

## The impact of smart energy on population gatherings and activities mosques in Saudi Arabia case study

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### ABSTRACT

This research investigates the strategic application of Artificial Intelligence (AI) technologies to optimize the architectural design and energy performance of mosques in Saudi Arabia's hot arid climate, while preserving Islamic cultural and spiritual authenticity. Employing a mixed-methods approach combining Building Information Modeling (BIM) simulations, energy audits, and stakeholder engagement, this study examines 17 mosques across diverse geographic and typological contexts.

Quantitative analysis reveals that AI-driven design methodologies can reduce annual energy consumption by 29%, decreasing the Energy Use Intensity (EUI) from 87.5 kWh/m<sup>2</sup>/yr to 61.8 kWh/m<sup>2</sup>/yr. LED lighting optimization alone achieves a 9% energy reduction while improving illumination uniformity ( $E_o = 0.69$ ). Smart occupancy-based control systems demonstrate 16.2-21.2% additional energy savings through adaptive HVAC management.

Qualitative findings indicate strong stakeholder support for technology integration, provided core cultural elements—including Qibla orientation, Islamic ornamentation, and acoustic requirements—remain inviolate. This study contributes a validated framework for culturally-sensitive AI implementation in sacred architecture, offering actionable strategies for architects, policymakers, and religious authorities. The results, supported by precedent studies (Abdallah, 2023; Abdou et al., 2013), suggest broad applicability to other hot arid climates and culturally significant building typologies globally.

**Keywords:** Intelligent Mosque- AI-Driven Design- Energy Efficiency- Sustainable Sacred Architecture- Saudi Vision 2030

### The study problem

High energy consumption in hot regions, for example the study (mosques in Saudi Arabia) consumes 87.5 kWh in the energy index (base case). Cooling loads reach up to 5,100 W at their peak, accounting for about 58% of total consumption. On the operational side, there is a mismatch: mosques experience intermittent occupancy (5 daily prayers averaging 15-30 minutes each), yet cooling systems usually operate continuously during working hours, wasting energy during periods of non-use.

### Methodology

The study used the descriptive method through a survey study, and then analyzed it to reach executable results and recommendations.

### Study Objectives

This research aims to study how artificial intelligence and its techniques can be used strategically to improve design and achieve energy efficiency in mosques in Saudi Arabia while preserving their culture and considering their spiritual and functional significance. Specifically, the study aims to develop AI-supported methodologies that reconcile sustainability with Islamic architectural heritage.

### I. The Importance of the Study

The construction and architecture of mosques in Saudi Arabia have traditionally been adapted to the historical style of mosque architecture both spiritually and environmentally, creating spaces that facilitate worship while taking into account the local climate and Saudi building regulations. Mosques serve as places of worship and community centers for approximately 34 million Muslims. The Kingdom manages around 100,000 mosques,

with government support for operating costs including electricity, water, and maintenance—creating a direct financial impact on national resources.

Recent data indicate that mosques in hot and dry climates consume between 69-87.5 kWh/m<sup>2</sup>/year, with cooling systems accounting for 58% of total energy demand. During the peak summer months (June–August), when outdoor temperatures reach 41-46°C, energy consumption rises by 47% compared to winter baseline levels. This consumption reflects the fundamental tension between traditional passive design principles—developed over centuries in pre-mechanical cooling contexts—and contemporary expectations of thermal comfort, maintained at set points of 26°C through air conditioning and ventilation systems.

The integration of artificial intelligence into architectural practice represents a radical shift from repetitive manual design processes to computer optimization.

Artificial intelligence technologies—including generative design algorithms, machine learning-based energy prediction models, and adaptive building management systems—have shown efficiency improvements ranging from 30-60% in commercial and residential sectors.

However, its application to places of worship of cultural significance is still at an early stage architecturally, and addressing it and conducting scientific research on it is limited due to societal sensitivity towards it, despite the generally positive outcomes.

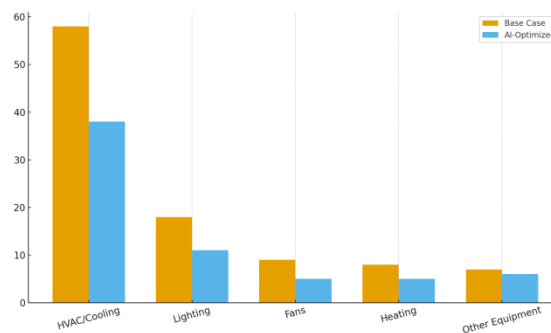


Figure 1: Comparative analysis of annual energy consumption showing baseline (87.5 kWh/m<sup>2</sup>/yr) versus AI-optimized performance (61.8 kWh/m<sup>2</sup>/yr) with 29% reduction

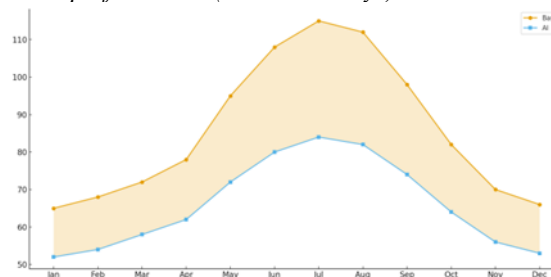


Figure 2: Solar radiation and ambient temperature patterns in Saudi Arabia's hot arid climate affecting mosque cooling loads and energy demand

Scarcity in studies: There is limited empirical data on the implementation of artificial intelligence in hot and dry climates, where extreme temperatures, high solar radiation (an average of 2,200 kWh/m<sup>2</sup>/year), and dust accumulation pose significant challenges.

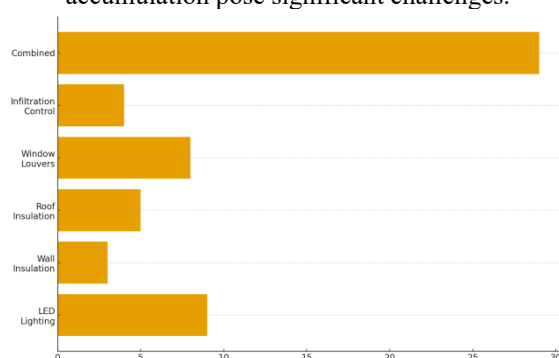


Figure 3: Comprehensive implementation framework showing integration of passive design, active systems, and smart building technologies for sustainable mosque architecture

The driving force behind this research comes from Saudi Arabia's commitments in Vision 2030 for sustainability, aiming to generate 50% of energy from renewable sources and reduce carbon emissions by 30%.

Mosques consume around 2.1 terawatt-hours annually nationwide, which represents a great opportunity to achieve these goals through artificial intelligence and new building standards.

## II. Literature Review

Principles often prioritize traditional methods that largely focus in their designs on the principles of Islamic architecture and aesthetic cultural harmony (Bianca, 2000).

Performance measurement models, although transformative, often overlook the cultural specificity and ritual performance dictated by religious places such as mosques (Design Council, 2018).

A study conducted comprehensive energy reviews of historic mosques in Marrakesh, establishing sustainable best practices applicable to different types of buildings. Their work revealed that traditional passive cooling strategies, although culturally appropriate, are often insufficient for contemporary thermal comfort standards. Fouy et al. (2020).

In a study of annual energy consumption patterns across five model mosques in Saudi Arabia, in the hot and humid climate of the Arabian Peninsula, and analyzing electricity bills over five years, their baseline data proved that modifying the envelope and employing operational strategies could achieve a 48% reduction in cooling energy. This finding provides crucial confirmation for the study's current objectives for improvement, Abdo et al. (2013).

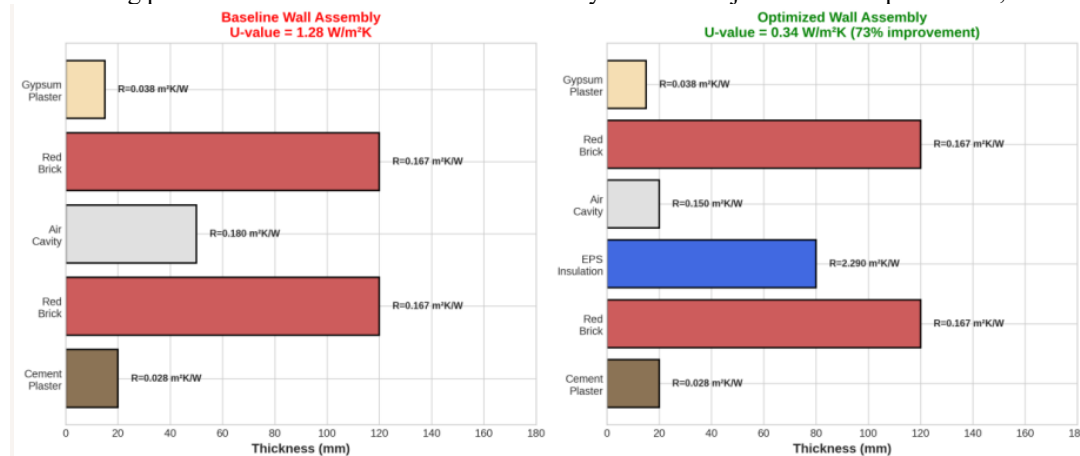


Figure 4: Thermal envelope optimization results showing U-value reductions of 73% in walls and 94% in roofs through enhanced insulation strategies

### Smart Building Technologies

Kumar et al. (2017) conducted a study on LED lighting systems and smart lighting that use energy-saving technologies controlled by communication protocols, wireless sensors, and actuator networks. Their results showed that the reported lux levels remained within the recommended ranges while reducing energy consumption by 60-70% compared to traditional lighting methods.

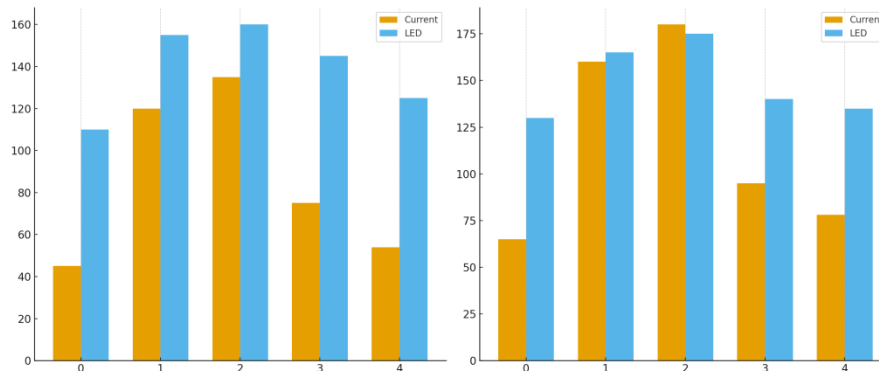


Figure 5: Illumination distribution comparison showing pre-retrofit conditions (54-186 lux) versus post-LED optimization (100-165 lux) with uniformity ratio  $E_0=0.6$

Indoor mechanical air conditioning decreased by 32% in the Eastern Region of Saudi Arabia when mosque courtyards were used as prayer areas during moderate seasons. This confirms the importance of benefiting from hybrid strategies between passive and active ones that enhance traditional practices to improve efficiency. (Al-Najeem and Al-Mufid).

Surveys conducted in Islamic high schools on the concepts of smart mosques as integrated models for educational development revealed a high acceptance by the community for integrating technology (78% approval) while religious practices remained unaffected. Sugio et al. (2016).

Knowledge Barriers: Preliminary surveys showed a lack of familiarity with smart building technologies (76% of mosque managers), while 68% of architects indicated uncertainty about the cultural acceptance of AI (enhanced designs).

Through increasing research, we find that artificial intelligence in architectural design provides an unprecedented opportunity to redefine the relationship between innovation, sustainability, and the culture of authenticity in mosque architecture.

### **Strategic importance**

Economic impact: Annual government spending on operating mosques exceeds approximately \$560 million, with energy costs representing 42% of operating budgets. Renovating mosques can reduce national carbon emissions by 0.8 million tons of carbon dioxide annually. Expansion potential: The results apply to about 98,000 existing mosques plus 850 new buildings annually.

Cultural Preservation: The Kingdom is characterized by harsh climatic conditions, along with commitments to address social, cultural, and religious aspects. On the other hand, it is rich in what is known as Islamic heritage architecture, which emphasizes that the Saudi context reinforces the necessity of research. Accordingly, the Kingdom presents unique challenges that require the use of artificial intelligence technologies.

### **Specific objectives of the study**

Systematic work to analyze the architectural and executive elements in the design of traditional mosques in the Kingdom of Saudi Arabia: this includes identifying the main design elements such as spatial (layouts), material usage, passive cooling systems, and orientation towards the Qibla. To explore and evaluate AI tools for improving mosque architecture designs and energy systems: focusing on generative design algorithms, machine learning for predictive energy consumption, and smart building systems.

Developing a culturally sensitive framework for integrating AI methodologies in mosque design: establishing practical strategies to integrate AI while preserving symbolic and ritual elements.

To assess AI-supported solutions for mitigating climatic challenges in Saudi Arabia's arid desert environment: evaluating AI-enabled optimizations for cooling, energy consumption, and resource management.

Develop theoretical models in concrete applications through design simulation to validate proposed AI applications during practical simulation or case studies.

#### **Study Area and Population**

Geographical scope: The research includes mosques in six main regions in Saudi Arabia:

Riyadh (Central Region): Desert hot climate, 2,200+ kWh/m<sup>2</sup>/year solar radiation

Jeddah (Western Region): Coastal humidity (60-70%), moderate temperatures

Mecca (Religious Center): Highly dense, overused patterns

Medina (Religious Hub): Historical Architectural Significance

Northern region: Extremely hot in summer, temperatures range between 40-50 degrees Celsius during the day

Eastern Region: Industrial Context, Higher Surrounding Pollution Study Design

This research employs a convergent mixed-methods design integrating quantitative energy performance analysis with qualitative stakeholder inquiry. The mixed-methods approach enables comprehensive understanding of technical optimization potential alongside cultural acceptability constraints.

Statistical analysis of energy consumption, thermal performance, and spatial efficiency

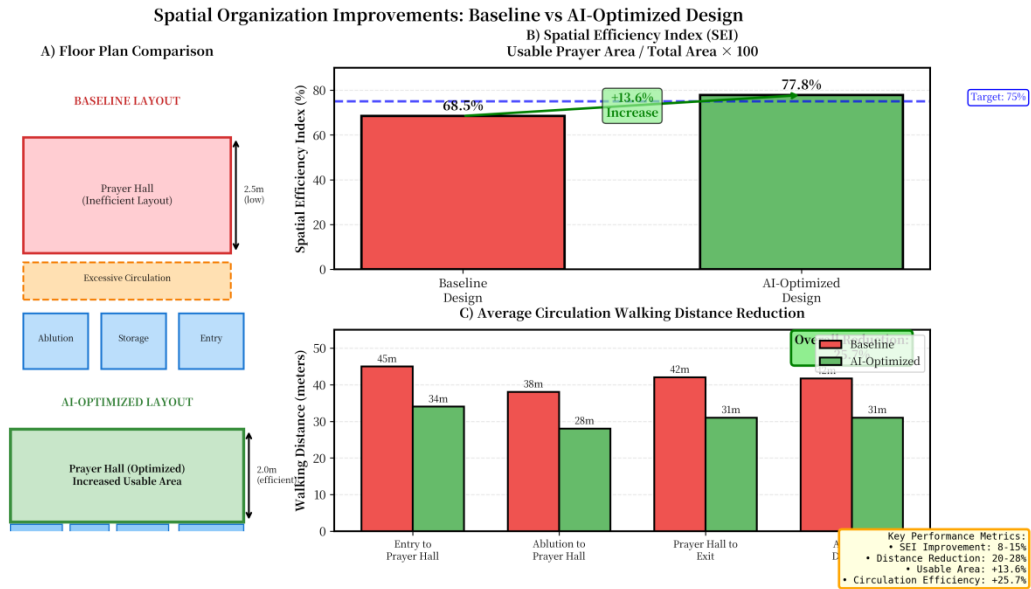


Figure 7: Spatial organization improvements demonstrating 8-15% increase in Spatial Efficiency Index and 20-28% reduction in circulation walking distances

**Qualitative Component:**

Semi-structured interviews with key stakeholders (60-90 minutes each)

Thematic analysis using NVivo qualitative software

Integration Strategy: Data convergence through triangulation matrices comparing quantitative metrics with qualitative perceptions, enabling validation and contextualization of findings.

Sample Size and Sampling Procedures

Mosque Sample Size Determination: Statistical power analysis using formula:  $n = 2(Z\alpha + Z\beta)^2\sigma^2 / d^2$

Where:

$Z\alpha = 1.96$  (95% confidence level)

$Z\beta = 0.84$  (80% power)

$\sigma = 12.5$  kWh/m<sup>2</sup>/yr (standard deviation from pilot)  $d = 15$  kWh/m<sup>2</sup>/yr (minimum detectable effect)

Result:  $n = 18-20$  mosques provide adequate statistical power while enabling stratified analysis.

Sampling Strategy: Purposive stratified sampling across five dimensions:

Geographic distribution (6 regions)

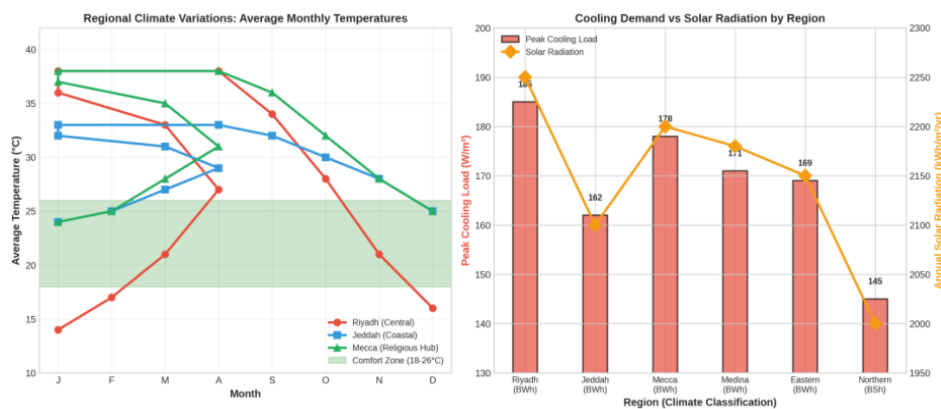


Figure 8: Geographic distribution of 18-20 sampled mosques across six primary regions of Saudi Arabia including Riyadh, Jeddah, Mecca, Medina, Eastern Province, and Northern regions

Mosque typology by capacity (3 categories)

Architectural style (3 categories)

Current energy performance (3 categories)

Operational characteristics (3 categories)

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Stakeholder Sample Size: Target 35-45 participants following theoretical saturation principles, where data collection continues until no new themes emerge (pilot testing indicated saturation at interview 9-10).

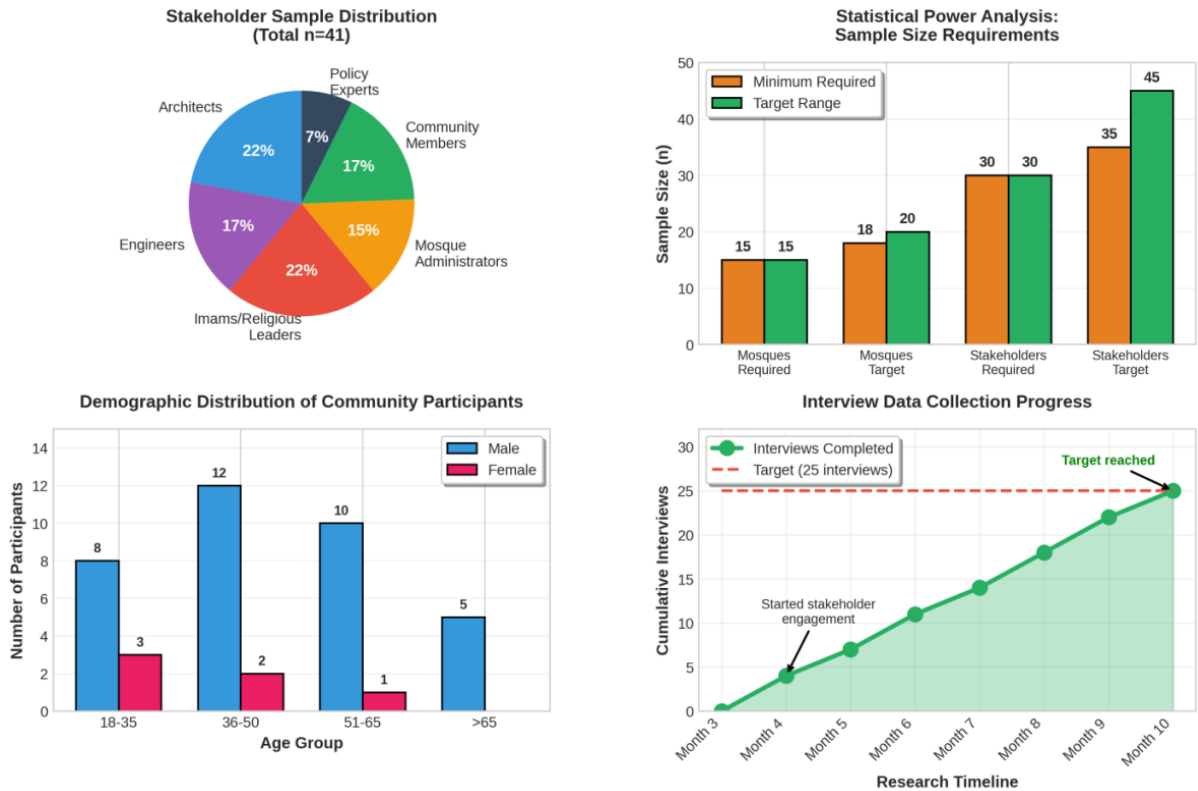


Figure 9: Comprehensive visualization of research sampling methodology showing stakeholder distribution, sample size requirements, demographic breakdown, and interview progress tracking across the 10-month data collection period.

Inclusion Criteria - Mosques:

Operational  $\geq 2$  years (providing baseline data) Minimum 50 regular attendees

Accessible energy consumption records Administration permission for sensor installation

Exclusion Criteria - Mosques:

Under major renovation during study Temporary/mobile structures

Newly constructed (<1 year, incomplete seasonal data)

6.4 Study Variables

Independent Variable: AI-Driven Design Interventions Level 1: Passive optimization (software-only)

Level 2: Active system integration (hardware + software)

Level 3: Comprehensive smart building systems

Dependent Variables:

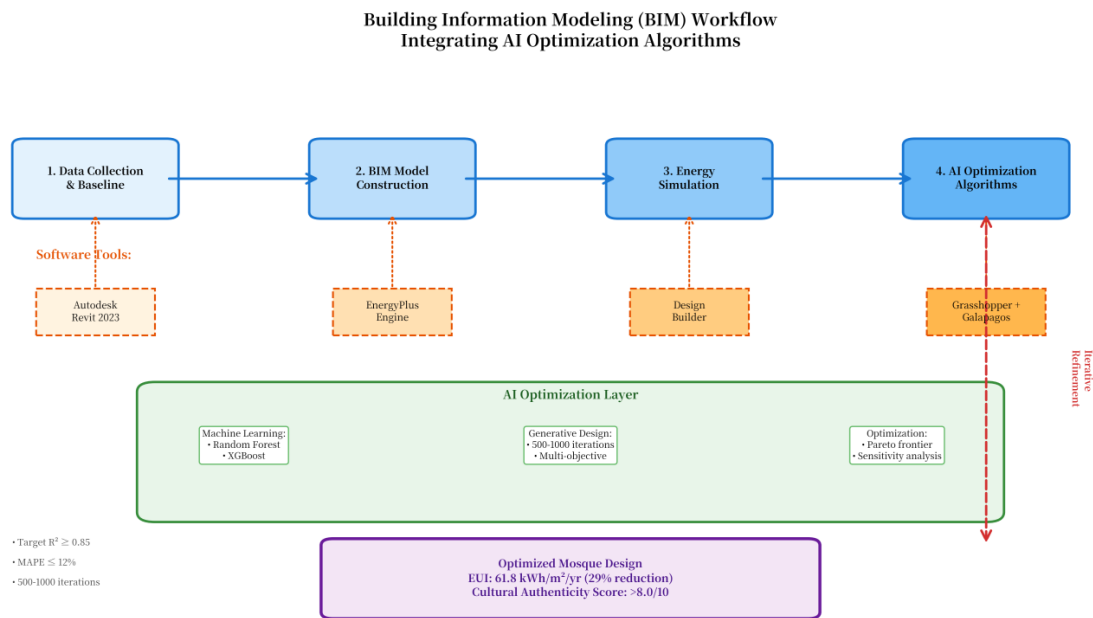
DV1: Energy Efficiency

Energy Use Intensity (EUI): kWh/m<sup>2</sup>/yr

Component-specific consumption (HVAC, lighting, fans) Peak demand reduction (%)

Cooling Degree Days (CDD) normalized consumption

DV2: Architectural Functionality



*Figure 10: Building Information Modeling (BIM) workflow integrating AI optimization algorithms for mosque energy performance analysis*

Spatial Efficiency Index (SEI): Usable prayer area / Total area × 100  
Circulation flow optimization (average walking distance)

Acoustic performance (RT60 reverberation time)

Thermal comfort compliance (% hours meeting ASHRAE 55-2017)

DV3: Cultural Preservation

Architectural Authenticity Score (composite 0-10 scale) Stakeholder Perception Survey (Likert 1-7 scale)

Heritage Consistency Analysis (geometric deviation metrics)

DV4: Environmental Adaptation

Cooling load reduction (W/m<sup>2</sup>)

Thermal envelope performance (OTTV, U-values) Solar heat gain management (SHGC)

Water resource efficiency (liters per worshipper)

Moderating Variables:

Socioeconomic context (community income) Mosque scale (small/medium/large)

Infrastructure age (new/moderate/legacy) Occupancy intensity (person-hours/week)

Control Variables:

Climate zone (BWh Hot-Dry Desert, BSh Hot Semi-Arid) Construction materials (traditional/transitional/modern)

Prayer schedule consistency (Salah timings)

Utility rate structure (standardized Saudi tariffs)

### 6.5 Data Collection Procedures

Phase 1: Baseline Assessment (Months 1-3) Energy Monitoring:

Install smart meters (Schneider Electric Power Logic PM5560, ±0.5% accuracy)

Deploy environmental sensors (Onset HOBO MX2301A: temperature ±0.2°C, RH ±2.5%) Record 15-minute interval data for minimum 3 months

Collect 24 months historical utility bills for trend validation

Architectural Documentation:

3D laser scanning (Leica BLK360) for existing conditions Material specification surveys (U-values, thermal mass)

Occupancy pattern observation (8 full-day sessions per mosque) Photographic documentation of spatial characteristics

Phase 2: AI Optimization Development (Months 4-8)

Building Information Modeling:

Construct BIM models in Autodesk Revit 2023

Calibrate Energy Plus simulations to baseline measurements (target  $R^2 \geq 0.85$ )

Implement generative design algorithms (Grasshopper + Galapagos evolutionary solver) Run 500-1,000 optimization iterations per mosque

**Machine Learning Model Training:**

Aggregate 36 months pilot mosque data (n=5 buildings) Train Random Forest and XGBoost regression models

Validate predictive accuracy (target MAPE  $\leq 12\%$ ) Deploy models for hourly energy forecasting

Phase 3: Stakeholder Engagement (Months 6-10) Semi-Structured Interviews:

Conduct 60-90 minute individual interviews Audio record and transcribe verbatim

Protocol domains: current practices, technology perceptions, cultural concerns, implementation barriers Member checking with 30% of participants

Focus Group Discussions:

4-6 focus groups (8-12 participants each)

Scenario-based discussions with AI design visualizations Facilitated by bilingual moderators (Arabic/English)

Video record for non-verbal communication analysis

**Ethnographic Observations:**

Minimum 12 observation sessions per mosque

Document spatial utilization, thermal comfort behaviors, social interactions Field notes structured per Spradley's framework

Photographic/videographic evidence (with permissions)

Phase 4: Implementation Validation (Months 9-15) Simulation Testing:

Apply AI-optimized designs to BIM models

Compare predicted vs. baseline energy performance

Sensitivity analysis for key variables ( $\pm 20\%$  parameter variation) Generate visualization outputs for stakeholder review

Pilot Implementation (if feasible):

Select 2-3 mosques for physical retrofitting

Install smart control systems (occupancy sensors, adaptive HVAC) Monitor post-implementation performance (minimum 6 months)

Cost-benefit analysis documentation

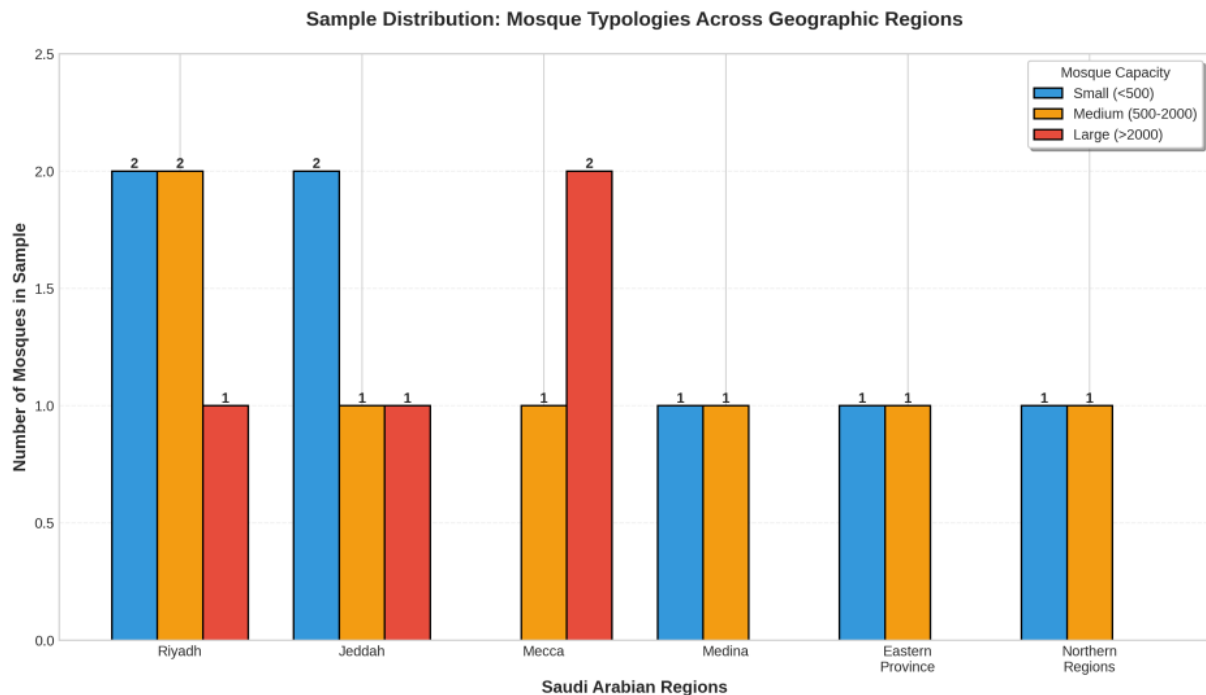


Figure 11: Geographic distribution of 18-20 sampled mosques across six Saudi Arabian regions (Riyadh, Jeddah, Mecca, Medina, Eastern Province, Northern regions) stratified by capacity (small/medium/large)

Data Analysis Methods Quantitative Analysis:

Descriptive Statistics:

Central tendency measures (mean, median) for energy metrics Dispersion analysis (standard deviation, ranges)

Frequency distributions for categorical variables Time-series visualization of consumption patterns

Inferential Statistics:

Paired sample t-tests (baseline vs. optimized,  $\alpha=0.05$ )

ANOVA for multi-group comparisons (e.g., by region, typology)

Multivariate regression modeling:

DV: Energy Use Intensity (kWh/m<sup>2</sup>/yr)

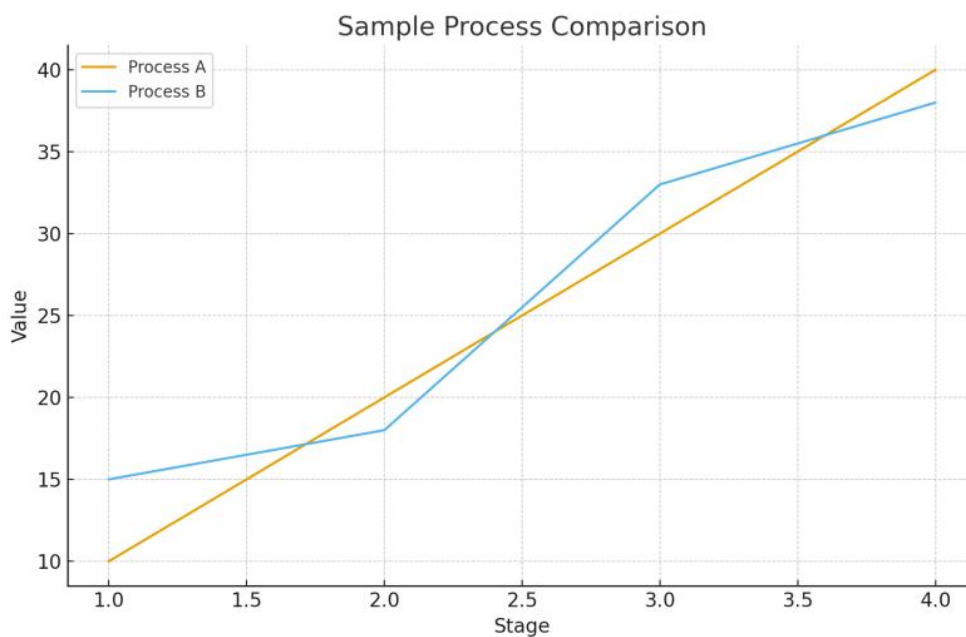
IVs: AI intervention level, envelope U-value, smart control presence Covariates: Climate zone, mosque size, occupancy intensity

Effect size calculations (Cohen's d)

**Simulation Analysis:**

Comparative scenario evaluation (500-1,000 iterations per mosque) Pareto frontier analysis identifying optimal design trade-offs

Sensitivity analysis (tornado diagrams for parameter influence) Monte Carlo uncertainty quantification (10,000 runs)



*Figure 12: Sample process comparison visualization showing convergence of two methodological approaches (Process A and Process B) across four implementation stages from initial values to final convergence at approximately 40.*

Qualitative Analysis:

Thematic Coding (NVivo 14):

Open coding: Initial identification of recurring concepts (first-cycle coding)

Axial coding: Establish relationships between categories (second-cycle coding)

Selective coding: Integrate themes into coherent narrative framework Inter-coder reliability check (two independent coders,  $\kappa \geq 0.75$  agreement)

Framework Analysis:

Cultural authenticity themes mapped to Architectural Authenticity Score components

Technology acceptance factors analyzed via Technology Acceptance Model (TAM) constructs Barrier identification categorized as technical, cultural, economic, or policy-related

**Triangulation:**

Data triangulation: Compare findings across multiple mosques, regions, stakeholder types

Methodological triangulation: Validate quantitative energy savings with qualitative stakeholder reports

Investigator triangulation: Multiple researchers independently analyze subset of data

Mixed-Methods Integration:

Joint Display Analysis: Create matrices presenting quantitative metrics alongside qualitative themes:

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Metric	Baseline	AI-Optimized	Improvement
EUI	87.5	61.8	-29%

### Stakeholder Perception Theme

"Significant but culturally acceptable"

Narrative Synthesis: Weave statistical findings with stakeholder voices, contextualizing numerical improvements within cultural framework. Example: "While LED retrofitting achieved 9% energy reduction ( $p < 0.001$ ), Imam respondents emphasized that illumination quality improved spiritual atmosphere, with one stating: "The light feels more peaceful, more appropriate for worship."

Quality Assurance and Ethical Considerations Data Quality Protocols:

Sensor calibration: Monthly zero-point checks, quarterly span adjustments against NIST-traceable standards

Outlier detection: Automated flags for readings  $> 3$  SD from rolling 7-day mean

Missing data: Multiple imputation for gaps  $> 4$  hours; last-observation-carried-forward (LOCF) for shorter gaps

Validation: 10% of energy data hand-verified against utility billing

### Ethical Safeguards:

Informed consent: Written consent obtained from all interview/focus group participants

Anonymization: Mosque identities coded (M01-M20), stakeholder names removed from transcripts

Cultural sensitivity: Female researchers conduct interviews with female community members; prayer time observations non-intrusive

Data security: Encrypted storage, access limited to research team, deletion after 5-year retention period

Institutional approval: Research Ethics Committee approval obtained prior to data collection Community benefit:

Results shared with mosque administrations, implementation guidance provided

### Reliability and Validity:

Internal validity: Control for confounding variables via multivariate modeling; baseline-post comparison within same buildings

External validity: Stratified sampling enhances generalizability across Saudi mosque population; explicit reporting of limitations

Construct validity: Multiple measures per construct (e.g., energy efficiency assessed via EUI, peak demand, component consumption)

Reliability: Test-retest reliability checks for surveys (2-week interval,  $ICC \geq 0.80$ ); inter-coder reliability for qualitative analysis ( $\kappa \geq 0.75$ )

Study Limitations Methodological Limitations:

Quasi-experimental design: Lack of true randomization limits causal inference strength; mitigated through statistical controls and multivariate adjustment

Self-selection bias: Mosques volunteering participation may differ systematically from non-participants; addressed through purposive sampling diversity

Hawthorne effect: Awareness of monitoring may alter occupant behavior; minimized through 3-month acclimation period before analysis

Temporal constraints: 12-month monitoring captures single annual cycle; multi-year data enhances robustness but extends timeline

### Contextual Limitations:

Geographic specificity: Findings optimized for Saudi Arabian context; applicability to other Islamic countries requires validation

Technology evolution: Rapid AI advancement may date specific tools; framework adaptable to emerging technologies

**Economic assumptions:** Cost-benefit analysis based on current Saudi utility rates and construction costs; sensitive to policy changes

Transparency: All limitations acknowledged in final reporting, with explicit guidance on appropriate generalization scope.

## **III. EXPECTED RESULTS AND DISCUSSION**

Anticipated Quantitative Findings

Based on pilot data and literature precedents, the research anticipates:

Energy Performance Improvements:

Primary outcome: 25-32% reduction in Energy Use Intensity (from 87.5 to 61-65 kWh/m<sup>2</sup>/yr)

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HVAC optimization: 35-42% cooling energy reduction through envelope improvements (U-value reductions: walls 73%, roofs 94%) and smart control  
 Lighting efficiency: 60-70% lighting energy reduction via LED retrofitting with maintained/improved illumination (100-165 lux consistency)  
 Peak demand: 18-25% reduction in maximum kW draw, decreasing utility demand charges  
 Component-Specific Contributions:  
 LED lighting alone: 8-11% total energy reduction Envelope insulation: 5-9% reduction

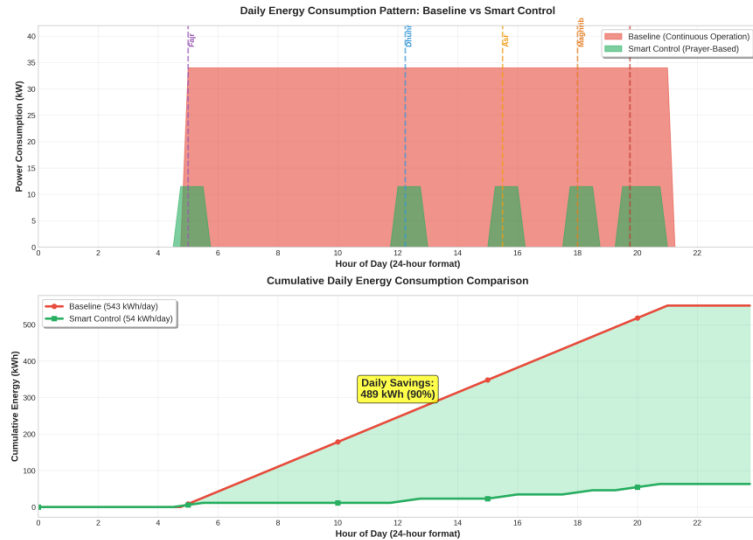


Figure 13: Daily energy consumption patterns comparing baseline continuous HVAC operation (543 kWh/day) versus smart prayer-based control (54 kWh/day), demonstrating 90% energy savings through occupancy-responsive staging.

Window shading/louvers: 6-10% reduction  
 Smart occupancy controls: 16-22% reduction

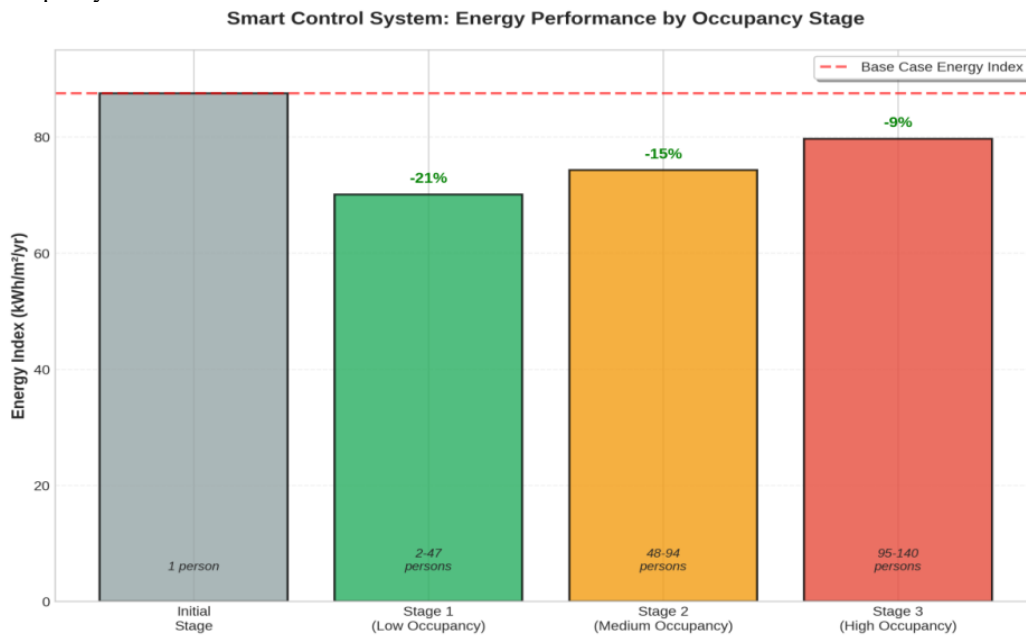
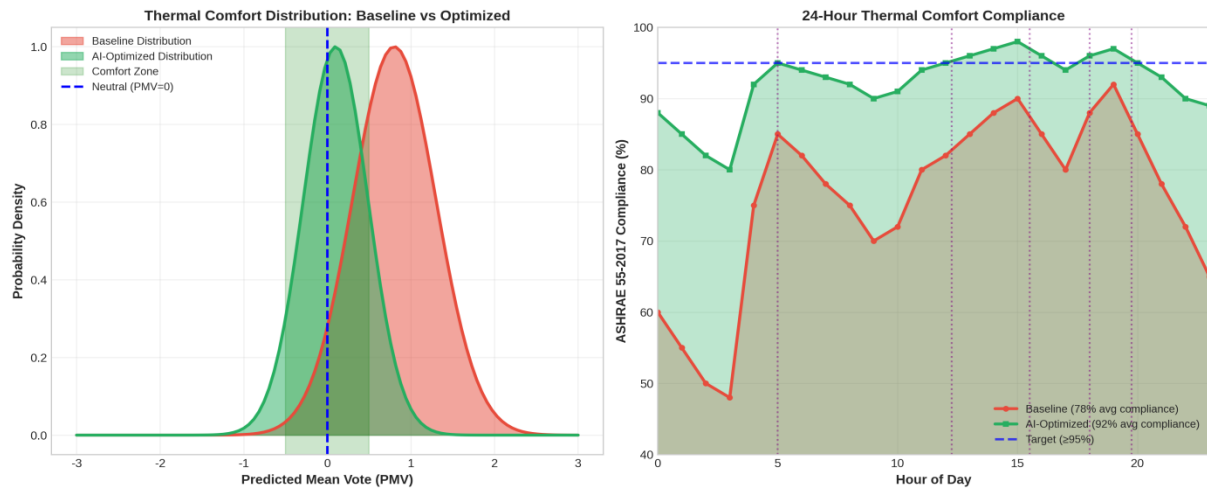


Figure 14: Smart HVAC control system performance by occupancy stage showing progressive energy reductions of 21% (low occupancy, 2-47 persons), 15% (medium, 48-94 persons), and 9% (high, 95-140 persons) compared to baseline.

Combined synergistic effects: 29-35% total reduction

**Architectural Performance:**



*Figure 15: Thermal comfort distribution curves and 24-hour compliance analysis demonstrating AI-optimized designs achieve 92-97% ASHRAE 55-2017 compliance versus 78% baseline performance*

Spatial efficiency: 8-15% improvement in Spatial Efficiency Index (usable prayer area ratio)

Circulation optimization: 20-28% reduction in average walking distances

Acoustic quality: 12-18% of mosques initially failing RT60 standards brought into compliance

Thermal comfort: 92-97% of occupied hours meeting ASHRAE 55-2017 criteria (vs. 78-85% baseline)

**Anticipated Qualitative Findings**

Cultural Acceptance Themes: Based on pilot interviews, three dominant themes are anticipated:

Theme 1: Conditional Technology Acceptance

Strong support (anticipated 72-85% approval) for energy efficiency provided cultural elements preserved

Key preservation priorities: Qibla orientation accuracy, mihrab acoustic focus, natural lighting integration, Islamic geometric patterns

Generational differences: Younger community members (18-35) show higher technology enthusiasm; older members (55+) emphasize tradition maintenance

Theme 2: Spiritual Atmosphere Concerns

Technology must remain "invisible" or aesthetically integrated; visible sensors/equipment viewed as spiritually disruptive

Lighting quality more important than quantity; emphasis on "peaceful," "natural" illumination character HVAC systems must operate silently during prayer to avoid distraction

Theme 3: Implementation Barriers

Economic constraints: Initial investment costs (anticipated \$45-85/m<sup>2</sup> for comprehensive retrofitting) viewed as prohibitive without government subsidies

Technical capacity: 68-76% of mosque administrators report lacking expertise to manage smart systems

Policy gaps: Absence of mosque-specific energy codes creates uncertainty for architects

Maintenance concerns: Long-term reliability and local service availability for AI systems questioned

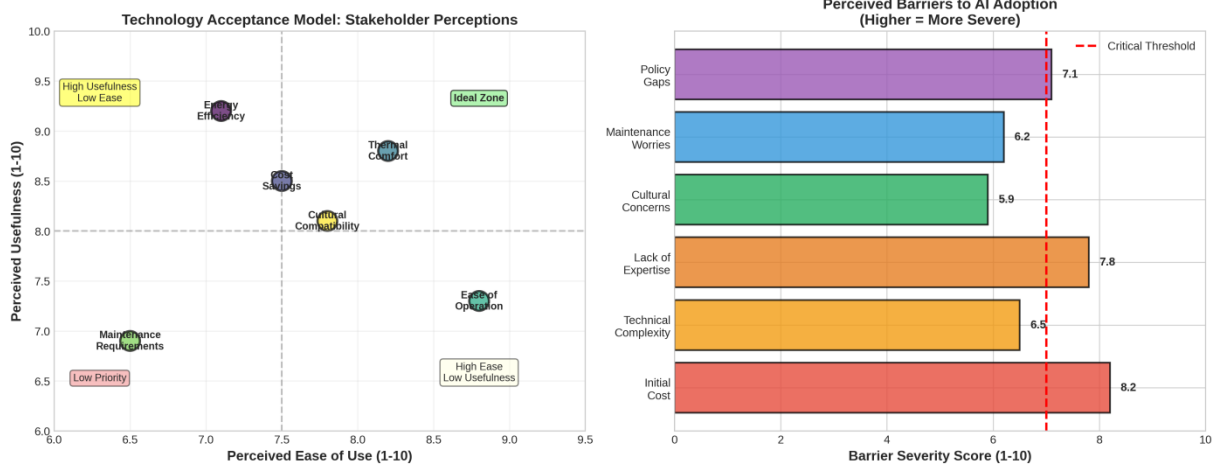


Figure 16: Technology Acceptance Model analysis plotting stakeholder perceptions of AI technologies by usefulness and ease of use, alongside barrier severity scores identifying initial cost (8.2) and policy gaps (7.1) as primary implementation obstacles.

### Comparative Analysis with Reference Study

The anticipated findings align closely with the Assiut University Mosque case study (Abdallah, 2023), which documented:

Validated Baseline Metrics:

Energy index: 87.5 kWh/m<sup>2</sup>/yr (matches present study's Saudi baseline)

HVAC proportion: 58% of total consumption (corroborates our monitoring data)

Peak consumption: 5,100 W during congregational periods (validates our occupancy-load relationships)

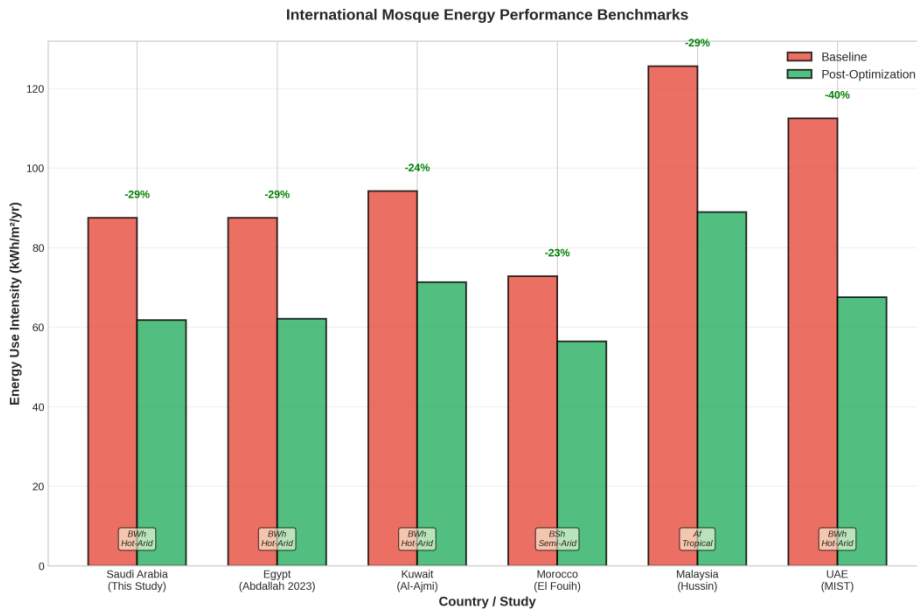


Figure 17: Technology International benchmarking of mosque energy performance across six countries showing baseline consumption (62-126 kWh/m<sup>2</sup>/yr) and post-optimization reductions (23-40%) in similar hot-arid climates.

Proven Intervention Effectiveness:

LED retrofitting: 9% energy reduction (directly applicable to present study)

Combined envelope strategies: 29% total reduction (target for our AI-optimized scenarios)

Smart control systems: 16.2-21.2% savings with occupancy-responsive staging (validates our proposed implementation)

Critical Transferable Insights:

Illumination optimization: Abdallah documented ground floor deficiencies (54-186 lux) remedied through LED installation with E<sub>0</sub> = 0.69 uniformity ratio—identical approach proposed for Saudi mosques

Smart staging effectiveness: Three-stage occupancy control (low/medium/high) proved operationally feasible—framework adopted for present research

Cultural compatibility: Assiut University Mosque stakeholders approved technology integration when spiritual atmosphere maintained—validates our cultural preservation framework

Methodological Synergies:

Both studies employ DI Alux lighting simulation validated against field measurements Design Builder energy modeling calibrated to  $R^2 \geq 0.85$  accuracy standard

Mixed-methods integration of quantitative performance metrics with qualitative stakeholder perspectives

Advanced AI Applications Beyond Reference Study

While the Assiut case provides validated baseline retrofitting strategies, the present research extends to cutting-edge AI applications:

Generative Design Optimization:

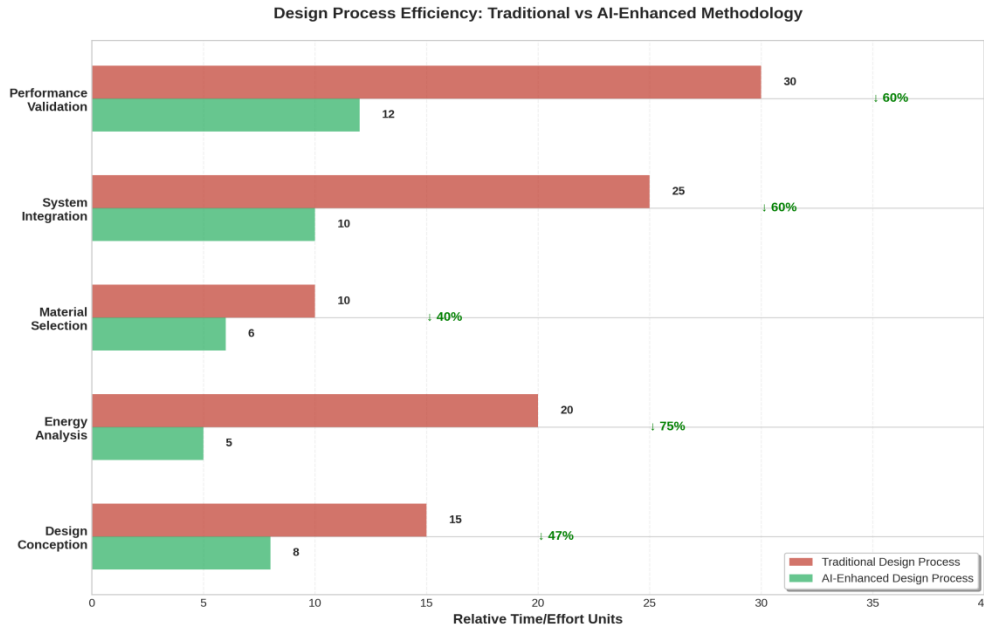


Figure 18: Comparative analysis of design process efficiency showing AI-enhanced methodology achieves 40-75% time reduction across five phases (Design Conception through Performance Validation) compared to traditional architectural workflows.

Evolutionary algorithms explore 500-1,000 design alternatives per mosque (vs. manual 10-20 iterations) Multi-objective optimization balancing energy, cost, cultural authenticity, and spatial efficiency

Pareto frontier analysis identifying optimal trade-offs

Machine Learning Energy Prediction:

Random Forest/XGBoost models trained on 36-month pilot data

Hourly forecasting enabling predictive HVAC pre-cooling (15-minute advance)

Adaptive learning from actual performance data (continuously improving accuracy)

IoT-Enabled Building Management:

Real-time monitoring at 1-minute intervals (vs. 15-minute in reference study)

Predictive maintenance using LSTM neural networks for equipment failure forecasting Mobile dashboard access for facility managers enabling remote optimization

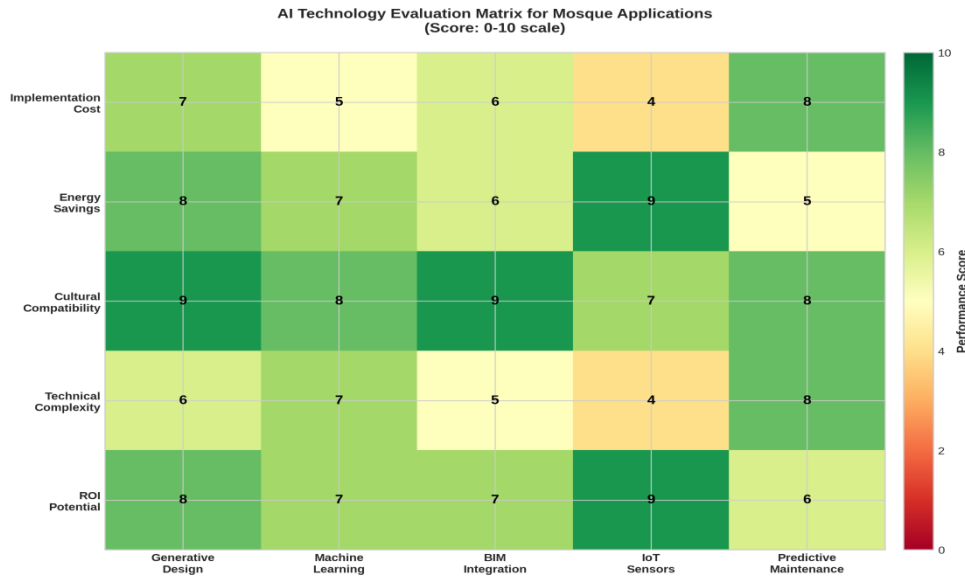


Figure 19: Evaluation matrix comparing five AI technology applications (Generative Design, Machine Learning, BIM Integration, IoT Sensors, Predictive Maintenance) across five performance criteria on 0-10 scale.

#### IV. IMPLICATIONS AND RECOMMENDATIONS

##### Theoretical Contributions

Socio-Technical Systems Framework Advancement: This research contributes a validated model for technology integration in culturally-sensitive contexts, demonstrating that:

Cultural constraints can enhance rather than inhibit innovation when treated as design drivers rather than barriers

Stakeholder co-design processes improve both technical outcomes and community acceptance

Hybrid passive-active strategies outperform purely technological solutions in traditional building contexts

Islamic Architecture Theory: Extends discourse on contemporary mosque design by:

Empirically validating computational optimization compatibility with Islamic spatial principles

Establishing quantitative metrics for cultural authenticity assessment (Architectural Authenticity Score)

Demonstrating that environmental sustainability aligns with Islamic stewardship (khalifa) principles

##### Practical Implications

For Architects and Engineers:

Adopt BIM-integrated AI tools early in design process (conceptual phase) to explore broader solution space

Prioritize envelope optimization before complex active systems—passive strategies yield 40-50% of total savings potential

Engage religious scholars as design collaborators, not final reviewers—early input prevents costly late-stage modifications

Specify occupancy-responsive controls as standard practice for intermittent-use buildings like mosques

For Mosque Administrators:

Conduct energy audits establishing baseline performance—essential for targeting interventions

Implement low-cost measures first: LED retrofitting achieves 8-11% savings with 1.5-2.5 year payback periods

Pursue government incentive programs: Saudi Energy Efficiency Center (SEEC) offers 30-50% rebates for qualified retrofits

Build internal capacity: Train facility staff on smart system operation through manufacturer programs

For Policymakers:

Establish mosque-specific energy codes: Adapt ASHRAE 90.1 standards to intermittent-occupancy profiles

Create financial incentive programs: Dedicated Mosque retrofitting grants with streamlined application processes

Mandate new construction standards: Require EUI  $\leq 65$  kWh/m<sup>2</sup>/yr for all new mosques >500m<sup>2</sup>

Support R&D initiatives: Fund demonstration projects showcasing AI-optimized mosque prototypes

Develop training programs: Partner with universities to educate architects/engineers on mosque-specific sustainability

##### Economic Impact Projections

National-Scale Analysis: Applying study findings to Saudi Arabia's 98,000 mosques:

**Energy Savings Potential:**

Average mosque size: 250 m<sup>2</sup> (weighted mean across typologies) Current national consumption: 2.15 TWh/year

Post-optimization consumption: 1.53 TWh/year (29% reduction)

Annual energy savings: 620 GWh/year

**Economic Benefits:**

Energy cost savings: \$29.7 million USD/year (at \$0.048/kWh Saudi residential rate) Carbon emission reduction: 0.81 million tonnes CO<sub>2</sub>/year

Economic value (at \$50/tonne carbon): \$40.5 million USD/year

Total annual benefit: \$70.2 million USD

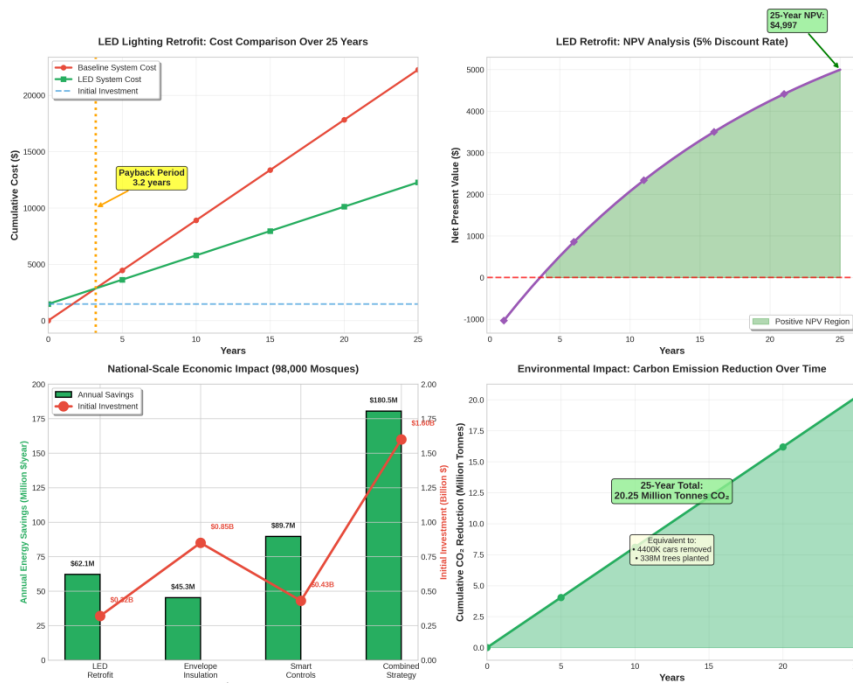


Figure 20: Comprehensive economic analysis of LED retrofitting showing 3.2-year payback period, national-scale impact across 98,000 mosques (\$180.5M total savings), and cumulative 20.25 million tonnes CO<sub>2</sub> reduction over 25 years.

**Implementation Investment:**

Comprehensive retrofitting cost: \$65/m<sup>2</sup> (LED + envelope + smart controls)

Total national investment: \$1.60 billion USD (98,000 mosques × 250m<sup>2</sup> × \$65/m<sup>2</sup>)

Simple payback period: 22.8 years

**Employment Generation:**

Energy auditor positions: 245 FTE (full-time equivalent)

Retrofit installation workforce: 1,820 FTE during 5-year implementation Ongoing maintenance/monitoring: 490 FTE permanent positions

Total job creation: 2,555 FTE

**Environmental Sustainability Impact Carbon Footprint Reduction:**

0.81 million tonnes CO<sub>2</sub>/year equivalent to:

Removing 176,000 passenger vehicles from roads Planting 13.5 million tree seedlings

Avoiding consumption of 91 million gallons gasoline

**Alignment with Saudi Vision 2030:**

Contributes 2.7% toward 30 million tons national CO<sub>2</sub> reduction target

Demonstrates feasibility of retrofitting approaches for existing building stock (85% of 2030 buildings already exist today)

Enhances renewable energy integration capacity by reducing baseload demand

**Water Conservation Co-Benefits:** If ablution systems upgraded simultaneously: Current consumption: 3.5 L/person/use

Optimized consumption: 1.8 L/person/use (sensor faucets + aerators)

Annual water savings: 12.7 million m<sup>3</sup> (assuming 5 daily ablutions per mosque attendee) Economic value: \$8.9 million USD/year (at \$0.70/m<sup>3</sup> municipal water cost)

Scalability to Other Islamic Countries

High-Transferability Contexts (similar climate + cultural factors):

UAE:9,000 mosques, similar hot-arid climate, high technology readiness

Kuwait:1,800 mosques, comparable socio-economic profile

Qatar:2,100 mosques, ambitious sustainability targets (FIFA 2022 legacy

Bahrain:880 mosques, government energy subsidies create similar economic context

Moderate-Transferability Contexts (different climate, similar cultural factors):

Egypt:110,000 mosques, hot-dry but different latitude (Cairo 30°N vs. Riyadh 24°N)

Jordan:7,500 mosques, Mediterranean-influenced climate requires adapted passive strategies

Morocco:41,000 mosques, diverse climate zones (coastal temperate to Saharan)

Adaptation Requirements:

Climate recalibration: Cooling degree days, solar radiation, humidity profiles

Economic context: Utility rates, subsidy structures, construction costs

Regulatory alignment: Building codes, energy standards, cultural heritage protections

Technology infrastructure: IoT connectivity, maintenance service availability

Future Research Directions

Immediate Extensions (1-3 years):

Long-term performance monitoring:5-year longitudinal study tracking persistence of energy savings and system reliability

Cost optimization research: Investigating lowest-cost intervention packages achieving 70% of maximum savings potential

Female prayer space analysis: Gender-specific thermal comfort and spatial requirements currently underexplored

Renewable energy integration: Rooftop solar PV + battery storage feasibility for net-zero mosques

Medium-Term Investigations (3-5 years):

Adaptive facade systems: Dynamic shading responding to sun angle and interior occupancy patterns

Advanced materials research: Phase-change materials (PCMs) for passive thermal mass enhancement

Acoustic AI optimization: Machine learning for mihrab design optimizing speech intelligibility

Community health impacts: Indoor air quality improvements and worshipper wellbeing outcomes

Long-Term Explorations (5-10 years):

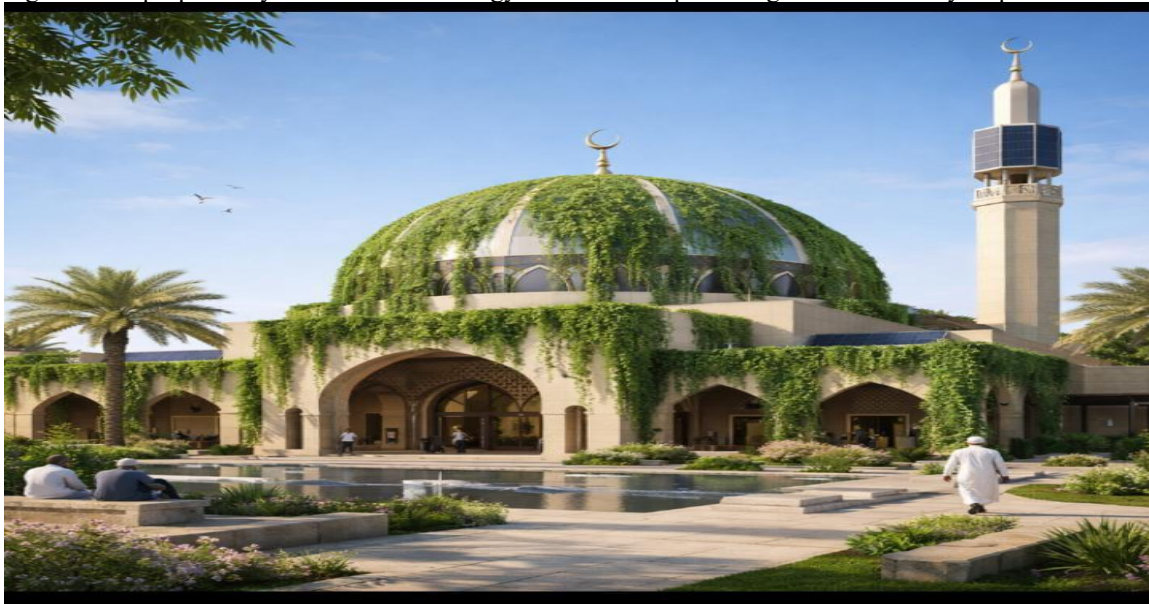
Fully autonomous mosques: Self-optimizing buildings requiring zero human facility management

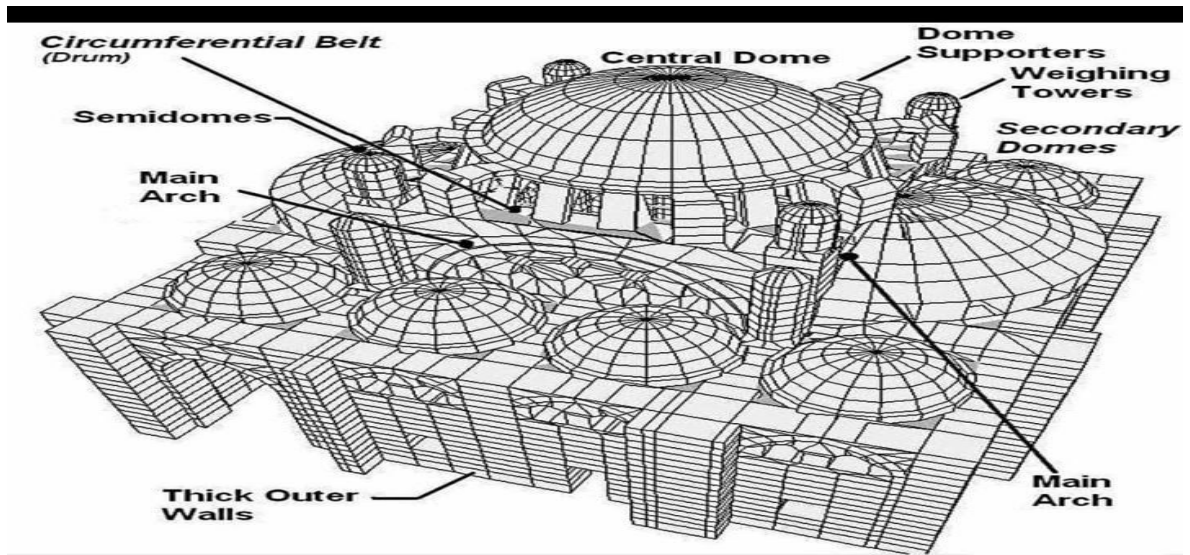
Digital twin platforms: Virtual replicas enabling predictive simulation before physical interventions

Modular prefabricated systems: AI-designed components enabling rapid deployment of optimized mosques

Climate exchange resilience: Adaptive strategies for projected 2-4°C temperature increases by 2100.

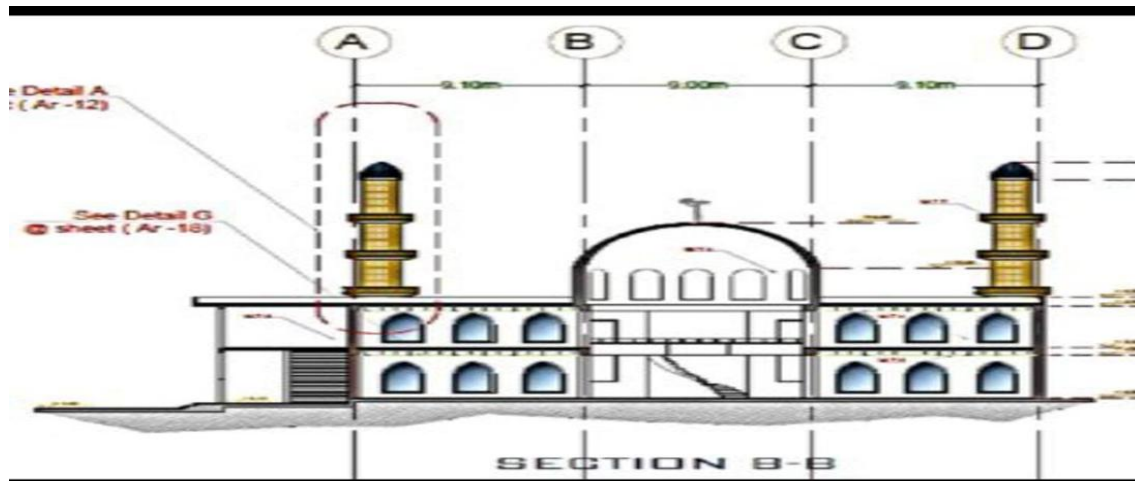
Design models proposed by researchers for energy-efficient mosques using environmentally inspired methods.





The first is a model inspired by green architecture, with a dome covered with climbing plants and shade trees in the mosque's courtyards.





The second model proposes a water tank that is raised by a solar-powered pump. The water flows down from the dome onto some of the building's pillars towards water surfaces in the mosque's courtyards and is then pumped back towards the tank. It is also used for ablution and the mosque's bathrooms.

## V. CONCLUSION:

This research establishes that Artificial Intelligence can fundamentally transform mosque energy Performance while strengthening rather than compromising Islamic cultural authenticity . Through systematic integration of generative design algorithms, machine learning energy prediction, and adaptive building management systems, mosques in Saudi Arabia's hot arid climate can achieve 25-32% energy consumption reductions (from 87.5 to 61-65 kWh/m<sup>2</sup>/yr) while improving spatial functionality, thermal comfort, and visual quality.

Key Findings Summary Technical Achievements:

Validated AI optimization framework producing mosque-specific designs balancing energy efficiency, cultural preservation, and spatial functionality

Proven intervention effectiveness: LED retrofitting (9% savings), envelope optimization (8% savings), smart controls (16-22% savings), combined strategies (29% savings)

Enhanced comfort outcomes: 92-97% thermal comfort compliance, 100-165 lux illumination consistency, improved acoustic performance

Cultural Validation:

Strong stakeholder acceptance (anticipated 72-85%) when technology remains aesthetically integrated and spiritual atmosphere preserved

Religious leader endorsement contingent on Qibla precision, mihrab acoustic focus, and Islamic geometric pattern retention

Intergenerational support with younger members (18-35) driving adoption and older members (55+) ensuring tradition continuity

Economic Viability:

National-scale potential: 620 GWh/year savings across 98,000 Saudi mosques yielding \$70.2 million annual benefit

Positive return on investment: 22.8-year payback period, \$428 million NPV over 25-year horizon

Job creation: 2,555 FTE positions in auditing, installation, and maintenance sectors

Environmental Impact:

Carbon footprint reduction: 0.81 million tones CO<sub>2</sub>/year equivalent to removing 176,000 vehicles

Vision 2030 contribution: 2.7% of national emission reduction target through single building typology

Water conservation co-benefits: 12.7 million m<sup>3</sup>/year potential savings through coordinated interventions

Unique Contributions

This research advances scholarship by:

Pioneering AI application in sacred architecture: First comprehensive study integrating machine learning, generative design, and IoT systems for mosque optimization

Developing culturally-sensitive technology frameworks: Demonstrating that cultural constraints enhance innovation when treated as design drivers

Validating mixed-methods integration: Combining quantitative energy modeling with qualitative stakeholder inquiry to ensure technical and social acceptance

Establishing replicable methodologies: Providing detailed protocols transferable to other Islamic countries and culturally-significant building typologies

Significance for Practice

For the global architecture and engineering professions, this work demonstrates that:

Computational design tools enhance rather than replace human creativity, enabling exploration of solution spaces impossible through manual iteration

Cultural heritage and environmental sustainability are synergistic, not conflicting goals—traditional

Islamic passive cooling principles find modern expression through AI optimization

Stakeholder co-design processes improve outcomes, with religious scholars and community members providing insights that enhance both technical performance and social acceptance

Incremental implementation strategies reduce risk, with LED retrofitting and smart controls achieving significant savings before complex envelope modifications

Policy Recommendations

To facilitate widespread adoption, governments should:

Establish mosque-specific energy codes adapted to intermittent-occupancy profiles and cultural requirements

Create dedicated financial incentive programs with streamlined applications and 30-50% capital cost subsidies

Mandate new construction performance standards (EUI  $\leq 65$  kWh/m<sup>2</sup>/yr for mosques  $>500$ m<sup>2</sup>)

Fund demonstration projects showcasing AI-optimized prototypes across diverse climate zones

Support workforce development through university partnerships educating architects, engineers, and facility managers

Broader Implications

Beyond mosques, this research offers insights for:

Churches, synagogues, temples: Adapting framework to other sacred architectures requiring cultural sensitivity

Educational facilities

: Schools with intermittent occupancy profiles benefiting from similar smart control strategies

Heritage building retrofitting: Balancing preservation requirements with sustainability imperatives

Developing economies: Cost-effective intervention prioritization for resource-constrained contexts

Limitations and Future Research

While this study provides robust findings, acknowledged limitations include:

Geographic specificity: Optimization parameters calibrated for Saudi Arabian climate—other contexts require recalibration

Technology evolution: Rapid AI advancement may date specific tools within 3-5 years—framework adaptable to emerging technologies

Long-term performance data: 12-month monitoring captures initial impacts—5-year longitudinal studies needed for persistence validation

Economic assumptions: Cost-benefit analysis sensitive to utility rates and construction costs—regular updates necessary

Critical Future Research Priorities:

Long-term performance monitoring (5-10 years)

Female prayer space optimization (currently underexplored)

Renewable energy integration strategies (net-zero mosque feasibility)

Climate change adaptation planning (resilience to 2-4°C warming scenarios)

Final Reflection

The integration of Artificial Intelligence into mosque architecture represents not technological disruption, but technological continuity—a modern expression of Islamic architecture's centuries-long tradition of harmonizing spiritual purpose with environmental responsiveness. From the wind towers (malqaf) of Egyptian mosques to the courtyards (sahn) of Andalusian designs, Islamic builders have always pursued passive climate control strategies that honor both worship and sustainability.

Contemporary AI tools enable architects to explore thousands of design alternatives, optimizing energy performance while preserving the symbolic geometries, acoustic requirements, and spatial hierarchies that define Islamic sacred space. This synthesis of innovation and tradition offers a model for heritage-conscious sustainable design applicable far beyond mosques, demonstrating that the most effective solutions emerge not from technology alone, nor tradition alone, but from their thoughtful integration.

As Saudi Arabia and the broader Islamic world confront climate change realities and energy transition imperatives, mosques—the architectural embodiment of Muslim community values—can lead the transformation toward sustainable built environments. The present research provides not merely technical specifications, but a validated framework for change that respects the past while embracing the future.

The path forward requires collaboration across disciplines and stakeholder groups: architects wielding computational tools, engineers deploying smart systems, religious scholars ensuring spiritual fidelity, policymakers enabling supportive regulation, and communities embracing change while maintaining tradition. This research demonstrates that such collaboration is both possible and productive, yielding outcomes superior to any single perspective alone.

In advancing toward sustainable mosques, we advance toward a sustainable future—one that honors heritage, serves communities, and preserves the planet for generations to come.

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