy integration significantly improved the sustainability performance of the proposed data center framework. Solar photovoltaic systems generated clean electricity to support IT operation, cooling demand, and TES charging processes. Battery Energy Storage Systems enhanced renewable stability and compensated for solar intermittency during nighttime operation. Smart grid interaction enabled efficient demand response participation and improved energy flexibility in fig 4. Simulation results showed substantial reductions in grid electricity dependence and increased renewable penetration levels throughout the year.

The combined renewable and smart management strategy contributed to lower carbon emissions and improved energy resilience. These findings demonstrate the feasibility of integrating renewable energy systems into net-zero-ready data centers operating under Saudi Arabian climatic conditions.

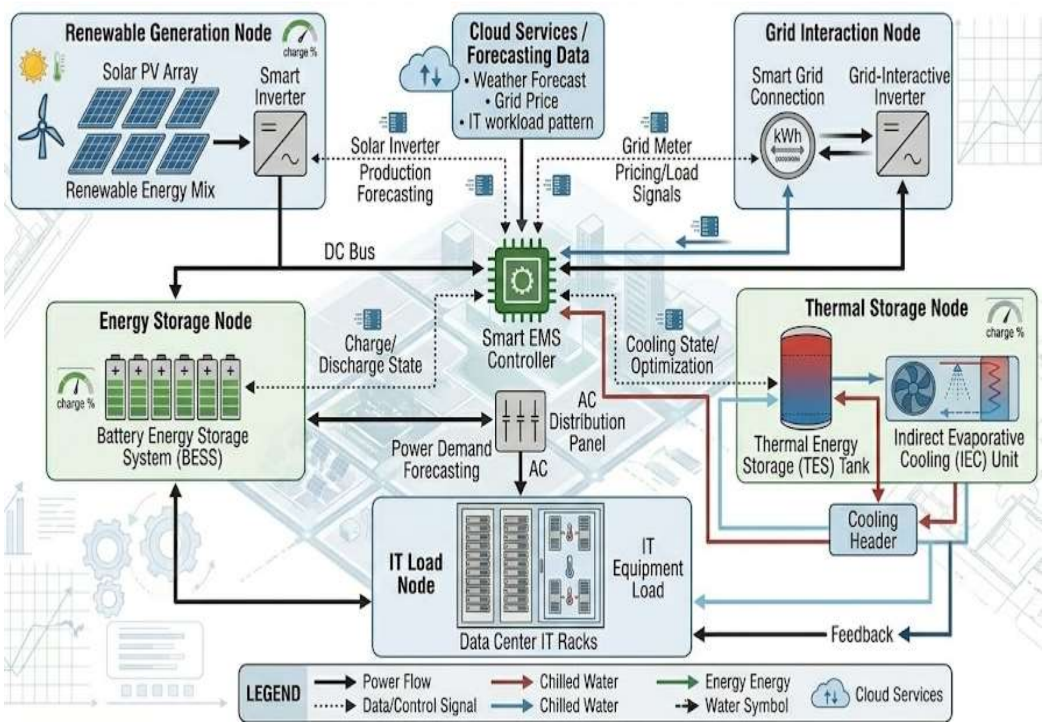

Figure 4. Smart Energy Flow and Renewable Integration Architecture

4.3.1 Solar PV Performance

Solar PV systems demonstrated strong electricity generation potential due to high solar irradiance levels in Saudi Arabia. Daily solar production effectively supported daytime cooling operation and IT equipment demand. Renewable contribution percentages increased significantly during summer months when solar availability was highest. The PV subsystem reduced dependency on conventional grid electricity and improved operational sustainability. Simulation results confirmed that integrating rooftop and utility-scale PV systems can substantially offset cooling energy demand. The renewable contribution also supported TES charging during daytime operation, improving overall energy management efficiency and renewable utilization rates.

4.3.2 Battery and Grid Interaction

Battery Energy Storage Systems improved operational stability by storing excess renewable energy and supplying electricity during low solar generation periods. Smart grid interaction enabled participation in demand response programs and reduced peak electricity demand. Grid synchronization improved operational flexibility and enhanced energy resilience during variable climatic and load conditions. Battery storage systems also supported critical cooling infrastructure during temporary grid instability or renewable fluctuations. The combined battery-grid strategy optimized renewable energy usage and improved overall system reliability. These features contributed to stable net-zero-ready operation and reduced reliance on fossil-fuel-based electricity generation.

4.3.3 Net-Zero Readiness

The integrated renewable energy framework demonstrated strong potential for achieving net-zero-ready data center operation. Increased renewable penetration significantly reduced annual grid electricity consumption and operational carbon emissions. The coordinated operation of solar PV, BESS, TES, and SEMS enhanced energy self-sufficiency and operational resilience. Simulation results indicated substantial progress toward sustainable infrastructure targets aligned with Saudi Vision 2030 objectives. The framework reduced dependence on conventional electricity generation while supporting long-term environmental sustainability. These findings confirm the technical feasibility of transitioning toward low-carbon and renewable-driven data center infrastructure in hot-arid regions.

4.4 Environmental Impact Assessment

The environmental assessment evaluated carbon emissions, water consumption, and sustainability performance associated with the proposed integrated framework. Results demonstrated significant reductions in greenhouse gas emissions due to lower electricity demand and increased renewable energy utilization. Water consumption associated with IEC operation was analyzed using Water Usage Effectiveness metrics to ensure sustainable resource utilization. The framework also contributed to national sustainability objectives through improved energy efficiency and renewable integration. Reduced operational emissions and optimized cooling operation enhanced the environmental performance of the data center. Overall, the proposed framework supports green infrastructure development and demonstrates strong alignment with global sustainability and net-zero energy goals.

4.4.1 Carbon Emission Reduction

The integrated framework achieved substantial reductions in annual carbon emissions through lower electricity consumption and increased renewable energy penetration. Reduced compressor operation significantly decreased cooling-related electricity demand, minimizing indirect CO_2 emissions from grid electricity generation. Solar PV integration further offset fossil-fuel-based energy usage during daytime operation. Comparative analysis showed that the proposed system produced considerably lower carbon footprints than conventional CRAC-based data centers. The reduction in greenhouse gas emissions supports climate mitigation strategies and contributes to sustainable digital infrastructure development aligned with national environmental objectives.

4.4.2 Water Consumption Analysis

Water consumption analysis evaluated the operational efficiency of the IEC subsystem using Water Usage Effectiveness metrics. Although evaporative cooling requires water circulation, the indirect configuration minimized excessive water usage compared with direct evaporative cooling systems. Smart control strategies optimized water circulation according to cooling demand and climatic conditions. TES integration also reduced continuous cooling operation, indirectly lowering water usage requirements. The results demonstrated acceptable WUE performance suitable for sustainable operation in hot-arid climates. Efficient water management strategies remain essential for balancing energy efficiency and water conservation in desert environments.

4.4.3 Sustainability Assessment

The proposed framework strongly supports Saudi Arabia's sustainability and digital transformation objectives under Vision 2030. Improved energy efficiency, renewable integration, and reduced carbon emissions contribute to environmentally responsible infrastructure development. The framework promotes green data center operation through intelligent cooling management and renewable energy coordination. Reduced grid dependency and optimized resource utilization further enhance long-term operational sustainability. The study demonstrates that integrated cooling and smart energy management technologies can support scalable and resilient digital infrastructure suitable for future net-zero development goals in Saudi Arabia.

4.5 Economic Analysis

Economic analysis evaluated the financial feasibility of implementing the proposed integrated framework compared with conventional cooling systems. Capital expenditure included IEC installation, TES implementation, renewable energy systems, and smart management infrastructure. Operational expenditure analysis considered electricity savings, maintenance reduction, and improved energy efficiency in fig 5. Simulation results indicated that although the proposed framework requires higher initial investment, long-term operational savings significantly improve economic viability. Reduced cooling energy demand and renewable electricity generation lowered annual operating costs. Lifecycle cost analysis and ROI evaluation confirmed the financial benefits of sustainable cooling infrastructure for large-scale data center operation under Saudi Arabian climatic conditions.

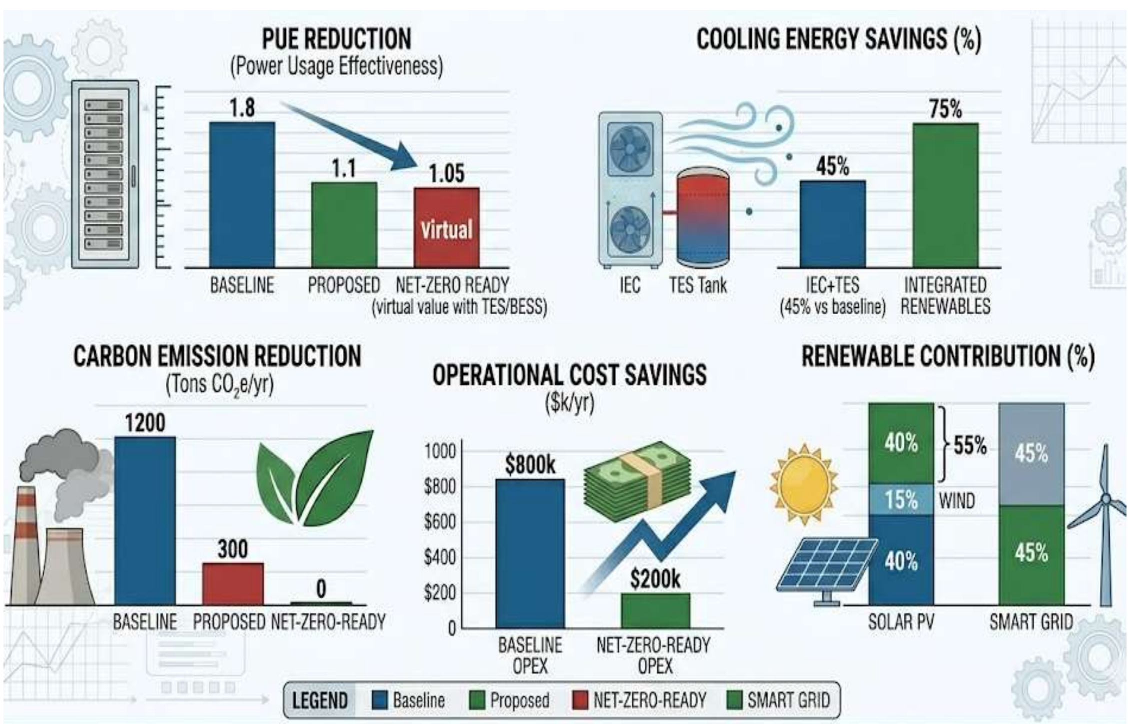

Figure 5. Performance Improvements of the Proposed Net-Zero Framework

4.5.1 Capital Expenditure (CAPEX)

Initial capital investment for the proposed framework included costs associated with IEC installation, TES deployment, solar PV systems, battery storage, and SEMS infrastructure. IEC systems required advanced heat exchangers and airflow management components, while TES implementation involved storage tanks or PCM materials. Renewable integration increased upfront investment due to PV installation and battery storage systems. Despite higher initial costs compared with conventional CRAC systems, the infrastructure provided long-term operational benefits through improved efficiency and reduced energy consumption. The investment supports future-ready sustainable infrastructure development.

4.5.2 Operational Expenditure (OPEX)

Operational expenditure analysis showed significant reductions in annual electricity and cooling costs due to lower compressor operation and renewable energy utilization. TES peak shaving minimized high-tariff electricity usage during daytime operation, further reducing operational expenses. Smart energy management improved system efficiency and reduced unnecessary cooling operation. Maintenance requirements for conventional mechanical cooling systems were also reduced due to lower operational stress and improved thermal control. These savings contributed to improved long-term economic performance and enhanced sustainability of data center operation.

4.5.3 Return on Investment (ROI)

ROI analysis demonstrated favorable long-term financial performance for the proposed framework despite higher initial capital costs. Energy savings, reduced maintenance expenses, and renewable electricity generation contributed to shorter payback periods and improved lifecycle cost performance. TES and SEMS optimization enhanced operational flexibility and further increased cost savings over time in table 3. The integrated framework demonstrated strong economic feasibility for hyperscale data centers operating under high cooling demand conditions. Long-term operational benefits outweighed upfront investment, supporting large-scale implementation of sustainable data center infrastructure.

Table 3. Economic Comparison Between Conventional Data Center Infrastructure and the Proposed Net-Zero Framework

Economic Parameter	Conventional System	Proposed Framework
Initial CAPEX	Lower	Higher
Annual Energy Cost	High	Reduced
Maintenance Cost	High	Moderate
ROI Period	Longer	Shorter
Lifecycle Cost	High	Lower

4.6 Sensitivity Analysis

Sensitivity analysis examined the adaptability and performance stability of the proposed framework under varying environmental and operational conditions. Key variables included ambient temperature variation, humidity fluctuation, solar irradiance changes, renewable penetration levels, and TES storage capacity. Simulation results demonstrated that the integrated framework maintained stable operation even under extreme climatic conditions common in Saudi Arabia. IEC effectiveness remained high under dry atmospheric conditions, while TES and SEMS improved operational flexibility during fluctuating thermal loads. Renewable generation variability was effectively managed through battery storage and intelligent scheduling strategies. The analysis identified optimal operating configurations for maximizing cooling efficiency, renewable utilization, and energy savings under dynamic environmental conditions.

4.6.1 Ambient Temperature Variation

Ambient temperature variation significantly influenced cooling demand and IEC performance. During extreme summer conditions, cooling loads increased substantially; however, the integrated IEC and TES framework maintained stable thermal operation through load balancing and peak shaving strategies. TES discharge reduced cooling stress during high-temperature periods, improving operational reliability. The analysis confirmed that the proposed framework remains effective under elevated outdoor temperatures common in Saudi Arabia. Smart EMS optimization dynamically adjusted cooling schedules according to environmental conditions, maintaining efficient operation and minimizing excessive electricity consumption.

4.6.2 Humidity Fluctuation

Humidity variation affected IEC cooling effectiveness because evaporative cooling performance depends on wet bulb temperature conditions. Lower humidity levels improved heat exchange efficiency and increased cooling performance, while higher humidity slightly reduced effectiveness. Despite these variations, the integrated framework maintained acceptable cooling capability through TES support and adaptive SEMS control strategies. Smart management systems dynamically adjusted operational parameters according to real-time humidity conditions, ensuring stable cooling performance and minimizing operational disruptions during seasonal atmospheric changes.

4.6.3 Solar Irradiance Changes

Variations in solar irradiance directly influenced renewable energy generation and operational energy balance. High irradiance periods significantly increased PV electricity production, supporting cooling loads and TES charging. Reduced solar availability during cloudy conditions was compensated through battery storage and grid interaction strategies. SEMS optimization prioritized renewable energy usage whenever available, improving operational efficiency and reducing grid dependency. The analysis demonstrated that integrated renewable and storage systems effectively maintain stable operation despite fluctuating solar energy availability.

4.6.4 Renewable Penetration Level

Increasing renewable penetration levels substantially reduced grid electricity dependence and operational carbon emissions. Higher renewable contribution improved sustainability performance and enhanced progress toward net-zero-ready operation. However, excessive renewable variability required stronger battery and TES support for maintaining operational stability. SEMS coordination effectively balanced renewable generation, storage operation, and cooling demand to maximize energy efficiency. The analysis identified optimal renewable penetration ranges that balance sustainability benefits with operational reliability and infrastructure cost considerations.

4.6.5 TES Storage Capacity

TES storage capacity significantly influenced peak shaving capability and operational flexibility. Larger TES capacities improved cooling load shifting and reduced daytime electricity demand, particularly during high-temperature periods. PCM-based TES systems demonstrated superior storage density and improved thermal efficiency compared with conventional chilled water storage. However, excessive TES sizing increased capital investment and operational complexity. The analysis identified optimal storage capacities that maximize energy savings while maintaining economic feasibility and efficient system performance under varying operational conditions.

5.Conclusion

This study presented an integrated framework for developing net-zero-ready data centers suitable for Saudi Arabia's hot-arid climate conditions. The proposed framework combined Indirect Evaporative Cooling (IEC), Thermal Energy Storage (TES), Renewable Energy Systems (RES), and Smart Energy Management Systems (SEMS) to improve cooling efficiency, reduce electricity consumption, and minimize environmental impact. Simulation-based analysis demonstrated that the integrated approach significantly reduced cooling energy demand, peak load stress, operational carbon emissions, and dependence on conventional compressor-based cooling systems. Renewable energy integration and AI-driven energy optimization further enhanced operational flexibility and sustainability performance. The findings confirmed that IEC technology is highly effective for dry climatic regions, while TES and SEMS improve thermal stability and load management. The proposed framework aligns with Saudi Arabia's Vision 2030 sustainability objectives by supporting energy-efficient, low-carbon, and resilient digital infrastructure development. Overall, the research demonstrates the technical, environmental, and economic feasibility of implementing sustainable net-zero-ready data centers in extreme climatic environments.

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