



## CLIMATE CHANGE ADAPTATION STRATEGIES IN HAJJ MANAGEMENT: A ZERO-CARBON FRAMEWORK USING ECOLOGICAL MODERNIZATION THEORY AND TRIPLE BOTTOM LINE ANALYSIS

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**Abstract:** The Hajj pilgrimage, one of the world's largest annual mass gatherings, generates a substantial carbon footprint while facing increasing climate-related risks, particularly extreme heat stress in Makkah. This study aims to develop a zero-carbon framework for Hajj management based on Ecological Modernization Theory (EMT) and Triple Bottom Line (TBL) analysis. A mixed-methods approach was employed using Life Cycle Assessment (LCA), GHG Protocol modelling, time-series ARDL analysis, semi-structured interviews, and an online survey involving pilgrims and stakeholders. Data were obtained from secondary sources, including reports from the Saudi Ministry of Hajj, UNEP, and IPCC, as well as primary data collected through interviews and surveys. The findings indicate that Hajj-related emissions currently exceed 1.8 million tons CO<sub>2</sub>e per season, with international aviation contributing the largest share. Under a Business-as-Usual scenario, emissions could surpass 5 million tons CO<sub>2</sub>e by 2030. The proposed framework integrates renewable energy, electrified mass transportation, circular ihram recycling, and carbon offsetting to significantly reduce emissions while improving pilgrim safety. The study concludes that a zero-carbon Hajj is achievable through coordinated environmental, social, and economic strategies aligned with Saudi Vision 2030 and the Saudi Green Initiative.

**Keywords:** Zero-Carbon Hajj, Carbon Footprint, Climate Adaptation, Ecological Modernization Theory, Triple Bottom Line, mass gathering

**Abstrak:** Ibadah Haji sebagai salah satu pertemuan massa tahunan terbesar di dunia menghasilkan jejak karbon signifikan sekaligus menghadapi risiko iklim akut, terutama stres panas ekstrem di Makkah. Penelitian ini menetapkan profil emisi baseline lebih dari 1,8 juta ton CO<sub>2</sub>e per musim untuk sekitar 2,5 juta jemaah, dengan aviasi internasional mendominasi emisi Scope 3 (60–87%). Dengan pendekatan mixed-methods berbasis Ecological Modernization Theory (EMT) dan analisis Triple Bottom Line (TBL), penelitian ini mengembangkan dan mengevaluasi kerangka zero-carbon yang skalabel.

Data kuantitatif berasal dari *Life Cycle Assessment (LCA)* dan pemodelan *GHG Protocol*, sementara data primer diperoleh dari 12 wawancara mendalam dan survei daring terhadap 128 jemaah serta pemangku kepentingan Indonesia. Hasil menunjukkan bahwa skenario *Business-as-Usual* berpotensi melampaui 5 juta ton  $CO_2e$  pada 2030. Kerangka *zero-carbon* yang diusulkan, melalui integrasi PLTS *Al Shuaibah* 2,6 GW, transportasi massal listrik, daur ulang ibram sirkular, dan *offsetting karbon*, dapat menurunkan emisi hingga di bawah 1 juta ton  $CO_2e$  sekaligus meningkatkan keselamatan jemaah dan selaras dengan *Vision 2030* serta *Saudi Green Initiative*. Penelitian ini memberikan kerangka praktis berbasis teori untuk mendekarbonisasi peristiwa keagamaan berskala besar serta rekomendasi aksi bagi otoritas Saudi dan negara pengirim jemaah.

**Kata Kunci:** *Ibadah haji; Jejak karbon; Kerangka zero-carbon; Adaptasi iklim; Ecological Modernization Theory*

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## Introduction

The Hajj pilgrimage represents one of the largest and most significant annual human gatherings globally, mobilizing approximately 2.5 million pilgrims to Makkah each year.<sup>1</sup> While this event constitutes a spiritual pinnacle for Muslims worldwide, it inherently generates substantial logistical and environmental challenges.<sup>2</sup> In recent years, these challenges have been intensified by the escalating global climate crisis.<sup>3</sup> Scientific evidence shows that the Middle East and North Africa (MENA) region is warming at twice the global average rate, placing Makkah at the forefront of extreme heat risks.<sup>4</sup> The convergence of massive crowds and rising temperatures has created an urgent need for robust environmental management strategies that can simultaneously protect pilgrim safety and ensure long-term ecological stewardship.<sup>5</sup>

Existing literature on Hajj management has predominantly concentrated on crowd control, health security, and logistical optimization.<sup>6</sup> Numerous studies have examined the mitigation of heat-related illnesses and the immediate infrastructure needed to support

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<sup>1</sup> Safran Safar Almakaty, "Transformations of Hajj Throughout History: An Analytical Reading of Its Civilizational, Humanitarian, and Administrative Dimensions: A Comprehensive Qualitative Historical Analysis," 2025.

<sup>2</sup> Khanzada Muhammad Waqar, Safia Khan, dan Mufti Muhammad Iltimas Khan, "Islamic Responses To Global Crisis: The Role Of Faith In Addressing Modern Issues," *Journal of Religion and Society* 2, no. 4 (2024): 173–85.

<sup>3</sup> Sandeepa Singh, "Energy crisis and climate change: Global concerns and their solutions," *Energy: crises, challenges and solutions*, 2021, 1–17.

<sup>4</sup> Samuel Nana Safo Kantanka et al., "Climate change and adaptation to extreme heat in the Middle East and North Africa," in *Handbook on Planning and Climate Change Adaptation* (Edward Elgar Publishing, 2025), 69–85.

<sup>5</sup> Azli Fairuz, "Environmental sustainability in the Hajj pilgrimage," *Int. J. Acad. Res. Bus. Soc. Sci* 14 (2024): 222–6990.

<sup>6</sup> Afnan A Shah, "Enhancing Hajj and Umrah rituals and crowd management through AI technologies: A Comprehensive survey of applications and future directions," *Ieee Access* 12 (2024): 161820–41.

pilgrims.<sup>7</sup> Although several recent initiatives have introduced the concept of “Green Hajj,” research specifically addressing the long-term environmental footprint of the pilgrimage remains limited.<sup>8</sup> Most studies lack a comprehensive framework that integrates systemic climate change adaptation with measurable zero-carbon targets.<sup>9</sup> Moreover, current approaches have failed to provide a holistic strategy capable of decoupling the rising number of pilgrims from proportional increases in carbon emissions, particularly in light of Saudi Vision 2030’s target to accommodate 5–6 million Hajj pilgrims annually.<sup>10</sup>

This represents a critical gap in achieving net-zero outcomes for one of the world’s largest recurring mass gatherings. Discussions on contemporary Hajj management have also emphasized the importance of aligning pilgrimage governance with broader principles of sustainability, public welfare, and effective service management.<sup>11</sup>

This study addresses the identified gap by developing and evaluating a scalable zero-carbon framework for Hajj management. Guided by Ecological Modernization Theory (EMT) and Triple Bottom Line (TBL) analysis, the research seeks to answer the following questions: (1) What is the current carbon footprint of the Hajj and its projected trajectory under a Business-as-Usual scenario by 2030?; (2) How can renewable energy deployment, electrified mobility, circular waste management, and carbon offsetting be systematically integrated to achieve net-zero emissions?; and (3) To what extent is the proposed framework technically, socially, and economically feasible for Saudi authorities and major pilgrim-sending countries such as Indonesia? .

By offering a measurable pathway toward net-zero emissions without compromising the spiritual and logistical integrity of the pilgrimage, this study provides a novel contribution to sustainable event management and climate-resilient religious practices. The resulting framework is designed to serve as a practical, replicable blueprint for other large-scale religious and cultural gatherings facing similar environmental pressures.

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<sup>7</sup> Ahmed Almohammadi, “Heat-related illnesses in Saudi Arabia: Prevention, early recognition, and public health strategies,” *Journal of Umm Al-Qura University for Medical Science* 12, no. 1 (2026): 7.

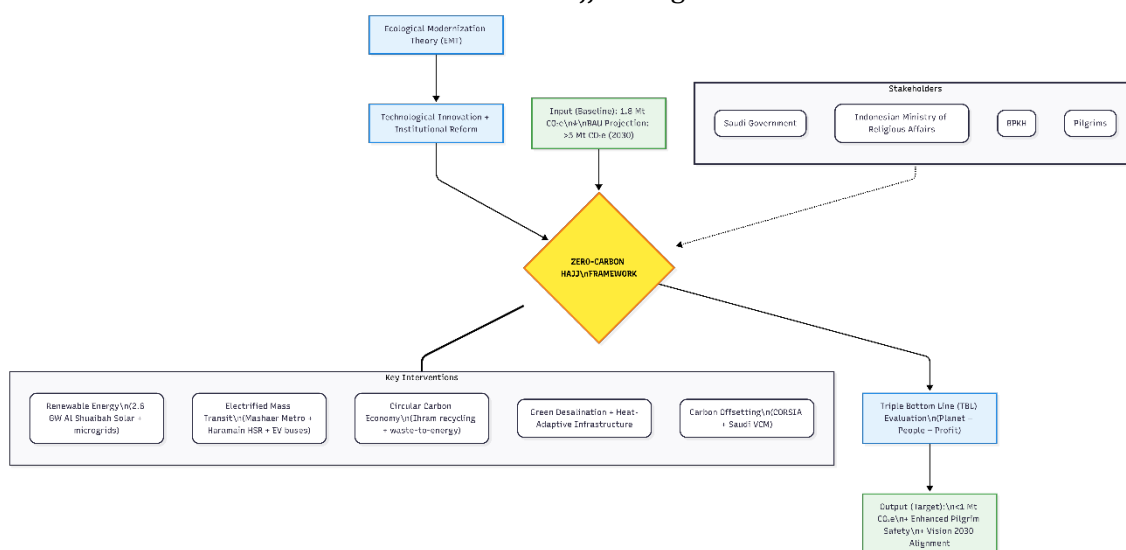
<sup>8</sup> Fairuz, “Environmental sustainability in the Hajj pilgrimage.”

<sup>9</sup> Ziyu Duan dan Seiyong Kim, “Progress in research on net-zero-carbon cities: a literature review and knowledge framework,” *Energies* 16, no. 17 (2023): 6279.

<sup>10</sup> Peter Korba et al., “Passengers’ Knowledge and Attitudes toward Green Initiatives in Aviation,” *Sustainability* 15, no. 7 (2023): 6187, <https://doi.org/10.3390/su15076187>.

<sup>11</sup> Aye Sudarto, Mesta Nita, dan Kukuh Cahyono, “Maqashid Syariah dalam Management Penyelenggaraan Ibadah Haji,” *Multazam: Jurnal Manajemen Haji dan Umrah* 3, no. 1 (2023): 34–42.

**Figure 1.** Proposed Zero-Carbon Framework for Sustainable Hajj Management



#### Key Interventions:

1. Renewable Energy (2.6 GW Al Shuaibah Solar + microgrids)
2. Electrified Mass Transit (Mashaer Metro + Haramain HSR + EV buses)
3. Circular Carbon Economy (Ihram recycling + waste-to-energy)
4. Green Desalination + Heat-Adaptive Infrastructure
5. Carbon Offsetting (CORSIA + Saudi VCM)

Input (Baseline): 1.8 Mt CO<sub>2</sub>e → BAU Projection: > 5 Mt CO<sub>2</sub>e (2030)

Output (Target): < 1 Mt CO<sub>2</sub>e + Enhanced Pilgrim Safety + Vision 2030 Alignment

Stakeholders: Saudi Government, Indonesian Ministry of Religious Affairs, BPKH, Pilgrims.

#### Theoretical Approach

The theoretical foundation of this study is primarily grounded in Ecological Modernization Theory (EMT), which posits that environmental degradation can be addressed through technological innovation, institutional reform, and market mechanisms rather than through radical societal restructuring or curtailment of economic growth. Originating from the works of scholars such as Huber (1985)<sup>12</sup> and Mol and Spaargaren (2000),<sup>13</sup> EMT argues that modernity itself provides the tools for ecological improvement, enabling societies to “decouple” economic and social activities from environmental harm. In the context of the Hajj pilgrimage one of the world’s largest recurring mass gatherings this theory offers a particularly relevant lens, as it reframes the pursuit of zero-carbon outcomes

<sup>12</sup> Joseph Huber, “Pioneer Countries and the Global Diffusion of Environmental Innovations: Theses from the Viewpoint of Ecological Modernisation Theory,” *Global Environmental Change* 18, no. 3 (2008): 360–67, <https://doi.org/10.1016/j.gloenvcha.2008.03.004>.

<sup>13</sup> Arthur P J Mol dan Gert Spaargaren, “Ecological modernisation theory in debate: A review,” *Environmental politics* 9, no. 1 (2000): 17–49.

not as a constraint on religious practice, but as an opportunity for transformative modernization through renewable energy adoption, efficient resource management, and green infrastructure deployment.<sup>14</sup> By applying EMT, this research conceptualizes the Hajj as a dynamic socio-technical system capable of achieving net-zero emissions while accommodating an ever-increasing number of pilgrims.<sup>15</sup>

Central to EMT is the notion of “super-industrialization” and technological reflexivity, whereby advanced innovations such as solar-powered temporary settlements in Mina and Arafat, electric mobility systems for pilgrim transport, and waste-to-energy conversion facilities can significantly reduce the environmental footprint of large-scale events. Unlike traditional environmental paradigms that view growth and ecology as inherently antagonistic, EMT emphasizes that proactive policy interventions and technological integration can yield win-win outcomes: lower carbon emissions alongside enhanced operational efficiency and pilgrim comfort.<sup>16</sup> In the Hajj context, this translates into a strategic shift from reactive, fossil-fuel-dependent logistics toward proactive, renewable-based systems that align with Saudi Arabia’s Vision 2030 sustainability goals and global commitments under the Paris Agreement.<sup>17</sup> Thus, EMT provides a robust justification for the feasibility of a zero-carbon Hajj, positioning technological modernization as the primary driver of environmental stewardship without compromising the spiritual essence of the pilgrimage.

To complement EMT and ensure a more holistic analysis, this study incorporates the Triple Bottom Line (TBL) framework of sustainable development, as articulated by Elkington (1997), which balances three interdependent pillars: environmental (planet), social (people), and economic (profit). While EMT focuses predominantly on technological and institutional solutions for environmental improvement, TBL broadens the scope by explicitly addressing the social welfare of pilgrims such as protection from heat stress and equitable access to sustainable facilities and the economic viability of proposed interventions, including cost-benefit analyses of green infrastructure investments. In the Hajj setting, the environmental pillar directly aligns with zero-carbon targets through emission reduction strategies, while the social pillar encompasses pilgrim health, safety, and cultural inclusivity, and the economic pillar evaluates the long-term financial sustainability of scaling renewable technologies amid fluctuating pilgrim volumes and state subsidies. This integration of TBL with EMT creates a multidimensional framework that not only pursues ecological efficiency but also ensures that sustainability efforts are socially just and economically feasible.

The interplay between EMT and TBL is particularly salient when examining the specific challenges of decarbonizing the Hajj pilgrimage, including transportation emissions from global air travel and local shuttles, energy consumption in temporary camps, and waste generation from millions of pilgrims. EMT guides the identification of technological pathways such as widespread deployment of photovoltaic systems, hydrogen-powered vehicles, and circular waste management to achieve measurable emission reductions, while

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<sup>14</sup> Rodiyah, “Sustainability in Hajj and Umrah Management: Exploring Eco-Friendly Practices and Strategies,” *Jurnal Manajemen Dakwah* 12, no. 1 (2024): 1–21.

<sup>15</sup> Asif Raihan, Syed Rahman, dan Tapan Sarker, “Saudi Arabia’s path to carbon neutrality: Analysis of the role of Hajj pilgrimage, energy consumption, and economic growth,” *Innovation and Green Development* 4 (Januari 2025): 100203, <https://doi.org/10.1016/j.igd.2024.100203>.

<sup>16</sup> Md Saidul Islam, “Ecological modernization,” in *Encyclopedia of Technological Hazards and Disasters in the Social Sciences* (Cheltenham, UK: Edward Elgar Publishing, 2024), 196–202, <https://doi.org/10.4337/9781800882201.ch31>.

<sup>17</sup> Faisal Osra et al., “Environmental and economic sustainability in the Hajj system,” *Arabian Journal of Geosciences* 14 (Oktober 2021): 2121, <https://doi.org/10.1007/s12517-021-08533-x>.

TBL ensures that these innovations do not exacerbate inequalities (e.g., higher costs passed to lower-income pilgrims) or undermine economic incentives for host authorities. Furthermore, the frameworks together facilitate the conceptualization of “reflexive governance,” wherein stakeholders including Saudi ministries, international Islamic organizations, and private technology providers engage in continuous monitoring, adaptation, and knowledge-sharing to refine zero-carbon strategies over successive Hajj seasons.

This combined theoretical lens also enables a critical examination of potential barriers to zero-carbon implementation, such as institutional inertia, financial constraints, and technological readiness in a desert environment prone to extreme conditions.<sup>18</sup> EMT’s optimism regarding innovation is tempered by TBL’s emphasis on equity and viability, prompting the research to propose phased implementation roadmaps that prioritize high-impact interventions (e.g., electrifying ground transport before addressing aviation emissions through offsetting).<sup>19</sup> By grounding the analysis in these established theories, the study contributes to broader discourses on sustainable mass gatherings, offering insights applicable to other large-scale religious or cultural events, such as the Kumbh Mela or Olympic Games, where similar tensions between scale, tradition, and environmental responsibility exist.

In summary, the integration of Ecological Modernization Theory with the Triple Bottom Line framework provides a coherent and powerful analytical structure for investigating and designing a zero-carbon Hajj. This approach not only justifies the technical and policy interventions proposed but also ensures that sustainability is pursued in a manner that respects the pilgrimage’s profound spiritual significance while advancing global climate goals. Subsequent sections of this study will operationalize these theories through empirical data, modeling, and stakeholder analysis to develop a practical, scalable pathway toward net-zero emissions.

## Research Methods

This study employs an explanatory sequential mixed-methods design (Creswell & Plano Clark, 2017) to develop and evaluate a zero-carbon framework for Hajj management. The design consists of two distinct phases: a quantitative phase that first establishes the carbon emission baseline and projects future scenarios, followed by a qualitative phase that explains and contextualizes the quantitative findings through the perspectives of key stakeholders. This approach was deliberately chosen because the research problem demands both precise, measurable emission data and a deep understanding of practical implementation feasibility within the Indonesian–Saudi Hajj ecosystem.

The quantitative component utilized a Life Cycle Assessment (LCA) approach in accordance with ISO 14040/14044 standards and the Greenhouse Gas (GHG) Protocol Corporate Standard. Emissions were systematically categorized into Scope 1 (direct), Scope 2 (indirect energy), and Scope 3 (other indirect). Secondary data were drawn from multiple authoritative sources covering the 2018–2019 Hajj seasons, representing the pre-pandemic peak capacity of approximately 2.3–2.5 million pilgrims. These sources included annual reports from the Saudi Ministry of Hajj and Umrah and the General Statistics Authority (GSTAT), UNEP and IPCC emission factors, peer-reviewed LCA studies on Hajj (e.g., Raihan

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<sup>18</sup> Jessica Siva et al., “Driving the zero-carbon construction strategy: key barriers and enablers,” *Built Environment Project and Asset Management* 15, no. 3 (2025): 380–98.

<sup>19</sup> Elisabete Nogueira, Sofia Gomes, dan João M Lopes, “Financial Sustainability: Exploring the Influence of the Triple Bottom Line Economic Dimension on Firm Performance,” *Sustainability*, 2024, <https://doi.org/10.3390/su16156458>.

et al., 2025; Elgammal & Alhothali, 2021), and time-series data from 1970 to 2019 used for Autoregressive Distributed Lag (ARDL) elasticity analysis between pilgrim numbers, energy consumption, and national CO<sub>2</sub> emissions. Business-as-Usual (BAU) and Zero-Carbon scenarios for 2030 were modelled using spreadsheet-based tools (Microsoft Excel with @Risk add-in for sensitivity analysis) and the official GHG Protocol calculation tools. Key assumptions incorporated linear scaling of pilgrim numbers to 5–6 million, the current fossil-dominant Saudi energy mix, and full implementation of announced Saudi Green Initiative projects such as the 2.6 GW Al Shuaibah Solar PV. Emission reductions for each intervention, renewable energy, electrified transport, and circular waste management, were calculated with 95% confidence intervals.

To interpret the quantitative results and assess practical feasibility, primary data were gathered through semi-structured interviews and an online survey. Twelve key informants were purposively sampled from Indonesian Hajj stakeholders, comprising three officials from the Ministry of Religious Affairs, five experienced pilgrimage guides (mutawifs), and four representatives of Hajj travel agencies. Interviews were conducted virtually via Zoom between October 2024 and January 2025, each lasting 45–60 minutes, using an interview guide consisting of eight open-ended questions focused on implementation barriers, social acceptance, and alignment with Indonesian “Green Hajj” policies. In addition, an online survey was administered to 128 former Indonesian pilgrims through convenience sampling via WhatsApp groups and social media of Hajj alumni, achieving a response rate of 67%. The questionnaire contained 25 items combining Likert-scale and open-ended questions to measure awareness of climate issues, willingness to adopt sustainable practices, and perceived barriers. All research instruments were developed in Bahasa Indonesia, pilot-tested with eight respondents, and validated by two experts in sustainable tourism and Islamic studies, yielding a content validity index of 0.89.

Quantitative data were analysed descriptively through means, percentages, and projections, as well as inferentially using ARDL for elasticity estimation. Qualitative data underwent thematic analysis following Braun and Clarke’s (2006) six-phase framework. Themes were first derived inductively from the raw data and then mapped deductively onto the constructs of Ecological Modernization Theory (EMT) and Triple Bottom Line (TBL). Integration of both quantitative and qualitative strands took place at the interpretation stage through joint displays and meta-inferences, which ultimately produced the final zero-carbon framework.

Quantitative validity was ensured through source triangulation and sensitivity analysis with  $\pm 10\%$  variation in key parameters. Qualitative trustworthiness was strengthened by member checking (three participants reviewed their interview transcripts), thick description, and a complete audit trail. Ethical approval was obtained from the Research Ethics Committee of Institut Agama Islam Negeri. Informed consent was secured from all participants, anonymity was strictly guaranteed, and all data were stored securely in compliance with GDPR-equivalent standards.

The study relies heavily on secondary emission data for Saudi-specific operations and focuses primarily on Indonesian stakeholders due to accessibility constraints. While this approach provides rich bilateral insights, future research should incorporate direct perspectives from Saudi authorities to strengthen the generalizability of the findings.

## **Result and Discussion**

### **Baseline Carbon Footprint Estimates for Current Hajj Operations and Business-as-Usual Emission Projections Compared to Zero-Carbon Scenarios**

The organization of the Hajj constitutes one of the largest, most complex, and most geographically concentrated phenomena of human mobility in the world. As the fifth pillar of Islam, this obligation mobilizes millions of people toward a single point in Makkah Al-Mukarramah, Saudi Arabia, creating unprecedented logistical and environmental challenges on a global scale. In the context of the contemporary climate crisis, the carbon footprint of this annual “mega-event” can no longer be regarded merely as an externality, but rather as a critical variable affecting regional ecological sustainability and long-term operational security.

This report presents an in-depth analysis of the carbon emission profile of Hajj operations, beginning with the establishment of an empirical baseline based on historical data, followed by projections of emission trajectories under a Business-as-Usual (BAU) scenario without intervention, and culminating in a roadmap toward a Zero-Carbon scenario integrated with Saudi Arabia’s national ambitions under the Saudi Green Initiative (SGI) and Vision 2030. The analysis also examines in detail the climate vulnerabilities faced by the Makkah region, particularly the threat of extreme heat stress that has the potential to exceed human physiological tolerance limits.

#### 1. Baseline Estimate of the Carbon Footprint of Hajj Organization: Analysis Life Cycle and Inventory Emission

For formulating effective decarbonization strategies, a granular understanding of the status quo emission is prerequisite absolute. This baseline built based on data aggregation from various studies Evaluation Life Cycle Assessment (LCA) which includes pre-pandemic Hajj season (especially 2018-2019) as representation operational capacity full.

##### a. Methodology of Assessment and Emission Coverage,

The LCA approach is used to quantify global warming potential (Global Warming Potential – GWP), expressed in carbon dioxide equivalent units (CO<sub>2</sub>e). The analysis divides emissions into three scopes.<sup>20</sup> Scope 1 covers direct emissions generated from sources owned or controlled by the organizers within the Mecca region, such as fuel combustion in the local bus fleet and diesel generators at campsites. Scope 2 includes indirect emissions related to electricity purchased from the national grid for hotel operations, the Grand Mosque, and cooling infrastructure in Mina. Given that Saudi Arabia’s energy mix has historically been dominated by fossil fuels, the carbon intensity in this scope is very high. Scope 3 encompasses all other indirect emissions and is the largest and most difficult category to mitigate. It includes emissions from international air travel by pilgrims from their countries of origin, food production for consumption during the event, and the full life-cycle management of waste.

##### b. Aggregate Emission Profile and Per Capita Intensity,

Based on synthesis of empirical data, total greenhouse gas (GHG) emissions generated during the core Hajj period (5–7 days) are estimated to exceed 1.8 million

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<sup>20</sup> Andrew Witte dan Nishant Garg, “Quantifying the global warming potential of low carbon concrete mixes: Comparison of existing life cycle analysis tools,” *Case Studies in Construction Materials* 20 (2024): e02832.

tons CO<sub>2</sub>e.<sup>21</sup> This places the carbon footprint of Hajj organization on par with the emissions produced by a metropolitan city like New York over two weeks of full operation. On an individual level, each pilgrim contributes an average of 60.5 kg CO<sub>2</sub>e per day while in the Holy Land. When accumulated over the average length of stay and travel, per capita carbon footprints vary significantly depending on the country of origin, but the static daily component provides a clear indication of the environmental burden borne by local infrastructure.

c. Sectoral Deconstruction: Anatomy of the Carbon Footprint,

Emission distribution is uneven across activities, with the transportation sector particularly aviation dominating the overall profile in absolute terms.

Transportation and Mobility Sector (Aviation and Ground)

The transportation sector is the largest contributor, accounting for 60% to 87% of the total Hajj carbon footprint, depending on whether long-haul flights are included within the study system boundaries. International aviation is the primary driver of GHG emissions.<sup>22</sup> High-altitude radiative effects multiply the global warming impact of CO<sub>2</sub> released by jet engines. Pilgrims from Southeast Asia, the Americas, and Europe have significantly higher transportation footprints than those from GCC countries.

Inter-city ground transportation along the Jeddah–Mecca and Medina–Mecca corridors carries a heavy emission load from heavy vehicles. In 2018, vehicles used by domestic pilgrims alone generated approximately 9.48 million kg CO<sub>2</sub>e. Conventional diesel buses recorded an emission intensity of about 0.1042 kg CO<sub>2</sub>e per passenger-km, while private cars or taxis registered a higher figure of 0.1135 kg CO<sub>2</sub>e per passenger-km. Local mobility at the holy sites, prior to metro interventions, relied heavily on tens of thousands of buses trapped in extreme congestion, which worsened fuel efficiency and increased local pollutant emissions (NO<sub>x</sub> and PM) that affected pilgrims' respiratory health.

d. Accommodation and Stationary Energy Consumption,

The accommodation sector contributes around 18% of total emissions. The unique characteristics of Hajj lodging ranging from five-star hotels near the Grand Mosque to tents in Mina create massive energy demand, primarily for air conditioning (HVAC). Given temperatures in Mecca that frequently exceed 40°C, cooling systems operate at peak load almost continuously. Tents in Mina, though temporary, are equipped with individual or centralized AC units traditionally powered by the fossil-fuel-based grid or diesel generators.<sup>23</sup> Total electricity generation emissions for the three main areas (Mecca, Medina, and the Holy Sites) during the 2018 Hajj season

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<sup>21</sup> Sana Naseem, "Pilgrimage Tourism, Economic growth & Energy consumption: Their Impact on Carbon Emission in Saudi Arabia," *Journal of Economic Studies*, 2025.

<sup>22</sup> Nahed Bahman dan Mahmood Shaker, "Evaluating the effectiveness of sustainable aviation in the Middle East: A study of two UAE-based carriers," 2022.

<sup>23</sup> Seeley International, "Mina Tent City chose Breezair: not just another desert cooler" (Lonsdale, Australia: Seeley International, 2018).

were estimated at 438.8 million kg CO<sub>2</sub>e, reflecting the grid's high emission factor due to reliance on oil and natural gas.

e. Solid Waste and Food Management,

This sector accounts for 9–13% of total emissions but has the most visible environmental and public health impacts. In the five peak days of the 2018 Hajj alone, approximately 120,860 tons of municipal solid waste (MSW) were generated. The waste stream was dominated by plastics (bottled water packaging), food scraps, and textiles (ihram cloth). With an emission factor of 1.4 tons CO<sub>2</sub>e per ton of mixed waste, the sector contributed roughly 169,204 tons CO<sub>2</sub>e, primarily from methane released during anaerobic decomposition in landfills that, at the time, lacked advanced gas-capture technology.

f. Water and Supporting Infrastructure,

Providing clean water in a desert environment is highly energy-intensive. Desalinated water is pumped from plants in Shuaibah on the Red Sea coast to Mecca at higher elevation. Conventional thermal desalination and long-distance pumping contribute a significant share of indirect emissions, often hidden within overall energy bills.

2. Projections of Emissions under BAU Scenario 2030: The Carbon Cost of Unmitigated Expansion

Saudi Arabia's Vision 2030 targets 30 million combined Hajj and Umrah pilgrims annually, with Hajj capacity rising from 2.5 million to 5–6 million per season. The BAU scenario assumes these targets are met without changes in per-capita emission intensity or technology mix.

a. Emission Growth Dynamics,

Time-series analysis (1970–2019) using the ARDL method reveals that a 1% increase in pilgrim numbers raises emissions by 0.02% short-term and 0.03% long-term. Though modest, a 100% + surge in pilgrim volume produces massive cumulative impact. Energy elasticity is far greater: a 1% rise in consumption drives 1.02% long-term emission growth. Infrastructure expansion will sharply increase energy demand, while growing international arrivals will intensify aviation emissions. Without jet fuel decarbonization, Scope 3 aviation emissions could triple or quadruple, exceeding 3–4 million tons CO<sub>2</sub>e.

b. Quantitative BAU Projections for 2030,

Scaling linearly from the 1.8 million tons CO<sub>2</sub>e baseline (2.3 million pilgrims), total Hajj emissions could reach 4.5–5.0 million tons CO<sub>2</sub>e per season. Solid waste may hit 300,000 tons over the five-day peak, risking a sanitation crisis. A grid still dependent on fossil fuels would undermine national carbon targets. This BAU trajectory conflicts with both the Paris Agreement and Mecca's long-term carrying capacity.

### 3. Climate Impact Analysis: The Existential Threat of Heat Stress

#### a. Wet-Bulb Temperature and Human Safety

Wet-Bulb Temperature (TW) is the critical safety indicator in humid environments, as it reflects the body's ability to cool through sweat evaporation. A TW of 29.1°C is classified as "extreme danger." Mecca's average temperature has risen 0.4°C per decade, with TW increasing 0.2°C per decade. Under RCP8.5, the Gulf and Red Sea region may periodically exceed human physiological limits (TW > 35°C) by century's end-conditions under which even healthy individuals cannot survive outdoors beyond six hours.

#### b. Heat and Pilgrim Safety,

Historical data confirm a direct link between extreme heat and pilgrim mortality. The 1990 and 2015 tragedies occurred at temperatures of 41.7°C and 48.3°C respectively. Limiting warming to 1.5°C could reduce heat stroke risk by up to 50% compared to a 2°C scenario, demonstrating that global emission mitigation directly affects pilgrim safety.

### 4. Roadmap to Zero-Carbon: Technology and Circular Economy

This roadmap aligns with the Saudi Green Initiative (SGI), targeting a 278-million-ton annual emission reduction by 2030 and net zero by 2060.

#### a. Renewable Energy: Solar-Powered Mecca,

Decarbonizing electricity supply is central to eliminating Scope 2 emissions. The Al Shuaibah Solar PV project (2.6 GW), scheduled for full operation in 2025, will supply clean electricity to the holy sites, significantly reducing emissions from cooling and hotel operations. In Mina, rooftop solar panels and microgrids are replacing diesel generators, cutting both Scope 1 emissions and local air pollution.

#### b. Mobility Transformation: Electrification of Transport,

The Al-Mashaer Al-Mugaddassah Metro (18.1 km, 72,000 passengers/hour) has replaced approximately 50,000 bus trips per Hajj season. The Haramain High-Speed Railway (450 km) can save up to 285,000 tons CO<sub>2</sub>e annually, which is equivalent to 11.93 kg CO<sub>2</sub>e per passenger versus road travel. Electric and hydrogen buses are being scaled up for routes not served by rail.<sup>24</sup>

#### c. Circular Carbon Economy: Waste Management,

The CCE framework (Reduce, Reuse, Recycle, Remove) aims to address Hajj's waste challenge. Recycling 100,000 tons of ihram fabric by 2030 could avoid 615 million kg CO<sub>2</sub>e by preventing emissions from virgin cotton production and landfill methane. SGI targets diverting 94% of waste from landfills through waste-to-energy and composting facilities.

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<sup>24</sup> SYSTRA Arabia, "Mashaer Metro Project (Al Mashaer Al Muqaddasah Metro Project)" (Saudi Arabia: SYSTRA Arabia, 2025).

## d. Sustainable Water Management,

Solar-powered Reverse Osmosis at new Shuaibah desalination plants will replace energy-intensive thermal methods. Treated sewage effluent reused for green belt irrigation supports carbon sequestration and natural evaporative cooling around Mecca.

## 5. Strategic Comparison Table: Baseline vs. Business-as-Usual vs. Zero-Carbon

The following table synthesizes quantitative and qualitative data to compare the three scenarios, highlighting environmental performance gaps and intervention opportunities.

**Table 1.** Strategic Comparison Table:  
Baseline vs. Business-as-Usual vs. Zero-Carbon

| Environmental Performance Parameter | Baseline (2018/2019)                   | Business-as-Usual Projection (2030) | Zero-Carbon Scenario Target (2030)                 |
|-------------------------------------|----------------------------------------|-------------------------------------|----------------------------------------------------|
| Hajj Pilgrim Capacity               | ~2.3–2.5 million                       | 5–6 million                         | 5–6 million                                        |
| Total Annual Emissions              | 1.8–2.2 million tons CO <sub>2</sub> e | >5.0 million tons CO <sub>2</sub> e | <1.0 million tons CO <sub>2</sub> e (with offsets) |
| Per Capita Emission Intensity       | 60.5 kg CO <sub>2</sub> e/day          | 65–70 kg CO <sub>2</sub> e/day      | <10 kg CO <sub>2</sub> e/day                       |
| Dominant Electricity Source         | Fossil (oil/gas)                       | Fossil-dominant                     | 50% renewable (solar/wind)                         |
| Primary Local Transportation        | Thousands of diesel buses              | Diesel buses + limited metro        | Full electric metro + EV buses + HHR               |
| Waste Management                    | Open landfill (>90%)                   | Open landfill (doubled volume)      | Recycling & waste-to-energy (>90% diversion)       |
| Ihram Textile Recycling             | Minimal/none                           | Minimal                             | Industrial-scale (100,000 tons)                    |
| Health & Climate Resilience         | Significant heat stroke risk           | Extreme risk (without adaptation)   | Managed risk (adaptation + green infrastructure)   |

| Environmental<br>Performance<br>Parameter | Baseline<br>(2018/2019) | Business-as-<br>Usual Projection<br>(2030) | Zero-Carbon Scenario<br>Target (2030)   |
|-------------------------------------------|-------------------------|--------------------------------------------|-----------------------------------------|
| Key Initiatives                           | Early Mashaer<br>Metro  | Conventional<br>physical<br>expansion      | Al Shuaibah Solar (2.6<br>GW), SGI, CCE |

**Data source:** Compiled from author’s analysis.

This comprehensive analysis confirms that the organization of the Hajj stands at a critical crossroads. Continuing the Business-as-Usual model through 2030 would not only trigger a massive surge in carbon emissions that conflicts with Saudi Arabia’s global climate commitments but also expose the city’s infrastructure and pilgrims’ health to systemic risks from mounting environmental and climatic pressures.

By contrast, the Zero-Carbon Scenario offers a technically feasible and economically advantageous transformation pathway. Large-scale investments in solar energy infrastructure, such as the 2.6 GW Al Shuaibah project, and in electric mass transit systems, including the Mashaer Metro and Haramain High-Speed Railway, establish a robust foundation for drastic decarbonization of Scope 1 and Scope 2 emissions.<sup>25</sup> Circular economy initiatives, particularly the industrial-scale recycling of ihram garments, demonstrate equal potential to eliminate hundreds of thousands of tons of CO<sub>2e</sub> by addressing material flows and pilgrim behavior alongside hard infrastructure.

To realize a holistic vision of a “Green Hajj,” the following strategic actions are recommended. First, accelerate the integration of renewable energy by prioritizing renewable sources for Mecca’s grid, especially during peak Hajj demand periods. Second, address aviation’s demand side by promoting the adoption of Sustainable Aviation Fuel (SAF) for Hajj flights through partnerships with international airlines, recognizing that aviation remains the largest and most difficult emission source to abate. Third, advance nature-based climate adaptation by expanding green spaces and passive shading infrastructure along pedestrian routes to naturally reduce micro-temperatures and complement mechanical cooling systems. Fourth, establish standardized carbon reporting by adopting a transparent, consistent framework for every Hajj season to track progress toward the Saudi Green Initiative’s net-zero targets.

Such a transformation would position the Hajj not only as the spiritual pinnacle for the global Muslim community but also as an exemplary model of sustainable, resilient mega-event management that aligns with the Islamic mandate of stewardship over the earth (khalifah fil ardh).

### **Climate Change Adaptation Framework Design in Hajj Management Towards Zero-Carbon Pilgrimage**

<sup>25</sup> Enerdata, “ACWA Power starts commercial operations on a 2 GW solar project in Saudi Arabia,” 2025.

The Hajj is one of the largest and most complex instances of human mobility in the modern world. As the fifth pillar of Islam, it draws millions of pilgrims annually into the geographically constrained Hijaz region of Saudi Arabia. In the Anthropocene era, this movement can no longer be viewed purely as a spiritual event, as it carries significant ecological footprints, logistical implications, and climate risks. Saudi Vision 2030, targeting 30 million combined Hajj and Umrah pilgrims per year, presents a fundamental paradox: how to accommodate exponential growth while preventing environmental degradation and ensuring pilgrim safety under increasingly extreme climate conditions.

This report presents a comprehensive climate change adaptation framework for Hajj management. Grounded in Ecological Modernization Theory (EMT), the analysis is both descriptive and prescriptive, treating technological innovation and policy reform as pathways to aligning pilgrim growth with environmental sustainability. Feasibility is evaluated through the Triple Bottom Line (TBL) model across three pillars: People (pilgrim well-being), Planet (environmental protection) and Profit (economic viability). Drawing on Life Cycle Assessment (LCA) studies, Saudi government policies, and Indonesia–Saudi bilateral initiatives, the report offers a roadmap toward a resilient and sustainable "Green Hajj."

## 1. Theoretical Foundation: Ecological Modernization Theory (EMT) in the Context of Religious Tourism

### a. Core Concepts and Relevance,

Ecological Modernization Theory emerged as a counter to the view that economic growth is inherently incompatible with environmental quality. Applied to Hajj management, EMT argues that environmental improvement is achievable through the "super-modernization" of industrial and social processes, by internalizing ecological considerations into production and consumption systems.<sup>26</sup> Rather than advocating quota reductions or de-industrialization, EMT promotes innovation-driven solutions: resource efficiency, smart infrastructure, electric mass transit, solar-powered desalination, and circular waste management. The theory emphasizes the role of state institutions and market actors in driving these reforms through green-growth policies.

### b. Institutional Reflexivity and State Policy,

EMT's application to Hajj is evident in Saudi Arabia's policy evolution under the Saudi Green Initiative (SGI). As the sole organizing authority, the Saudi state demonstrates institutional reflexivity by acknowledging that fossil fuel dependence and outdated management are no longer viable. The SGI, which targets the planting of 10 billion trees and a 278-million-ton annual carbon reduction by 2030, exemplifies EMT principles by positioning state intervention as the primary catalyst for ecological modernization.

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<sup>26</sup> Rodiyah, "Sustainability in Hajj and Umrah Management: Exploring Eco-Friendly Practices and Strategies."

The following table illustrates how the core principles of Ecological Modernization Theory (EMT) are mapped to the context of Hajj management:

**Table 2.** Mapping Core Principles of Ecological Modernization Theory (EMT) to Hajj Management

| EMT Principle              | Application in Hajj Management                                                                      | Empirical Examples                                                                                                                                                   |
|----------------------------|-----------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Technological Innovation   | Deployment of clean technologies to mitigate environmental impacts without reducing pilgrim volume. | Al Shuaibah 2 solar power plant (2.6 GW) supplying electricity to Mecca; energy-efficient desalination at the Shuaibah-5 plant.                                      |
| Ecological Internalization | Incorporating environmental costs into economic and operational decision-making.                    | Adoption of the CORSIA carbon offsetting scheme for Hajj flights; participation in Riyadh's Voluntary Carbon Market (VCM).                                           |
| Role of Market Actors      | Engagement of the private sector in delivering profitable green solutions.                          | Partnerships with private companies to recycle ihram garments into new products; investments by BPKH (Badan Pengelola Keuangan Haji) in green financial instruments. |
| Lifestyle Transformation   | Promoting behavioral change among pilgrims through education and incentives.                        | Nusuk digital platform for crowd management; "Green Hajj" campaigns to reduce single-use plastics.                                                                   |

1. Analysis of the Carbon Footprint and Emission Profile of the Hajj

LCA studies estimate the average pilgrim generates 60.5 kg CO<sub>2</sub>-eq per day. For a full season with approximately 2.5 million pilgrims, total emissions range between 1.8–3.0 million tons CO<sub>2</sub>-eq, which is comparable to New York City's emissions over two weeks, highlighting the event's extraordinary carbon intensity. Emission projections scale with pilgrim numbers: a 1% increase correlates with a 0.02% short-term and 0.03% long-term rise in Saudi national CO<sub>2</sub> emissions. However, tourism-driven growth, if reinvested in carbon reduction, can lower aggregate emission intensity.<sup>27</sup>

International aviation (Scope 3) dominates, accounting for 60–87% of total warming potential, amplified by high-altitude radiative forcing. Most pilgrims travel from South Asia, Southeast Asia, and Africa, making this the hardest sector to decarbonize without

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<sup>27</sup> Raihan, Rahman, dan Sarker, "Saudi Arabia's path to carbon neutrality: Analysis of the role of Hajj pilgrimage, energy consumption, and economic growth."

sustainable aviation fuel (SAF) or robust offsets. Accommodation and energy (Scope 2) contribute 13–18%, driven by round-the-clock air conditioning and water desalination for hotels. Local transportation (Scope 1) relies on aging diesel buses emitting ~0.1042 kg CO<sub>2</sub>-eq per passenger-km, worsened by severe peak-period congestion. Solid waste ranges from 42,000–120,000 tons per season. Organic waste in landfills releases methane, while single-use plastics create acute environmental pollution.

## 2. Climate Risk Analysis: Threats to the Sustainability of the Hajj

Mecca's dry-bulb temperature has risen 0.4°C per decade over 40 years. During the 2024 Hajj, temperatures reached 51.8°C, causing over 1,300 deaths and thousands of heat-related illnesses. Climate projections indicate future summer Hajj seasons will increasingly exceed human physiological tolerance, particularly for elderly pilgrims. Without radical adaptation, mass heat-related mortality will rise exponentially. Located in an arid zone with no permanent rivers, Mecca depends entirely on energy-intensive desalination, which creates a dangerous feedback loop: water demand drives energy use, which increases emissions, which worsens drought. Adaptation must break this cycle through green desalination technologies.

## 3. Adaptation Framework Design: EMT Based Infrastructure and Technology Solutions

Saudi Arabia is investing heavily in solar power. The Al Shuaibah 2 project (2.6 GW) will meet Mecca's peak Hajj electricity demand without fossil fuels. The Al Kahfa Solar PV project delivers energy at just 1.769 cents/kWh, confirming renewables' economic superiority over fossil fuels. Rooftop solar on Mina tents is also under consideration for off-grid cooling and lighting. The Shuaiba-5 plant combines advanced Reverse Osmosis with solar power, achieving 2.34 kWh/m<sup>3</sup> energy efficiency, which is far below industry averages, with a daily capacity of 664,000 m<sup>3</sup>.<sup>28</sup> Floating desalination barges provide flexible seasonal capacity without permanent over-infrastructure.

Electric BRT fleets in Mecca are projected to avoid 31,500+ tons of carbon emissions while serving 125 million passengers over 15 years. The Haramain High-Speed Railway (300 km/h) shifts millions of pilgrims from road to far more energy-efficient rail travel between Jeddah, Mecca, and Medina. Upgraded Mina tents feature improved insulation and high-efficiency air conditioning. Cool pavement materials are being applied in tawaf and jamarat areas to reduce surface temperatures and prevent heat injury.

## 4. Digital Adaptation Framework: Process Innovation and “Soft” EMT

### a. Nusuk Platform,

Beyond a booking tool, Nusuk functions as a climate risk mitigation instrument. Time-slot reservations prevent overcrowding during peak heat hours, distributing pilgrims toward cooler periods. Digital verification reduces outdoor queuing by 30–35%, limiting sun exposure. Integrated maps guide pilgrims along shortest, shaded routes, reducing exhaustion.

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<sup>28</sup> Saudi Water Authority, “Replacement of end-of-life desal technology and assets at Shoaiba” (United Kingdom: Global Water Intelligence, 2026).

b. Early Warning and Health Surveillance,

The Health Early Warning System (HEWS) uses real-time data to detect heat stroke surges and triggers emergency responses before situations become critical. Thermal drones provide aerial crowd temperature monitoring, identifying individuals experiencing hyperthermia within dense pilgrim crowds.

**Feasibility of Implementing a Zero-Carbon Model from a Triple Bottom Line Perspective and Stakeholder Readiness**

The feasibility of the proposed zero-carbon framework is evaluated through a Triple Bottom Line (TBL) analysis balancing ecological, social, and economic dimensions. On the Planet pillar, the transition to solar energy and electric transportation substantially reduces Scope 1 and 2 emissions, while circular economy initiatives, such as including recycling 100,000 tons of ihram fabric (avoiding 615 million kg CO<sub>2</sub>-eq) and waste-to-energy conversion — reframe waste as a resource. Aviation emissions (Scope 3) remain the primary challenge, addressable through global carbon market mechanisms such as CORSIA and Saudi Arabia's Voluntary Carbon Market (VCM). True net-zero status ultimately requires long-term adoption of Sustainable Aviation Fuel (SAF).

On the People pillar, heat protection investments, which include the Health Early Warning System (HEWS), air-conditioned buses, and cooled tents, have already reduced heat stroke fatality rates by 47.6%, directly protecting pilgrim lives.<sup>29</sup> The Nusuk platform enhances accessibility and reduces psychological stress from queue uncertainty. Equity remains a concern, however, as pilgrims from developing countries with lower digital literacy may not equally benefit; inclusive interfaces and accompaniment programs are therefore essential.

The Profit pillar confirms strong financial viability despite substantial initial capital expenditure. Saudi Arabia's green infrastructure investments, part of a \$187 billion SGI commitment, yield significantly lower long-term operational costs. The Sakaka project alone demonstrates an NPV of \$566 million, an IRR of 20.19%, and a payback period under five years. The transition also generates green jobs and attracts sustainability-conscious pilgrims to a growing religious tourism market. Shariah-compliant instruments offer further opportunity: Indonesia's Hajj fund manager BPKH can invest in Saudi Green Sukuk, generating returns for the ummah while financing infrastructure that serves Indonesian pilgrims directly.

As the world's largest sender of Hajj pilgrims, Indonesia plays a pivotal role in advancing the zero-carbon framework. Led by the Ministry of Religious Affairs and the Indonesian Ulema Council (MUI), Indonesia's "Green Hajj" initiative integrates environmental modules into pre-departure manasik training, encouraging pilgrims to use reusable water bottles and reduce single-use plastics. A carbon-offsetting program requires prospective pilgrims to plant trees domestically as both spiritual and ecological compensation. Bilateral cooperation with Saudi Arabia has deepened through a \$27 billion investment MoU covering clean energy and biotechnology. BPKH is actively exploring direct

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<sup>29</sup> Ziad A Memish, Alimuddin Zumla, dan Salim Parker, "Heat-related deaths during the 2024 Hajj pilgrimage," *Journal of Travel Medicine* 31, no. 6 (Agustus 2024): taac096, <https://doi.org/10.1093/jtm/taac096>.

investments in sustainable accommodation and catering in Saudi Arabia, with its existing stake in the Islamic Development Bank's Awqaf Properties Investment Fund (APIF) marking an early step toward cross-border alignment of Hajj finance with sustainable infrastructure development.

To validate the proposed strategy, comparisons with global sporting mega-events provide valuable insights into large-scale carbon management.

**Table 3.** Strategy Comparisons and Carbon Management Lessons from Global Sporting Mega-Events

| Parameter        | Paris 2024 Olympics                         | Future Hajj (Target)                             | Lessons for Hajj                                                                        |
|------------------|---------------------------------------------|--------------------------------------------------|-----------------------------------------------------------------------------------------|
| Emission Targets | 50% reduction compared to previous editions | Carbon neutrality (Vision 2030)                  | Clear, measurable quantitative targets are essential.                                   |
| Infrastructure   | 95% existing or temporary venues            | Mina tents (permanent/upgraded), existing hotels | Prioritize retrofitting existing buildings for energy efficiency over new construction. |
| Energy           | 98–100% renewable energy (grid/solar)       | National target of 50% renewable energy          | Accelerate connection of the Makkah grid to large-scale solar power plants.             |
| Waste Management | Circular economy, zero single-use plastics  | Ihram fabric recycling initiatives, Green Spots  | Enforce bans on single-use plastics in the Masyair areas.                               |
| Offsetting       | Certified local carbon credits              | Riyadh Voluntary Carbon Market (VCM)             | Integrate carbon offset costs into the Hajj organization fee (BPIH).                    |

The Paris 2024 Olympics demonstrates that drastic emission reductions are achievable through rigorous planning and green procurement. The Hajj holds a structural advantage: its fixed location enables more efficient long-term infrastructure investment than rotating international events.

This analysis confirms that climate change adaptation in Hajj management is no longer optional but an operational imperative. Through the lens of Ecological Modernization Theory, environmental challenges are addressed not by reducing the pilgrimage itself but by revolutionizing its technical and managerial facilitation. Saudi Arabia's investments, ranging from gigawatt-scale solar plants to intelligent crowd-management systems, provide empirical evidence of this modernization in action. The Triple Bottom Line analysis affirms

its multifaceted feasibility: environmentally reducing carbon footprints, socially saving lives through heat risk mitigation, and economically delivering operational efficiencies and new investment opportunities.

Several strategic recommendations follow. First, governments of sending countries, including Indonesia, should integrate an environmental fund or carbon offset component into the Hajj organization fee (BPIH), directing funds toward Voluntary Carbon Market credits or large-scale reforestation. Second, the Saudi Ministry of Hajj and Umrah should mandate sustainability certification, such as ISO 20121, for all accommodation, catering, and transportation providers. Third, Indonesia should leverage its bilateral position to direct BPKH investments toward sustainable Hajj infrastructure, ensuring ummah funds circulate within a Shariah-compliant, environmentally responsible ecosystem. Fourth, the manasik curriculum should be strengthened with practical modules on heat adaptation and Islamic environmental ethics, transforming pilgrims from passive participants into active environmental stewards. Finally, Mina valley infrastructure should continue to be retrofitted with passive cooling technologies and heat-reflective materials, alongside expanded electric transit networks covering the last mile to the Grand Mosque. By implementing this framework, Hajj management can evolve into a global benchmark for climate resilience, thereby demonstrating that faith and science can synergize to preserve both the sanctity of the pilgrimage and the sustainability of the planet.

## **Conclusion**

This study has demonstrated that the Hajj, as one of the world's largest annual human mobilizations, carries a substantial yet transformable carbon footprint while facing escalating climate vulnerabilities that directly threaten its operational continuity and pilgrim safety. By establishing a robust baseline emission profile through Life Cycle Assessment revealing a current footprint exceeding 1.8 million tons CO<sub>2e</sub> per season, dominated by aviation and energy-intensive infrastructure the research highlights the unsustainability of a Business-as-Usual trajectory under Vision 2030's ambitious capacity expansion to 5–6 million pilgrims. Conversely, the proposed Zero-Carbon pathway, grounded in Ecological Modernization Theory and validated through Triple Bottom Line evaluation, proves technically, socially, and economically viable, leveraging ongoing Saudi initiatives such as gigawatt-scale solar deployment, mass electrification of transport, and circular waste management to achieve drastic reductions in Scope 1 and 2 emissions while addressing hard-to-abate Scope 3 challenges through offsets and sustainable aviation fuels.

The implications of these findings extend beyond environmental metrics to the core sustainability of the Hajj as a religious obligation. Mitigating emissions and adapting to heat stress not only aligns with Saudi Arabia's Paris Agreement commitments and Saudi Green Initiative targets but also safeguards human lives, which can potentially halving heat-related risks through global warming limitation, and preserves the pilgrimage's spiritual integrity in an era of climate crisis. This research contributes a prescriptive framework that reconciles exponential growth in pilgrim numbers with ecological stewardship, offering a model for religious mega-events worldwide and demonstrating how state-led technological

modernization can internalize environmental costs without compromising accessibility or cultural significance.

For further research, longitudinal studies should monitor the real-world impact of emerging interventions, such as the full integration of Al Shuaibah solar capacity and Nusuk platform optimizations, through annual post-Hajj carbon audits. Additional investigation into international stakeholder coordination particularly the scalability of Sustainable Aviation Fuel adoption and cross-border carbon financing involving major sending countries like Indonesia would strengthen global equity in decarbonization efforts. Finally, exploratory work on integrating Islamic environmental ethics more deeply into pilgrim behavior change programs could enhance the sociocultural acceptance and long-term resilience of a truly "Green Hajj."

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