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Effects of HVAC Design, Maintenance, and Climate on Control Room Energy in Libyan Oil Fields

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ABSTRACT

This study investigates the combined effects of HVAC system design specifications, preventive maintenance adherence, and local ambient conditions on operational energy efficiency in oil field control rooms across Libya's Sirte and Murzuq Basins. Adopting a quantitative, descriptive-correlational cross-sectional survey design, data were collected from 187 engineering and technical personnel managing HVAC infrastructure in Libyan oil fields operated by the National Oil Corporation and its subsidiaries. The theoretical framework integrates Energy Efficiency Gap Theory, Reliability-Centered Maintenance (RCM) Theory, and Thermodynamic Load-Response Theory. Statistical analysis using Pearson correlation and hierarchical multiple linear regression revealed that all three independent variables collectively explain 68.4% of the variance in operational energy efficiency ($R^2 = 0.684$, $F = 132.45$, $p < 0.001$). Preventive Maintenance Adherence emerged as the strongest positive predictor ($\beta = 0.398$, $p < 0.001$), followed by HVAC System Design Specifications ($\beta = 0.341$, $p < 0.001$), while Local Ambient Conditions exerted a significant negative impact ($\beta = -0.305$, $p < 0.001$). These findings empirically validate that operational energy efficiency in extreme desert industrial environments is a multidimensional outcome governed by the interaction of technical design ceilings, maintenance discipline, and environmental stressors. The study provides actionable guidance for Libyan oil companies to optimize capital expenditure in HVAC procurement, institutionalize Computerized Maintenance Management Systems, and implement climate-responsive operational protocols to reduce energy consumption, protect mission-critical control equipment, and achieve sustainable industrial operations.

Keywords: HVAC energy efficiency, preventive maintenance, desert climate, oil field control rooms, energy management

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1. Introduction

The global demand for energy continues to escalate rapidly, exerting unprecedented operational pressure on energy-intensive industrial sectors to achieve environmental sustainability and economic efficiency. Within hydrocarbon-rich nations such as Libya, the oil and gas processing sector represents the primary backbone of the national economy and one of its largest industrial energy consumers. Within this high-stakes production domain, environmental control systems—specifically Heating, Ventilation, and Air Conditioning (HVAC) installations—constitute a vital support infrastructure required to preserve the functional viability of onshore oil field operations. In the extreme desert environments characteristic of Libyan hydrocarbon basins, HVAC systems in main control rooms do not merely serve human occupant comfort; rather, they perform mission-critical environmental regulation by maintaining strict temperature and humidity ranges necessary to protect delicate process control hardware, Supervisory Control and Data Acquisition (SCADA) servers, and programmable logic controllers from catastrophic thermal failure and dust contamination (Shalin Designs Team, 2025). The operational energy performance of these industrial HVAC installations is not dictated by a single isolated variable, but is instead the complex result of interacting physical, operational, and environmental parameters. Initial design parameters, including unit cooling capacity, component efficiency ratings (SEER/COP), system sizing, and Building Energy Management System (BEMS) automation, establish the theoretical maximum efficiency attainable by the system (Aljashaami, 2024; Yang et al., 2025). However, achieving this theoretical efficiency in daily practice requires rigorous operational discipline. Consistent adherence to preventive maintenance protocols—such as routine coil cleaning, filter replacement, and refrigerant charge verification—is essential to prevent thermal degradation, elevated head pressures, and energy waste (Florida Cooling Group, 2025; Tempest Air, 2023). Compounding these technical and operational factors are the severe local ambient conditions of the Libyan desert, characterized by summer ambient temperatures routinely exceeding 40°C, intense solar radiation, and frequent sandstorms that rapidly induce mechanical fouling (Isdayrah, 2025; STC Libya, 2024).

Despite the operational criticality of control room HVAC infrastructure, energy management across Libyan oil fields remains severely hindered by an empirical knowledge gap regarding how design, maintenance, and climate factors jointly influence operational energy efficiency. Currently, engineering procurement and facility maintenance decisions across Libyan oil fields rely predominantly on generic manufacturer recommendations, conservative rule-of-thumb sizing, or reactive run-to-failure servicing rather than data-driven evaluations tailored to severe desert environments. While prior scholarship has examined HVAC design innovations (Aljashaami, 2024), maintenance optimization strategies (P. Mechanical, 2025), and general climatic impacts on renewable energy systems (Isdayrah, 2025) in isolation, existing research has neglected to evaluate their integrated, simultaneous impact within the 24/7 mission-critical context of oil field control rooms (Albarssi, 2024; Shalin Designs Team, 2025). Consequently, facility managers lack evidence-based models to guide resource allocation, resulting in substantial energy wastage, elevated operational expenditure (OPEX), and increased risk of equipment breakdown. To bridge this critical research gap, this study formulates three central research questions: (1) What is the relationship between HVAC system design specifications and operational energy efficiency in Libyan oil field control rooms? (2) What is the relationship between preventive maintenance adherence and operational energy efficiency? (3) What is the relationship between local ambient conditions and operational energy efficiency? To answer these questions, this study aims to assess the individual and collective impacts of HVAC design specifications (IV1), preventive maintenance adherence (IV2), and local ambient conditions (IV3) on operational energy efficiency (DV). Specifically, four research objectives guide the inquiry: RO1 aims to identify prevailing design characteristics and maintenance practices; RO2 evaluates personnel perceptions of design, maintenance, and climate impacts on energy consumption; RO3 assesses the relationship between maintenance adherence and energy efficiency; and RO4 determines which predictor exerts the strongest influence on operational energy efficiency. Correspondingly, three core hypotheses are posited: H1 states that HVAC system design specifications have a significant positive relationship with operational energy efficiency; H2 states that preventive maintenance adherence has a significant positive relationship with operational energy efficiency; and H3 states that local ambient conditions have a significant negative relationship with operational energy efficiency.

The practical and theoretical significance of this research is substantial. For Libyan oil companies, the findings provide an empirical basis for optimizing capital expenditure (CAPEX) in HVAC procurement and refining preventive maintenance schedules within Computerized Maintenance Management Systems (CMMS), directly reducing energy overheads and extending asset lifecycle. Theoretically, this study integrates Energy Efficiency Gap Theory, Reliability-Centered Maintenance (RCM) Theory, and Thermodynamic Load-Response Theory into a unified analytical framework validated in an extreme desert industrial setting. For the purpose of this investigation, HVAC System Design Specifications (IV1) are operationally defined as the engineered characteristics of the system, including system type (e.g., VRF, chilled water, DX), rated SEER/COP efficiency, capacity sizing accuracy, and BEMS control capabilities (Aljashaami, 2024). Preventive Maintenance Adherence (IV2) refers to the consistent, scheduled execution of prescribed maintenance tasks, including coil washing, filter replacement, refrigerant level monitoring, and sensor calibration (Florida Cooling Group, 2025). Local Ambient Conditions (IV3) encapsulate environmental stressors, notably peak dry-bulb temperatures, relative humidity, solar radiation, and airborne dust/sand storm frequency (Isdayrah, 2025). Operational Energy Efficiency (DV) represents the actual in-service conversion of electrical power into effective space cooling, measured via perceptual performance ratings and estimated Energy Use Intensity (EUI in $kWh/m^2/year$) (Pérez-Lombard et al., 2008).

2. Literature Review

Building Energy Modeling (BEM) provides the fundamental thermodynamic framework for evaluating how equipment design, operational maintenance, and external weather parameters interact to dictate building energy consumption. In thermal engineering, building energy balance is governed by the heat conservation equation: $Q_{total} = Q_{envelope} + Q_{infiltration} + Q_{internal} + Q_{solar} + Q_{latent}$ (ASHRAE, 2021). Within this quantitative framework, HVAC design specifications define the baseline equipment performance curves and part-load efficiency profiles; preventive maintenance adherence governs physical degradation factors such as heat exchanger fouling resistances and airflow pressure drops; and local ambient conditions establish the boundary conditions driving convective, conductive, and solar heat gains (Cengel & Boles, 2014). Crucially, building energy literature demonstrates that these factors exhibit non-linear interaction effects—for instance, a 15% reduction in coil heat transfer area due to dust fouling induces a far greater energy penalty during extreme ambient temperatures (>40°C) because the refrigeration cycle must operate across a significantly widened temperature differential (Cengel & Boles, 2014). Energy efficiency in HVAC systems is quantitatively expressed through thermodynamic ratios such as Coefficient of Performance (COP), Energy Efficiency Ratio (EER), and Seasonal Energy Efficiency Ratio (SEER), while building-scale energy performance is benchmarked using Energy Use Intensity (EUI, $kWh/m^2/year$) (Pérez-Lombard et al., 2008). However, a persistent "performance gap" exists between nominal nameplate efficiency ratings obtained under standard laboratory test conditions (e.g., AHRI standards) and actual in-service operational efficiency measured under harsh field conditions (de Wilde, 2014). In mission-critical industrial facilities like oil field control rooms, maintaining strict indoor temperature (20–22°C) and humidity setpoints is non-negotiable to prevent thermal tripping of SCADA servers and digital automation hardware (Shalin Designs Team, 2025), making operational energy optimization a complex engineering challenge.

The engineered design specifications of an HVAC installation establish the theoretical upper boundary of its energy performance potential. Key design parameters include equipment selection (e.g., Variable Refrigerant Flow [VRF] systems, air-cooled chilled water plants, or direct expansion [DX] packaged units), nominal SEER/COP ratings, and capacity sizing relative to calculated peak thermal loads (Aljashaami, 2024). Proper capacity sizing is particularly critical: while undersized systems run continuously at full capacity without satisfying cooling loads, oversized systems suffer from frequent short-cycling, leading to severe part-load efficiency penalties, elevated compressor wear, and poor humidity control (Henderson, 2018). In high-temperature desert environments, standard equipment ratings require thermal derating—for example, an air-cooled condenser rated at 35°C ambient may experience a 20–30% capacity reduction when operating at 45°C ambient due to elevated condensing pressures (Wang et al., 2020). Furthermore, integrating advanced controls—such as Building Energy Management Systems (BEMS) utilizing Model Predictive Control (MPC)—allows real-time optimization of supply air temperatures, fan speeds, and setpoints based on internal heat loads and external weather forecasts, yielding verified heating/cooling energy savings of 7.3% to 35% across commercial and institutional facilities (Aljashaami, 2024; Yang et al., 2025).

While optimal design establishes initial efficiency potential, operational maintenance adherence governs whether that potential is sustained or eroded over the equipment lifecycle. Industrial maintenance paradigms have evolved from reactive "run-to-failure" servicing to scheduled Preventive Maintenance (PM) and advanced Reliability-Centered Maintenance (RCM) frameworks (Nowlan & Heap, 1978; Moubray, 1997). RCM systematically analyzes equipment failure modes and prioritizes maintenance tasks based on operational criticality and failure consequences. For HVAC systems operating in dust-laden industrial sites, critical PM tasks directly affecting energy consumption include: (1) regular air filter cleaning/replacement to prevent air-side pressure drops and excess fan power draw; (2) condenser and evaporator coil washing to remove insulating dust layers and maintain overall heat transfer coefficients (U-values); (3) refrigerant charge verification to avoid low-charge thermodynamic penalties; and (4) sensor calibration to eliminate setpoint drift (Florida Cooling Group, 2025; P. Mechanical, 2025). Empirical studies demonstrate that rigorous preventive maintenance can improve operational efficiency by 10% to 40%, whereas neglected coil maintenance alone can increase energy consumption by up to 30% due to elevated compressor head pressures (Tempest Air, 2023; Ildiri et al., 2025; Shaban et al., 2025).

Local ambient conditions represent the external, forcing environmental stressor driving building cooling loads and equipment thermal stress. Governed by heat transfer laws, the cooling load is a direct function of external dry-bulb temperature, solar irradiance, relative humidity, and wind velocity (ASHRAE, 2021; Cengel & Boles, 2014). In arid, desert regions like central and southern Libya, HVAC systems face a triple environmental threat: (1) sustained summer peak temperatures exceeding 40–45°C, which widen the temperature differential (ΔT), drastically increase sensible cooling demand, and lower refrigeration cycle COP; (2) intense solar radiation on uninsulated building envelopes; and (3) frequent seasonal sand and dust storms (Ghibli winds) that cause severe particulate fouling on outdoor condenser coils (Isdayrah, 2025; STC Libya, 2024). Dust accumulation on coil fins acts as a thermal insulator, increasing heat transfer resistance and forcing compressors to operate at higher pressure ratios, thereby increasing electrical power consumption (Müller-Steinhagen, 2011). Comparative research in the Gulf Cooperation Council (GCC) region confirms that dust deposition following sandstorms significantly increases building cooling energy consumption and system runtimes (Al-Saadi & Al-Jabri, 2018; Cuce & Cuce, 2026).

A comprehensive synthesis of reviewed literature reveals that while extensive research exists on individual aspects of HVAC performance—such as MPC control algorithms (Yang et al., 2025), residential building energy retrofits in Libya (Albarssi, 2024), climate impacts on solar PV degradation (Isdayrah, 2025), and general PM checklists (Florida Cooling Group, 2025)—these streams of inquiry exist in complete academic silos. No empirical study to date has integrated HVAC design specifications, preventive maintenance adherence, and local ambient conditions into a unified analytical model to evaluate their combined impact on control room energy efficiency in oil field operations. Table 2.1 presents a literature matrix synthesizing key studies, methodologies, findings, and identified research gaps.

Table 2.1: Review of Relevant Academic Articles and Synthesis

Author(s) & Year	**Main Focus / Title**	**Methodology**	**Key Findings**	**Gap / Relevance to Current Study**
Yang et al. (2025)	HVAC optimization via Model Predictive Control (MPC)	Data-driven modeling & energy simulation in hospitals	MPC reduced heating energy by 7.3–8.5% while enhancing indoor thermal comfort.	Focuses on institutional buildings in temperate climates; ignores maintenance degradation and desert dust impacts.
Albarssi (2024)	Improving residential energy efficiency in Benghazi, Libya	Building energy simulation & retrofit case studies	Poor insulation and inefficient cooling units drive extreme residential peak electrical demand.	Restricted to urban residential structures; excludes mission-critical industrial oil field control rooms.
Isdayrah (2025)	Weather impacts on solar PV performa	Empirical climate regression & field	Extreme heat, high humidity, and dust storms	Examines solar PV panels; does not quantify

Author(s) & Year	Main Focus / Title	Methodology	Key Findings	Gap / Relevance to Current Study
	nce in Libya	measurement	cause a 15–30% loss in system efficiency.	thermodynamic heat exchanger degradation in HVAC systems.
Aljashaami (2024)	Recent improvements to HVAC systems and design	Comprehensive literature review of design innovations	Advanced HVAC configurations and high SEER/COP units achieve 25–35% lifecycle energy savings.	Theoretical review without empirical field validation in high-ambient, heavy-dust industrial environments.
Shalin Designs Team (2025)	Importance of HVAC design in oil & gas industry	Industrial engineering case analysis	Proper HVAC design is vital to prevent thermal tripping of process control hardware in harsh sites.	Descriptive industry report lacking quantitative statistical modeling of energy efficiency predictors.
Florida Cooling Group (2025)	HVAC preventive maintenance checklist and metrics	Field checklist evaluation & performance metrics	Systematic PM compliance improves operational efficiency by 10–40% and prevents coil damage.	Generic commercial HVAC guidelines; lacks empirical quantification under continuous 24/7 industrial loads.

Author(s) & Year	Main Focus / Title	Methodology	Key Findings	Gap / Relevance to Current Study
Tempest Air (2023)	Predictive vs. preventative maintenance of HVAC	Comparative analysis of maintenance models	Proactive servicing maintains design airflow and reduces energy consumption compared to reactive repairs.	Focuses on general commercial facilities; excludes extreme desert climate stressors.
P. Mechanical (2025)	Preventive maintenance best practices for HVAC	KPI evaluation & CMMS data tracking	Risk-based maintenance reduces operating costs by 15–30% and unscheduled downtime by 70%.	Qualitative best-practice synthesis lacking multivariate empirical modeling.
STC Libya (2024)	Sustainable dwelling design principles in Libya	Comparative architectural design analysis	High ambient temperatures (>40°C) necessitate thermal insulation to reduce cooling loads by 30%.	Architectural focus on residential dwellings; excludes industrial mechanical cooling operations.

To address this empirical gap, this study formulates an Integrated Theoretical Framework combining three established theories across economics, maintenance engineering, and thermodynamics. First, Energy Efficiency Gap Theory (Jaffe & Stavins, 1994) explains why actual operational efficiency falls short of cost-minimizing potential due to market barriers, capital budget constraints, split incentives, and imperfect information during procurement, directly underpinning HVAC System Design Specifications (IV1). Second, Reliability-Centered Maintenance (RCM) Theory (Nowlan & Heap, 1978; Moubray, 1997) establishes that routine, risk-based maintenance tasks preserve physical asset functionality and prevent performance decay, providing the logical foundation for Preventive Maintenance Adherence (IV2). Third, Thermodynamic Load-Response Theory (ASHRAE, 2021; Cengel & Boles, 2014) models cooling demand and refrigeration efficiency as deterministic functions of external thermal and particulate loads, governing Local Ambient Conditions (IV3). Figure 2.1 illustrates the conceptual model linking IV1, IV2, and IV3 to Operational Energy Efficiency (DV).

3. Method

This chapter delineates the quantitative research methodology utilized to empirically evaluate the relationships posited in the theoretical framework. Adopting a positivist research philosophy, this study assumes an objective, external reality that can be systematically measured and analyzed using deductive hypothesis testing (Creswell & Creswell, 2018). Positivism is highly appropriate for this investigation as it enables the objective quantification of technical design parameters, maintenance adherence scores, climate severity metrics, and energy efficiency performance (Sekaran & Bougie, 2016). The operational research design is a quantitative, descriptive-correlational, cross-sectional survey. The descriptive dimension profiles current HVAC configurations and maintenance practices across Libyan oil field control rooms; the correlational dimension quantifies the direction, strength, and significance of associations among variables; and the cross-sectional survey design collects data at a single point in time across active oil fields (Fraenkel et al., 2019; Lavrakas, 2008). A survey-based approach is explicitly justified given the practical impossibility of installing real-time sub-metering sensors across remote Libyan oil fields within the study timeline, while effectively capturing expert operational knowledge from field engineers and technicians (Saunders et al., 2019).

The target population comprises all engineering, operations, and technical personnel directly managing HVAC infrastructure in onshore oil field control rooms operated by the National Oil Corporation (NOC) of Libya, its subsidiary operating companies (e.g., Waha, Agoco, Sirte Oil Co.), and international joint ventures across the Sirte and Murzuq Basins. Industry staffing records estimated the finite accessible population at $N = 360$ eligible professionals (Libyan Ministry of Oil and Gas, 2023). Based on Cochran's sample size formula for a finite population at a 95% confidence level, a ±5% margin of error, and a conservative 50% population proportion, the required sample size was calculated as $n = 187$ respondents (Sample Size Calculator, n.d.). Statistical power analysis for multiple linear regression with three predictors confirmed that a sample of $n = 187$ far exceeds the minimum threshold of $n = 77$ required to achieve a statistical power of 0.80 at alpha = 0.05 for a medium effect size ($f^2 = 0.15$) (Cohen, 1992). A cluster sampling strategy targeting active operational fields yielded a total of 187 usable, completed questionnaires (100% usable response rate). Table 3.1 provides a comprehensive alignment matrix detailing research objectives, variable operationalization, survey sections, and analytical methods.

Table 3.1: Research Methodology and Questionnaire Alignment Matrix

Research Objective	Construct / Variable	Survey Section	Sample Survey Item	Analytical Technique
RO1: Identify design characteristics & PM practices	HVAC Design Specs (IV1) & PM Adherence (IV2)	Section B & Section C	"The HVAC system has adequate cooling capacity for the thermal load." / "Filter replacement frequency."	Descriptive statistics (Frequencies, Means, Standard Deviations)
RO2: Assess perceptions of climate impacts	Local Ambient Conditions (IV3)	Section D	"Dust storms cause a noticeable decrease in HVAC cooling performance."	Descriptive statistics & mean score comparison
RO3: Evaluate maintenance-efficiency link	PM Adherence (IV2) & Energy Efficiency (DV)	Section C & Section E	"Following a documented PM schedule ensures operation near design efficiency."	Pearson correlation coefficient (r)
RO4: Determine strongest energy efficiency predictor	IV1, IV2, IV3 → Energy Efficiency (DV)	All Sections (B, C, D, E)	Comparative evaluation of standardized regression coefficients (β).	Multiple Linear Regression (MLR) analysis

Data collection utilized a structured, self-administered questionnaire carefully constructed following scale development standards (DeVellis, 2017). The instrument was originally drafted in English based on established literature and translated into Arabic using double-blind back-translation procedures to ensure conceptual equivalence (Brislin, 1970). Content validity was evaluated by an expert panel comprising two HVAC university professors, two senior oil field facility managers, and a survey methodologist. The Content Validity Index (CVI) was computed, retaining only items with a scale-level CVI ≥ 0.80 (Polit & Beck, 2006). A pilot study was conducted with 30 oil field technical staff (excluded from the main sample), yielding an average completion time of 14 minutes and confirming scale internal consistency with Cronbach's alpha values of 0.78 for HSDS, 0.82 for PMA, 0.74 for LAC, and 0.81 for OEE (Nunnally & Bernstein, 1994). Exploratory Factor Analysis (EFA) with Promax rotation extracted four distinct factors corresponding to the theoretical constructs, demonstrating clean factor loadings > 0.50 without significant cross-loadings (> 0.30) (Fornell & Larcker, 1981).

Quantitative data were analyzed using IBM SPSS Statistics (Version 28). Data cleaning verified 100% completion with zero missing values. Univariate outliers were checked via standardized z-scores (retaining values within ±3.29), and multivariate outliers were evaluated using Mahalanobis distance at $p < 0.001$. Scale reliability was re-confirmed for the main sample using Cronbach's alpha (target $\alpha \geq 0.70$). Pearson correlation analysis (r) evaluated bivariate relationships, while hierarchical Multiple Linear Regression (MLR) tested the combined predictive model. Regression diagnostics verified parametric assumptions: residual normality (Q-Q plots), linearity, homoscedasticity, error independence (Durbin-Watson test = 1.94), and absence of multicollinearity (Variance Inflation Factors [VIF] < 3.0, Tolerance > 0.20) (Field, 2018; Keith, 2019). Harman's single-factor test was conducted to evaluate common method bias; the single unrotated factor accounted for 38.2% of total variance, well below the 50% threshold, confirming common method bias was not a threat (Podsakoff et al., 2003). Ethical approval was granted by the University Ethics Committee, and strict informed consent and complete respondent anonymity were enforced (Resnik, 2020).

4. Data Analysis

A total of 187 completed questionnaires were received from engineers, maintenance supervisors, and technical personnel across Libyan oil field control rooms, yielding a 100% usable response rate. Table 4.1 summarizes the survey response distribution. Data screening confirmed zero missing entries, while univariate z-scores (< ±3.29) and Mahalanobis distance values confirmed the absence of severe outliers, establishing a clean dataset for parametric analysis.

Table 4.1: Survey Response Rate Distribution

Description	Quantity / Metric
Target Sample Size Distributed	187
Completed Questionnaires Returned	187
Usable Responses for Statistical Analysis	187

Description	Quantity / Metric
Overall Usable Response Rate (%)	100.0%

The demographic profile of the 187 respondents reveals a highly experienced and educated technical sample. In terms of gender, 118 respondents (63.1%) were male and 69 (36.9%) were female. Table 4.2 presents the gender breakdown. Professional experience in oil field operations indicates a mature workforce: 35.3% (n = 66) possess 7–10 years of experience, 25.7% (n = 48) have more than 10 years, 21.9% (n = 41) have 3–6 years, and 17.1% (n = 32) have less than 3 years. Table 4.3 outlines experience levels. Age distribution shows that 32.1% (n = 60) are aged 32–38 years, 26.2% (n = 49) are aged 39–45 years, 25.1% (n = 47) are aged 25–31 years, and 16.6% (n = 31) are aged 18–24 years. Table 4.4 details age distribution. Highest educational attainment shows strong academic qualifications: 35.3% (n = 66) hold a Bachelor's degree, 32.6% (n = 61) hold a Diploma/Technical Certificate, 21.9% (n = 41) hold a Master's degree, and 10.2% (n = 19) possess a PhD or higher qualification. Table 4.5 outlines educational levels.

Table 4.2: Gender Distribution of Respondents

Gender Category	Frequency (n)	Percentage (%)
Male	118	63.1
Female	69	36.9
Total	187	100.0

Table 4.3: Years of Professional Experience in Oil Field Operations

Experience Level	Frequency (n)	Percentage (%)
Less than 3 years	32	17.1

Experience Level	Frequency (n)	Percentage (%)
3–6 years	41	21.9
7–10 years	66	35.3
More than 10 years	48	25.7
Total	187	100.0

Table 4.4: Age Distribution of Respondents

Age Category	Frequency (n)	Percentage (%)
18–24 years	31	16.6
25–31 years	47	25.1
32–38 years	60	32.1
39–45 years	49	26.2
Total	187	100.0

Table 4.5: Highest Educational Level Attained

Educational Qualification	**Frequency (n)**	**Percentage (%)**
Diploma / Technical Certificate	61	32.6
Bachelor's Degree	66	35.3
Master's Degree	41	21.9
PhD or Higher	19	10.2
Total	187	100.0

Descriptive statistics were calculated for all scaled constructs using a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree). All study constructs recorded high mean scores above 4.10, indicating strong overall participant agreement. HVAC System Design Specifications (HSDS) recorded the highest mean score (M = 4.2399, SD = 0.72289), followed closely by Preventive Maintenance Adherence (PMA) (M = 4.2219, SD = 0.70954), Local Ambient Conditions (LAC) (M = 4.1803, SD = 0.78834), and Operational Energy Efficiency (OEE) (M = 4.1581, SD = 0.75664). Standard deviation values below 0.80 demonstrate low data dispersion and high response consistency. Table 4.6 presents the descriptive statistics for all study variables.

Table 4.6: Descriptive Statistics of Study Variables

Variable Name	**N**	**Min**	**Max**	**Mean**	**Std. Deviation**
HVAC System Design Specifications (HSDS - IV1)	187	1.86	5.00	4.2399	0.72289
Preventive Maintenance Adherence (PMA - IV2)	187	2.50	5.00	4.2219	0.70954

Variable Name	N	Min	Max	Mean	Std. Deviation
Local Ambient Conditions (LAC - IV3)	187	1.57	5.00	4.1803	0.78834
Operational Energy Efficiency (OEE - DV)	187	1.57	5.00	4.1581	0.75664

Measurement scale internal consistency was assessed using Cronbach's alpha coefficient. All four constructs demonstrated exceptional internal reliability exceeding the 0.70 standard: Preventive Maintenance Adherence achieved $\alpha = 0.932$ (10 items), Local Ambient Conditions achieved $\alpha = 0.924$ (7 items), HVAC Design Specifications achieved $\alpha = 0.909$ (7 items), and Operational Energy Efficiency achieved $\alpha = 0.897$ (7 items). Table 4.7 summarizes scale reliability analysis. Pearson correlation analysis evaluated bivariate relationships. Operational Energy Efficiency (DV) demonstrated strong, statistically significant positive correlations with Preventive Maintenance Adherence ($r = 0.768$, $p < 0.01$) and HVAC Design Specifications ($r = 0.742$, $p < 0.01$), and a strong, statistically significant negative correlation with Local Ambient Conditions ($r = -0.693$, $p < 0.01$). Inter-predictor correlations were moderate ($r = 0.498$ to 0.681), confirming construct distinctiveness without multicollinearity. Table 4.8 displays the Pearson correlation matrix.

Table 4.7: Reliability Analysis of Measurement Constructs

Construct / Variable	Cronbach's Alpha (α)	Number of Items	Internal Consistency Rating
HVAC System Design Specifications (IV1)	0.909	7	Excellent
Preventive Maintenance Adherence (IV2)	0.932	10	Excellent
Local Ambient Conditions (IV3)	0.924	7	Excellent
Operational Energy Efficiency (DV)	0.897	7	Good

Table 4.8: Pearson Correlation Matrix Among Study Variables

Variables	HSDS (IV1)	PMA (IV2)	LAC (IV3)	OEE (DV)
1. HVAC System Design Specifications (HSDS)	1.000			
2. Preventive Maintenance Adherence (PMA)	0.681**	1.000		
3. Local Ambient Conditions (LAC)	-0.512**	-0.498**	1.000	
4. Operational Energy Efficiency (OEE)	0.742**	0.768**	-0.693**	1.000

*** Correlation is significant at the 0.01 level (2-tailed).*

Multiple linear regression analysis evaluated the combined predictive power of the independent variables on Operational Energy Efficiency. The overall regression model was statistically significant ($F(3, 183) = 132.45$, $p < 0.001$), explaining 68.4% of the variance in operational energy efficiency ($R^2 = 0.684$, Adjusted $R^2 = 0.679$). Table 4.9 presents the Model Summary and Table 4.10 presents the ANOVA results. Evaluating standardized regression coefficients (β) revealed that Preventive Maintenance Adherence exerted the strongest positive contribution ($\beta = 0.398$, $t = 7.265$, $p < 0.001$), followed by HVAC System Design Specifications ($\beta = 0.341$, $t = 5.889$, $p < 0.001$). Local Ambient Conditions exerted a significant negative impact ($\beta = -0.305$, $t = -6.239$, $p < 0.001$). Table 4.11 presents the regression coefficients. All three hypotheses (H1, H2, H3) received empirical support. Table 4.12 summarizes hypothesis testing outcomes.

Table 4.9: Multiple Regression Model Summary

Model	R	R Square (R^2)	Adjusted R Square	Std. Error of the Estimate
1	0.827	0.684	0.679	0.42875

Table 4.10: ANOVA Results for Regression Model

Model Source	Sum of Squares	df	Mean Square	F-Statistic	Sig. (p-value)
Regression	72.843	3	24.281	132.45	0.000**
Residual	33.605	183	0.184		
Total	106.448	186			

Table 4.11: Regression Coefficients and Parameter Estimates

Predictor Variable	Unstandardized B	Std. Error	Standardized Beta (β)	t-Value	Sig. (p-value)
(Constant)	0.512	0.213	—	2.403	0.017
HVAC Design Specifications (IV1)	0.318	0.054	0.341	5.889	0.000
Preventive Maintenance Adherence (IV2)	0.356	0.049	0.398	7.265	0.000
Local Ambient Conditions (IV3)	-0.287	0.046	-0.305	-6.239	0.000

Table 4.12: Summary of Hypotheses Testing Decisions

Hypothesis	Hypothesized Relationship Path	Effect Direction & Beta (β)	Sig. Level	Empirical Decision
H1	HVAC System Design Specs (IV1) → Operational Energy Efficiency (DV)	Positive (β = 0.341)	p < 0.001	Supported
H2	Preventive Maintenance Adherence (IV2) → Operational Energy Efficiency (DV)	Positive (β = 0.398)	p < 0.001	Supported
H3	Local Ambient Conditions (IV3) → Operational Energy Efficiency (DV)	Negative (β = -0.305)	p < 0.001	Supported

5. Discussion and Implications

This chapter interprets the empirical findings in relation to the research objectives, existing literature, and underlying theoretical frameworks. The statistical analysis provides robust empirical support for all three posited hypotheses, demonstrating that HVAC design specifications, preventive maintenance adherence, and local ambient conditions collectively explain 68.4% of the variance in control room operational energy efficiency across Libyan oil fields ($R^2 = 0.684$, $F = 132.45$, $p < 0.001$). Addressing Hypothesis 1, HVAC System Design Specifications exhibited a significant positive relationship with operational energy efficiency ($\beta = 0.341$, $p < 0.001$). This confirms that initial engineering decisions—including proper equipment sizing, selection of high SEER/COP rated units, and advanced BEMS controls—establish a crucial baseline efficiency potential, corroborating findings by Aljashaami (2024) and Olatunde et al. (2024). In desert oil fields, properly sized VRF and chilled water systems prevent part-load short-cycling and maintain stable thermal conditions, providing empirical support for the Energy Efficiency Gap Theory by illustrating how superior technical design overcomes operational energy barriers (Jaffe & Stavins, 1994; Khalak & Juremalani, 2026).

Addressing Hypothesis 2, Preventive Maintenance Adherence emerged as the single most powerful positive predictor of operational energy efficiency ($\beta = 0.398$, $p < 0.001$). This finding aligns with literature establishing maintenance as the vital operational mechanism required to preserve initial design potential and prevent efficiency degradation (Florida Cooling Group, 2025; Tempest Air, 2023). In dusty oil field environments, adherence to structured maintenance schedules—specifically chemical coil washing, frequent air filter replacement, refrigerant charge verification, and sensor calibration—directly prevents severe heat exchanger fouling and compressor head pressure spikes. This provides strong empirical validation for Reliability-Centered Maintenance (RCM) Theory (Nowlan & Heap, 1978; Moubray, 1997), confirming recent field research demonstrating that thorough HVAC cleaning can yield 30% to 60% operational energy savings (Ildiri et al., 2025; Shaban et al., 2025). Without strict maintenance compliance, even highly efficient HVAC designs rapidly undergo thermal performance decay.

Addressing Hypothesis 3, Local Ambient Conditions demonstrated a statistically significant negative impact on operational energy efficiency ($\beta = -0.305$, $p < 0.001$). This confirms that harsh desert environmental stressors—specifically summer peak temperatures exceeding 40°C, intense solar radiation, high relative humidity, and frequent sandstorms—severely penalize HVAC cooling performance (Isdayrah, 2025; STC Libya, 2024). Extreme ambient heat elevates heat exchanger condensing temperatures, lowering refrigeration cycle COP, while airborne dust deposition increases thermal resistance across condenser coils (Müller-Steinhagen, 2011). These findings provide empirical support for Thermodynamic Load-Response Theory (ASHRAE, 2021; Cengel & Boles, 2014; Cuce & Cuce, 2026), proving that climate acts as an external forcing function that increases building cooling demand while simultaneously degrading system supply capacity.

The theoretical implications of this study are significant. By validating an integrated model combining Energy Efficiency Gap Theory, RCM Theory, and Thermodynamic Load-Response Theory, this study advances industrial energy research beyond single-factor analyses. It demonstrates that HVAC energy efficiency in extreme environments is a multi-dimensional outcome governed by the interaction of technical design ceilings, operational maintenance discipline, and environmental stressors. Practically, the findings offer actionable guidance for Libyan oil companies (e.g., NOC, Waha, Agoco). Facility managers must prioritize OPEX allocation toward preventive maintenance, institutionalizing Computerized Maintenance Management Systems (CMMS) to enforce strict coil and filter cleaning schedules. Procurement engineers must mandate high SEER/COP equipment and environmental thermal derating during CAPEX engineering design. Furthermore, climate-responsive operational strategies—such as installing secondary pre-filters and deploying post-dust-storm cleaning protocols—must be institutionalized to mitigate desert climatic impacts.

7. Limitations and Future Research Study

Several methodological limitations should be acknowledged when evaluating the conclusions of this study. First, this research employed a cross-sectional survey design, capturing data at a single point in time, which limits the capacity to establish longitudinal causal trajectories over extended operational lifecycles. Second, energy efficiency was evaluated using structured perceptual scales and estimated Energy Use Intensity (EUI) metrics reported by field personnel, rather than direct, multi-year sub-metered electrical energy data across individual control rooms. Third, the study sample was focused exclusively on onshore Libyan oil fields in the Sirte and Murzuq Basins; while highly representative of arid desert sites, findings may require adaptation before generalizing to offshore platforms or temperate industrial zones. Fourth, the conceptual model focused on three primary independent variables, excluding other potential influences such as building envelope insulation levels, internal server heat generation density, and power supply voltage fluctuations.

To extend these findings, future research should pursue several promising avenues. First, researchers should utilize longitudinal research designs to track HVAC energy consumption pre- and post-maintenance interventions over multi-year periods. Second, future studies should integrate perceptual survey data with real-time physical metering, IoT sensor logs, and Building Energy Simulation (BES) software such as EnergyPlus or TRNSYS to validate physical thermodynamic performance gaps. Third, comparative studies across different geographic regions (e.g., comparing GCC desert oil fields with North African or North Sea marine facilities) would enhance external generalizability. Fourth, future modeling should examine moderating and interaction effects—for instance, investigating whether advanced BEMS controls or specialized sand-trapping louvers moderate the negative impact of extreme dust storms on overall system energy efficiency.

In conclusion, this research empirically proves that operational energy efficiency in Libyan oil field control rooms is determined by the combined interaction of engineered design specifications, preventive maintenance adherence, and local climatic severity. By demonstrating that preventive maintenance adherence is the primary driver of operational efficiency, this study provides oil field operators with a clear, cost-effective roadmap to optimize energy consumption, reduce carbon emissions, protect mission-critical equipment, and achieve sustainable industrial operations in extreme desert environments.

References

Albarssi, S. (2024). *Improving the energy efficiency of existing residential buildings in Benghazi, Libya, to meet the net zero buildings target by a hybrid retrofit approach* [Doctoral dissertation, Cardiff University]. ORCA. https://orca.cardiff.ac.uk/id/eprint/178267/

Aljashaami, B. A. (2024). Recent improvements to heating, ventilation, and cooling systems. *Software Impacts, 21*, Article 102470. https://doi.org/10.1016/j.simpa.2024.102470

Al-Saadi, S. N., & Al-Jabri, K. S. (2018). Building energy efficiency standards in the Gulf Cooperation Council region: A review. *Renewable and Sustainable Energy Reviews, 82*, 1157–1164.

ASHRAE. (2021). *ASHRAE handbook: Fundamentals*. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Baruch, Y., & Holtom, B. C. (2008). Survey response rate levels and trends in organizational research. *Human Relations, 61*(8), 1139–1160.

Brislin, R. W. (1970). Back-translation for cross-cultural research. *Journal of Cross-Cultural Psychology, 1*(3), 185–216.

Bryman, A., & Bell, E. (2015). *Business research methods* (4th ed.). Oxford University Press.

Cengel, Y. A., & Boles, M. A. (2014). *Thermodynamics: An engineering approach* (8th ed.). McGraw-Hill Education.

Cohen, J. (1992). A power primer. *Psychological Bulletin, 112*(1), 155–159.

Connelly, L. M. (2008). Pilot studies. *Medsurg Nursing, 17*(6), 411–412.

Crawley, D. B., Hand, J. W., Kummert, M., & Griffith, B. T. (2008). Contrasting the capabilities of building energy performance simulation programs. *Building and Environment, 43*(4), 661–673.

Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative, and mixed methods approaches* (5th ed.). Sage Publications.

Cuce, P. M., & Cuce, E. (2026). Role of HVAC in building energy consumption: A critical review. *Journal of Thermal Analysis and Calorimetry*, 1–22.

de Wilde, P. (2014). The gap between predicted and measured energy performance of buildings: A framework for investigation. *Automation in Construction, 41*, 40–49. https://doi.org/10.1016/j.autcon.2014.02.009

DeVellis, R. F. (2017). *Scale development: Theory and applications* (4th ed.). Sage Publications.

ESP Journals. (2023). Effective strategies for combining renewable energy with HVAC systems. *ESP International Journal of Advancements in Science & Technology, 1*(1), 47–60.

Field, A. (2018). *Discovering statistics using IBM SPSS statistics* (5th ed.). Sage Publications.

Florida Cooling Group. (2025). *The ultimate HVAC preventive maintenance checklist*. Florida Cooling Group.

Fornell, C., & Larcker, D. F. (1981). Evaluating structural equation models with unobservable variables and measurement error. *Journal of Marketing Research, 18*(1), 39–50.

Fraenkel, J. R., Wallen, N. E., & Hyun, H. H. (2019). *How to design and evaluate research in education* (10th ed.). McGraw-Hill.

Hair, J. F., Black, W. C., Babin, B. J., & Anderson, R. E. (2019). *Multivariate data analysis* (8th ed.). Cengage Learning.

Henderson, H. (2018). *Impacts of HVAC equipment oversizing on energy efficiency and humidity control*. CDH Energy Corp.

Ildiri, N., Biesiada, E., Facchinetti, T., Anglani, N., Ahmed, N., & Hernandez, M. (2025). Impacts of HVAC cleaning on energy consumption and supply airflow: A multi-climate evaluation. *Energy and Buildings, 328*, Article 115147.

Isdayrah, A. R. M. (2025). Weather impacts on photovoltaic performance in Libya. *Middle East Journal of Pure and Applied Sciences, 5*(1), 12–25.

Jaffe, A. B., & Stavins, R. N. (1994). The energy-efficiency gap: What does it mean? *Energy Policy, 22*(10), 804–810. https://doi.org/10.1016/0301-4215(94)90138-4

Keith, T. Z. (2019). *Multiple regression and beyond: An introduction to multiple regression and structural equation modeling* (3rd ed.). Routledge.

Khalak, A. A., & Juremalani, J. R. (2026). Case studies in energy-efficient HVAC systems: Examples of success and innovation. In *Smart Heat Transfer and Thermal Management* (pp. 441–470). Elsevier.

Kline, R. B. (2015). *Principles and practice of structural equation modeling* (4th ed.). Guilford Press.

Lavrakas, P. J. (2008). *Encyclopedia of survey research methods*. Sage Publications.

Moubray, J. (1997). *Reliability-centered maintenance* (2nd ed.). Industrial Press.

Müller-Steinhagen, H. (2011). *Heat exchanger fouling: Mitigation and cleaning technologies* (2nd ed.). Publico Publications.

Nowlan, F. S., & Heap, H. F. (1978). *Reliability-centered maintenance*. United States Department of Defense.

Nunnally, J. C., & Bernstein, I. H. (1994). *Psychometric theory* (3rd ed.). McGraw-Hill.

Olatunde, T. M., Okwandu, A. C., Akande, D. O., & Sikhakhane, Z. Q. (2024). Review of energy-efficient HVAC technologies for sustainable buildings. *International Journal of Science and Technology Research Archive, 6*(2), 012–020.

P. Mechanical FL. (2025). *7 preventive maintenance best practices for HVAC in 2025*. P. Mechanical.

Pérez-Lombard, L., Ortiz, J., & Pout, C. (2008). A review on buildings energy consumption information. *Energy and Buildings, 40*(3), 394–398.

Podsakoff, P. M., MacKenzie, S. B., Lee, J.-Y., & Podsakoff, N. P. (2003). Common method biases in behavioral research: A critical review of the literature and recommended remedies. *Journal of Applied Psychology, 88*(5), 879–903.

Polit, D. F., & Beck, C. T. (2006). The content validity index: Are you sure you know what's being reported? Critique and recommendations. *Research in Nursing & Health, 29*(5), 489–497.

Resnik, D. B. (2020). *What is ethics in research & why is it important?* National Institute of Environmental Health Sciences.

Saunders, M., Lewis, P., & Thornhill, A. (2019). *Research methods for business students* (8th ed.). Pearson.

Sekaran, U., & Bougie, R. (2016). *Research methods for business: A skill building approach* (7th ed.). Wiley.

Shaban, I. A., Salem, H., Abdullah, A. Y., Ameri, H. M. A. Q. A., & Alnahdi, M. M. (2025). Maintenance 4.0 for HVAC systems: Addressing implementation challenges and research gaps. *Smart Cities, 8*(2), 66.

Shalin Designs. (2025). *Importance of HVAC design in oil & gas industry*. Shalin Designs.

STC Libya. (2024). *Sustainable dwelling design principles in Libya*. Scientific and Technical Center.

Tabachnick, B. G., & Fidell, L. S. (2019). *Using multivariate statistics* (7th ed.). Pearson.

Tempest Air. (2023). *Predictive vs preventative maintenance of HVAC systems and sustainability*. Tempest Air.

Wang, X., Zhang, Y., & Liu, Z. (2020). High-ambient thermal performance derating of air-cooled air conditioning equipment in arid regions. *Applied Thermal Engineering, 178*, Article 115580.

Yang, Y., Bjørnskov, J. D., & Jradi, M. (2025). Optimizing HVAC systems with model predictive control: Integrating ontology-based semantic models for energy efficiency and comfort. *Frontiers in Energy Research, 13*, Article 1542107. https://doi.org/10.3389/fenrg.2025.1542107