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Article

Evaluating Energy Consumption drivers in Saudi Arabia and Prioritizing Sustainable Solutions: An FAHP Approach

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Abstract: Saudi Arabia faces rising energy demand driven by rapid urbanization, industrialization, and population growth, presenting major sustainability challenges. This study employs the Fuzzy Analytic Hierarchy Process (FAHP) to evaluate the key determinants of energy consumption and to prioritize sustainable alternatives. energy-consumption drivers and strategies were identified through a systematic literature review and assessed using expert-based pairwise comparisons. A panel of highly experienced experts (n=7) independently completed full pairwise comparison matrices. After individual consistency testing, corresponding judgments were transformed into triangular fuzzy numbers and aggregated component-wise using the geometric mean before fuzzy weighting, defuzzification, and normalization. Results reveal that the industrial sector (0.385) and urbanization (0.208) are the most influential drivers of energy demand, reflecting the energy-intensive nature of manufacturing and the growing reliance on air conditioning in households. Economic growth and transportation also play substantial roles, whereas climate conditions and the residential sector were less significant. Among alternatives, sustainable urban form (0.322) and sustainable infrastructure (0.301) ranked highest, supported by energy-efficient buildings and urban greening. These findings align with global studies emphasizing efficiency and infrastructure as pillars of sustainable urban planning, while reflecting Saudi-specific priorities. The study highlights FAHP's utility in structuring expert judgment under uncertainty and provides actionable insights for integrating energy efficiency into Saudi Vision 2030, offering a balanced framework for managing the country's energy transition.

Keywords: Energy Consumption, FAHP, Saudi Arabia, Industrial Sector, Residential Energy Demand, Urbanization, Climate Conditions

1. Introduction

Urbanization and socioeconomic growth are placing immense pressure on environmental sustainability. By 2050, nearly 68% of the world's population, about 9.7 billion will live in cities, with Asia and Africa accounting for most of this increase. Although cities cover only 2% of the Earth's surface, they consume up to 75% of global energy and produce over 75% of CO2 emissions, making them central contributors to climate change and its associated risks, including extreme weather events, sea-level rise, and public health challenges (World Bank, 2022; Seto et al., 2012; Dano et al., 2023). Energy consumption is a critical driver of development, and Saudi Arabia is no exception. Since urban areas house over half of the world's population, consume nearly two-thirds of global energy, and generate about three-quarters of greenhouse gas emissions, effective urban development and governance are central to climate mitigation strategies (UN-Habitat, 2022). As a nation undergoing rapid economic growth and industrialization, Saudi Arabia faces the dual challenge of meeting its rising energy demand while ensuring long-term sustainability (Rimi and Lawal, 2020). Understanding the key drivers of energy consumption and identifying effective solutions is therefore essential for enhancing efficiency, reducing environmental impacts, and strengthening energy security.

Previous studies provide valuable insights into the energy–growth nexus, confirming that energy often plays a contributory role in stimulating economic expansion. For example, Caraiani et al. (2015) demonstrated strong linkages between energy use and GDP in Eastern European economies, while Fernandes and Reddy (2020) reported long-term cointegration between the two in six newly industrialized Asian economies, with causality patterns varying by country. In Saudi Arabia, Al Shammre et al. (2024) highlighted the persistent tension between economic expansion and emission reduction, showing that growth continues to drive energy demand. Among the structural energy-consumption drivers, urbanization is a major driver, intensifying industrial activity, electricity consumption, and transport demand. Cross-country evidence confirms its positive correlation with energy use (Ma et al., 2024), while Saudi-specific studies show that GDP and urban population are significant causal drivers of road-transport energy demand (Javid, 2024). The industrial sector also exerts a powerful influence: Saudi industrial energy consumption grew by about 8.3% annually between 1990 and 2019 (Alajmi, 2024), and nearly 46% of the country's direct CO_2 emissions originate from industry, underscoring its outsized role in national energy and emissions (Almogbel et al., 2020).

The residential sector contributes heavily to electricity demand. Buildings account for more than half of Saudi electricity consumption, with roughly two-thirds of that load stemming from air conditioning (Krarti and Howarth, 2020). Efficiency improvements could mitigate this demand; studies show that widespread adoption of high-efficiency air conditioners could substantially reduce residential consumption (Rahman et al., 2022). The transport sector is similarly central, with evidence confirming that energy demand is tightly coupled with both GDP and urbanization (Howarth et al., 2020). Moreover, transport remains a growing source of CO_2 emissions, reinforcing its dual significance in energy and environmental planning (Al Shammre, 2024). Climatic conditions further intensify these pressures. Extreme heat has been shown to sharply increase demand for air conditioning, making energy consumption highly climate-sensitive (Howarth et al., 2020). Cooling Degree-Day analyses suggest that future warming will exacerbate these trends, raising electricity requirements and complicating long-term planning (Mehmood et al., 2023).

Recent studies have emphasized the role of energy and exergy analysis in identifying major sources of inefficiency in power generation and industrial processes. Elwardany et al. (2023, 2024a) found that combustion chambers, boilers, and heat-recovery systems account for a substantial share of exergy destruction in gas-turbine and combined-cycle power plants, while higher ambient temperatures reduce efficiency and power output. Broader reviews similarly show that improving combustion conditions, heat recovery, steam parameters, materials, and operating pressure can significantly enhance thermal-power performance and reduce environmental impacts (Elwardany, 2024; Elwardany et al., 2024b). Industrial energy research also highlights the importance of process optimization and technological innovation. Rafeek et al. (2025a) and Rafeek et al. (2025b) showed that crude-distillation efficiency can be improved through heat integration, advanced control, exergy analysis, process intensification, solar-assisted heating, and AI-based optimization. High-temperature heat pumps also offer strong potential for recovering waste heat and reducing industrial emissions, although their adoption depends on cost, refrigerants, and system integration (Elwardany et al., 2026).

Renewable-energy studies further demonstrate the value of computational modelling and integrated systems. Abdelrazik et al. (2022, 2023, 2026) showed that photovoltaic/thermal, phase-change-material, and concentrating solar systems can improve building and solar-energy performance when design, cooling, storage, radiation, and climatic conditions are properly optimized. Solar-powered desalination systems also provide opportunities to reduce energy demand in water production, particularly in regions with abundant solar resources (Elwardany et al., 2024c). Recent research further demonstrates that energy sustainability depends on the coordinated development of renewable generation, storage, smart-grid management, and climate-responsive building systems. Al-Ashwal et al. (2026) found photovoltaic grid parity to be technically, economically, and environmentally viable in Yemen, illustrating how distributed solar systems can enhance electricity access while reducing carbon emissions. However, renewable-energy expansion must be accompanied by reliable storage and grid-management systems. Riffat and Samaei (2026) showed that increasing renewable intermittency reduced the energy reliability and load-matching performance of phase-change-material thermal storage, highlighting the importance of evaluating not only stored energy but also its availability during periods of demand. Similarly, Danaci and Akkaya (2026) demonstrated that deep-learning-based detection of power-quality disturbances can improve smart-grid efficiency and reliability, with their one-dimensional convolutional neural network achieving greater classification accuracy than the time-frequency model. These findings emphasize that sustainable infrastructure requires the integration of renewable generation, storage reliability, intelligent monitoring, and demand-responsive operation.

Advances in building-energy technologies also provide important pathways for reducing cooling demand and strengthening resilience under changing climatic conditions. Samaei and Riffat (2026) proposed a self-healing digital twin that combined physics-based modelling, data assimilation, and adaptive control to preserve thermal comfort and operational stability under heatwaves, occupancy changes, sensor drift, and equipment degradation. Wu et al. (2026) demonstrated that combining seasonal shading with a fan-assisted Trombe wall reduced total annual energy use while improving thermal comfort, although the results also revealed seasonal operational trade-offs. Razak et al. (2026) further developed an integrated experimental and predictive-modelling framework for thermoelectric HVAC systems, linking machine-learning prediction with thermodynamic validation and an interactive decision-support interface. Collectively, these studies show that energy-efficient buildings increasingly depend on climate-responsive design, adaptive digital control, predictive modelling, and the practical deployment of intelligent energy-management tools. However, most of these studies focus on individual technologies or facilities. Limited research has systematically prioritized the broader structural drivers of energy consumption and sustainable policy alternatives in Saudi Arabia, which provides the justification for the present FAHP study.

Several local studies corroborate these findings. For example, Mezghani and Ben Haddad (2017) confirmed strong linkages between electricity use, GDP, and emissions across both oil and non-oil sectors, while Jaber et al. (2019) identified the industrial and transportation sectors as the highest energy consumers. Warsame (2022) further demonstrated that population growth, urbanization, and economic development are key drivers of rising demand, reinforcing the importance of integrating these variables into energy policy and planning. Figure 1 illustrates the historical growth in Saudi Arabia's energy consumption between 2001 and 2019, demonstrating the sustained increase in demand associated with rapid economic growth, population expansion, and urbanization prior to the structural changes introduced by the COVID-19 pandemic and the acceleration of Vision 2030 energy reforms. Similarly, Figure 2 presents historical residential electricity consumption over the same period, highlighting the long-term increase in household energy demand that motivated the present investigation.

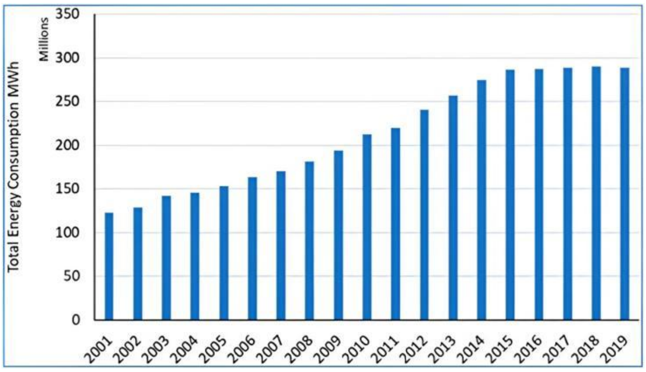

Figure 1. Historical trend of total energy consumption in Saudi Arabia (2001–2019) (Aldhubaib, 2022)

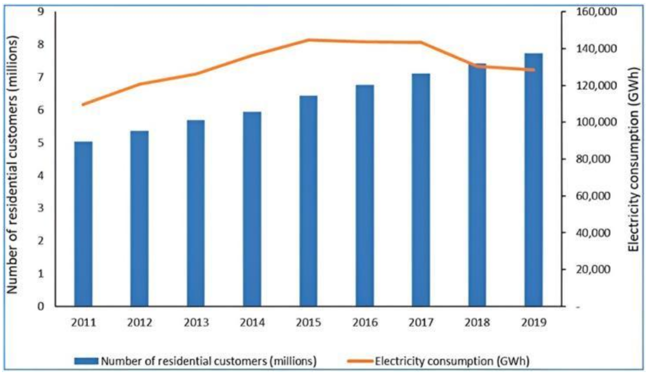

Figure 2. Historical trend of residential electricity consumption in Saudi Arabia (2001–2019) (Aldhubaib, 2022)

The existing literature has substantially improved the understanding of energy consumption in Saudi Arabia and the GCC. Previous studies have primarily examined the relationships between energy consumption, economic growth, urbanization, industrial development, residential electricity demand, transportation, and climate using econometric analyses, machine-learning models, engineering simulations, and energy-exergy assessments (Al Shammre, 2024; Elwardany et al., 2024a; Rahman et al., 2022; Rafeek et al., 2025a; Mezghani and Haddad, 2017). In parallel, multi-criteria decision-making (MCDM) techniques have been increasingly applied to renewable-energy planning and infrastructure development (Table 1). For example, Al Garni and Awasthi (2017a) and Al Garni and Awasthi (2017b) employed GIS-AHP and fuzzy AHP-GIS approaches to prioritize utility-scale solar photovoltaic sites in Saudi Arabia, while Rehman et al. (2020) optimized onshore wind-farm layouts. More recently, Almasad et al. (2022) integrated GIS with fuzzy MCDM to evaluate solar PV site suitability, and Amiri et al. (2024) proposed an AHP-TOPSIS framework for renewable-energy source selection in Saudi Arabia. Furthermore, Shao et al. (2020) demonstrated through a comprehensive review that most MCDM applications in the energy sector focus on renewable-energy technology selection, project sitting, and resource assessment.

Despite these important contributions, important research gaps remain. Existing studies have generally focused either on identifying the determinants of energy demand using conventional analytical techniques or on supporting renewable-energy planning through technology selection and site-suitability assessment. Consequently, they do not provide a structured prioritization of the relative importance of multiple national energy-consumption drivers alongside competing sustainable policy interventions within a unified decision-support framework. Moreover, applications of the Fuzzy Analytic Hierarchy Process (FAHP) in Saudi Arabia have remained relatively limited and have largely concentrated on renewable-energy planning, environmental management, or other sector-specific applications rather than comprehensive national energy policy. This study addresses these gaps by applying FAHP to simultaneously evaluate the relative importance of six key energy-consumption drivers, namely economic growth, industrial activity, urbanization, residential demand, transportation, and climate conditions, together with five sustainable alternatives for reducing energy consumption. By integrating expert judgment within a transparent fuzzy multi-criteria decision-making framework, supported by consistency-ratio assessment, systematic aggregation of expert opinions, and sensitivity analysis, the study provides a comprehensive decision-support tool for sustainable energy planning and contributes practical evidence to support the implementation of Saudi Vision 2030. Table 1 compares representative MCDM and FAHP studies with the present research. The comparison demonstrates that previous applications have primarily concentrated on renewable-energy technology selection, wind- and solar-energy planning, or spatial site suitability. By contrast, the present study applies FAHP to jointly prioritize the principal drivers of national energy consumption and sustainable policy interventions, thereby extending the application of MCDM from project-level decision-making to strategic national energy planning under Saudi Vision 2030.

Table 1. Comparative analysis of previous MCDM/FAHP studies and the contribution of the present research

Study	Country/Context	Method	Research focus	Limitation relative to the present study
Al Garni & Awasthi (2017a)	Saudi Arabia	GIS–AHP	Utility-scale solar PV site selection	Focuses on identifying suitable PV locations rather than evaluating national energy-consumption drivers.
Al Garni & Awasthi (2017b)	Saudi Arabia	Fuzzy AHP–GIS	Prioritization of utility-scale solar PV sites under uncertainty	Limited to renewable-energy site selection and does not consider broader energy-demand determinants.
Rehman et al. (2020)	Saudi Arabia	Heuristic optimization	Onshore wind-farm siting and layout optimization	Focuses on wind-farm design and energy production rather than national energy planning.
Almasad et al. (2022)	Saudi Arabia	GIS–Fuzzy MCDM	Solar PV site suitability assessment	Addresses spatial suitability for solar-energy deployment without evaluating energy-consumption drivers or policy alternatives.
Amiri et al. (2024)	Saudi Arabia	AHP–TOPSIS	Renewable-energy source selection	Compares renewable-energy technologies but does not prioritize the underlying drivers of national energy demand.
Asakereh et al. (2017)	Iran	GIS–Fuzzy AHP	Solar farm location suitability	Focuses on renewable-energy siting rather than integrated national energy planning.
Merrouni et al. (2018)	Morocco	GIS–AHP	Large-scale PV site selection	Emphasizes project location selection without considering cross-sectoral energy-demand drivers.
Shao et al. (2020)	International	Review of MCDM applications	Review of renewable-energy site-selection methods	Reviews methodological developments but does not propose an integrated framework for prioritizing national energy-consumption drivers.
Present study	Saudi Arabia	FAHP	Joint prioritization of six national energy-consumption drivers and five sustainable policy alternatives	Provides an integrated demand-side decision-support framework by simultaneously evaluating structural energy-consumption drivers and sustainable interventions. The study further strengthens methodological transparency through expert profiling, consistency-ratio assessment, fuzzy geometric aggregation, and sensitivity analysis.

2. Materials and Method

2.1. Study Setting

Saudi Arabia, the largest country in the Middle East, spans approximately 2.15 million square kilometers and occupies nearly 80% of the Arabian Peninsula (CIA, 2019). Strategically located at the intersection of Asia, Africa, and Europe, the country's diverse physical landscape is dominated by deserts, mountain ranges, and limited arable land (Figure 3). The nation experiences an arid climate with scarce rainfall, high evapotranspiration, and rising average annual temperatures projected to exceed global warming trends (Darfaoui and Al Assiri, 2015). Although it has limited arable land, around 2%, the country's geography is dominated by deserts and mountain ranges, with agriculture largely restricted to dates, vegetables, and fruits (Al-Maamary et al., 2017). Saudi Arabia's population is about 34.6 million, with nearly 84% living in urban areas, and is projected to reach 37.6 million by 2025 (World Population Review, 2025; GAS, 2010). The country is divided into 13 administrative regions, with population density ranging widely from 118.7 persons per km² in Jazan to just 2.9 in the Northern Borders (Gazzeh and Abubakar, 2018). Economically, Saudi Arabia remains the wealthiest nation in the Middle East and North Africa, with a GDP of USD 1.775 trillion in 2017, and is endowed with vast mineral resources, 15.6% of global oil reserves, and the world's largest crude oil exports (CIA, 2019) (BP, 2017).

The present study focuses on analyzing the factors contributing to energy consumption and prioritizing sustainable solutions. The study encompasses various sectors, including residential, industrial, and transportation, as well as relevant policies and climate conditions. Data collection and analysis are carried out to provide insights and recommendations for energy management and decision-making in the country.

Figure 3. Map of Saudi Arabia showing its 13 administrative provinces, international borders, and coastlines along the Red Sea and Arabian Gulf

2.2. Data Collection and Analysis

This study employed the FAHP to evaluate the relative importance of factors influencing energy consumption in Saudi Arabia and to prioritize potential sustainable alternatives. FAHP was selected as it combines the structured decision-making framework of the traditional AHP with the flexibility of fuzzy logic, allowing for the handling of uncertainty and imprecision in expert judgments. The factors and alternatives considered in this study were identified through an extensive literature review. Multiple academic databases and search engines, including Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar, were systematically explored using relevant keywords such as energy consumption energy-consumption drivers, urbanization and energy demand, industrial sector energy use, residential energy consumption, transportation energy, climate change and energy demand, and sustainable energy solutions. The inclusion criteria focused on peer-reviewed articles published between 2000 and 2026 that examined the drivers of energy consumption, sustainable technologies, and energy-management strategies within Saudi Arabia, the GCC, and comparable international contexts. This process yielded a refined set of six energy-consumption drivers: economic growth, urbanization, industrial sector, residential sector, transportation sector, and climate conditions, and five alternatives: energy-efficient buildings, sustainable infrastructure, low-carbon transportation, sustainable urban form, and urban greening.

The final criteria and alternatives were selected through a multi-stage consolidation process. First, the literature search generated a broader list of economic, demographic, sectoral, climatic, technological, regulatory, and behavioural factors associated with energy consumption. Second, conceptually overlapping variables were grouped under broader dimensions to avoid redundancy in the pairwise comparison model. For example, population concentration, land-use expansion, and growth in municipal services were incorporated within urbanization, while manufacturing expansion, industrial production, and process-energy demand were grouped under the industrial-sector criterion. Air-conditioning demand, heat exposure, and seasonal temperature effects were represented under climate conditions and residential energy demand, depending on whether their primary influence was environmental or building-related. Third, the candidate criteria were assessed against four inclusion requirements: relevance to national energy demand, support in Saudi or GCC literature, conceptual distinctiveness, and suitability for expert pairwise comparison. The final six criteria were those that satisfied all four requirements and collectively represented the principal structural, sectoral, and environmental dimensions of Saudi energy consumption.

Several relevant variables were not included as independent criteria to maintain a manageable and non-redundant FAHP hierarchy. Energy pricing, electricity tariffs, and subsidy reform were treated as policy instruments that influence the six principal demand drivers rather than as independent physical or structural sources of consumption. Renewable-energy penetration was considered primarily a supply-side transition variable and was therefore reflected in the sustainable alternatives rather than included as a consumption driver. Building codes and industrial-efficiency regulations were similarly treated as implementation mechanisms associated with energy-efficient buildings and sustainable infrastructure. Behavioural factors were excluded because of their considerable heterogeneity across households, firms, and regions and because their reliable assessment would require a separate behavioural survey. These exclusions do not imply that the variables are unimportant; rather, they define the analytical boundary of the present study and are acknowledged as priorities for future model expansion. The treatment of the candidate variables is summarized in Table 2, which distinguishes the six factors retained as primary evaluation criteria from variables treated as policy instruments, implementation mechanisms, supply-side considerations, or areas for future research.

Table 2. Inclusion and treatment of candidate energy-consumption variables

Candidate variable	Treatment in the model	Justification
Economic growth	Included as a criterion	Broad structural driver of production, mobility, infrastructure, and electricity demand
Urbanization	Included as a criterion	Captures population concentration, urban expansion, service demand, and land-use change
Industrial activity	Included as a criterion	Represents manufacturing, refining, processing, and industrial electricity and fuel demand
Residential demand	Included as a criterion	Captures household electricity use, appliances, cooling, and building-related consumption
Transportation	Included as a criterion	Represents mobility demand, fuel use, and urban transport pressures
Climate conditions	Included as a criterion	Captures heat exposure, seasonal demand, humidity, and cooling-related pressures
Energy pricing and tariffs	Excluded as an independent criterion	Treated as policy instruments affecting demand across multiple sectors
Subsidy reform	Excluded as an independent criterion	Considered a policy mechanism rather than an underlying consumption driver
Renewable-energy penetration	Reflected in alternatives	Primarily relates to supply diversification and sustainable-system transition
Building codes	Reflected in alternatives	Implementation instrument for energy-efficient buildings
Industrial-efficiency regulations	Reflected in alternatives	Policy mechanism for cleaner industrial processes and sustainable infrastructure
Behavioural factors	Reserved for future research	Require household- or firm-level behavioural data beyond the present expert model

As shown in Table 2, the model prioritizes broad and conceptually distinct drivers of national energy consumption, while variables such as tariffs, subsidy reform, building codes, and industrial-efficiency regulations are treated as policy instruments or implementation mechanisms rather than independent consumption drivers.

Care was taken to ensure that the collective expertise of the panel adequately covered each of the six evaluation criteria, including economic growth, industrial development, urbanization, residential energy demand, transportation systems, and climate-related energy impacts. To ensure the reliability and credibility of the FAHP analysis, expert judgments were obtained from a purposively selected panel of seven specialists with extensive expertise in energy systems, urban planning, environmental engineering, industrial sustainability, transportation planning, climate adaptation, and sustainable development. Experts were selected based on four criteria: (i) possession of a relevant postgraduate qualification or an equivalent professional qualification supported by substantial sectoral experience; (ii) a minimum of ten years of professional or research experience; (iii) demonstrated expertise through peer-reviewed publications, professional practice, or policy development related to energy, urban sustainability, or environmental management; and (iv) familiarity with the Saudi Arabian or Gulf regional context. The panel deliberately included experts from different institutional sectors to ensure balanced perspectives across the six evaluation criteria investigated in this study, namely economic growth, urbanization, industrial sector, residential sector, transportation sector, and climate conditions. The panel comprised university academics, government practitioners, engineering consultants, and sustainability specialists.

To preserve participant confidentiality while enhancing methodological transparency, anonymized profiles of the experts are presented in Table 3. Although the panel consisted of seven experts, this number is consistent with recommendations for expert-based multi-criteria decision-making studies where participants possess substantial domain expertise. Previous FAHP and AHP studies have similarly employed relatively small expert panels, including eight experts (Dahri and Abida, 2017), nine experts (Danumah et al., 2016; Papaioannou et al., 2015), ten experts (Abbas and Routray, 2014; Gigović et al., 2017), sixteen experts (Ouma and Tateishi, 2014), and eighteen experts (Dano et al., 2023). Furthermore, Saaty and Özdemir (2014) argue that decision quality depends more on the expertise of panel members than on the absolute number of experts.

Table 3. Anonymized Profile of the Expert Panel

Expert	Primary Expertise	Sector	Highest Qualification	Professional Experience	Main Contribution
E1	Energy Engineering	University	PhD	13 years	Industrial energy systems
E2	Urban Planning	University	PhD	15 years	Urbanization and sustainable cities
E3	Environmental Engineering	Government	MSc	17 years	Climate and environmental management
E4	Industrial Sustainability	Industry	MSc	20 years	Industrial energy efficiency
E5	Transportation Planning	Government	Bachelor	14 years	Transport energy demand
E6	Sustainable Development	Consultancy	MSc	16 years	Sustainable infrastructure
E7	Energy Policy	University	PhD	10 years	National energy policy and Vision 2030

Structured pairwise comparison questionnaires were administered independently to the seven experts. Each expert completed two full reciprocal comparison matrices: a 6×6 matrix comparing the six factors influencing energy consumption and a 5×5 matrix comparing the five sustainable alternatives. The experts did not complete the questionnaires collectively, and no consensus discussion was conducted before the individual judgments were recorded. Each expert was therefore able to express an independent professional assessment. The group FAHP analysis was implemented in seven sequential steps. First, the internal consistency of each expert's original crisp pairwise comparison matrices was evaluated using the Consistency Index and Consistency Ratio described in Section 2.3. Matrices with CR ≥ 0.10 were reviewed and revised before being retained for group aggregation. Second, each accepted crisp judgment on Saaty's 1–9 scale was transformed into its corresponding triangular fuzzy number, using the fuzzy conversion scale presented in Table 4. Third, the seven individual fuzzy matrices were combined into one group fuzzy comparison matrix by aggregating each corresponding comparison element component-wise using the geometric mean:

$$\tilde{a}_{ij}^{G} = \left(\prod_{k=1}^{K} l_{ij}^{(k)} \right)^{1/K}, \left(\prod_{k=1}^{K} m_{ij}^{(k)} \right)^{1/K}, \left(\prod_{k=1}^{K} u_{ij}^{(k)} \right)^{1/K} \tag{1}$$

where $\tilde{a}_{ij}^{G}$ is the aggregated fuzzy judgment for items i and j, $K = 7$ is the number of experts, and

l, m, and u represent the lower, modal, and upper values of the triangular fuzzy number, respectively. All experts were assigned equal weight because each participant met the predetermined eligibility requirements and was considered to possess relevant domain expertise. Accordingly, no expert judgment was given greater influence than another. Fourth, disagreements among the experts were accommodated through geometric aggregation rather than eliminated through arithmetic averaging or majority voting. The geometric mean moderates extreme judgments while preserving the reciprocal structure of the pairwise comparison matrix. No individual matrix was excluded as an outlier after it satisfied the required consistency threshold. Fifth, following Buckley's (1985) fuzzy geometric mean method, the fuzzy geometric mean for each row of the aggregated group matrix was calculated as:

$$\tilde{r}_i = \left(\prod_{j=1}^{n} \tilde{a}_{ij}^{G}\right)^{1/n} \tag{2}$$

where represents the number of factors or alternatives. Sixth, the fuzzy priority weight of each item was obtained by normalizing its fuzzy row geometric mean:

$$\tilde{\omega}_i = \tilde{r}_i \otimes \left(\tilde{r}_1 \oplus \tilde{r}_2 \oplus \cdots \oplus \tilde{r}_n\right)^{-1} \tag{3}$$

Seventh, the resulting fuzzy weights were defuzzified using the centroid method:

$$D\left(\tilde{\omega}_i\right) = \frac{l_i + m_i + u_i}{3} \tag{4}$$

The defuzzified values were subsequently normalized so that their sum equaled one, and the factors and alternatives were ranked from the highest to the lowest normalized weight. Thus, aggregation of the seven experts' judgments occurred at the fuzzy comparison-matrix stage and before the calculation of fuzzy weights, defuzzification, and final normalization.

Table 4. Fuzzy Pairwise Comparison Scale

Linguistic Variable	Saaty's Scale	Fuzzy Triangular Number (l, m, u)	Reciprocal (l^{-1}, m^{-1}, u^{-1})
Equal importance	1	(1, 1, 1)	(1, 1, 1)
Weak importance	2	(1, 2, 3)	(1/3, 1/2, 1)
Moderate importance	3	(2, 3, 4)	(1/4, 1/3, 1/2)
Moderate plus importance	4	(3, 4, 5)	(1/5, 1/4, 1/3)
Strong importance	5	(4, 5, 6)	(1/6, 1/5, 1/4)
Strong plus importance	6	(5, 6, 7)	(1/7, 1/6, 1/5)
Very strong importance	7	(6, 7, 8)	(1/8, 1/7, 1/6)
Very, very strong importance	8	(7, 8, 9)	(1/9, 1/8, 1/7)
Extreme importance	9	(9, 9, 9)	(1/9, 1/9, 1/9)

2.3. Consistency Assessment of the Pairwise Comparison Matrices

To ensure the reliability of the pairwise comparisons provided by the experts, the consistency of each judgment matrix was evaluated using Saaty's Consistency Index (CI) and Consistency Ratio (CR). The consistency measures were computed using:

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{5}$$

$$CR = \frac{CI}{RI} \tag{6}$$

where $\lambda_{\max}$ is the principal eigenvalue of the comparison matrix, n is the number of criteria (or alternatives), and RI is Saaty's Random Index. A matrix was considered acceptable when $CR < 0.10$ (Saaty and Özdemir, 2014). The initial expert judgments were assessed individually. Matrices exceeding = 0.10 were returned to the corresponding experts together with consistency diagnostics. The experts reconsidered the judgments responsible for the largest inconsistencies while retaining the reciprocal structure and the original 1-9 comparison scale. The revised matrices were then reassessed, and only matrices satisfying < 0.10 were retained for group aggregation as illustrated in Table 5.

Table 5. Consistency assessment of the experts' pairwise comparison matrices before and after revision

Matrix	Expert	Original λ_{max}	Original CI	Original CR	Adjusted λ_{max}	Adjusted CI	Adjusted CR
Criteria	E1	8.576	0.515	0.416	6.514	0.103	0.083
Criteria	E2	12.544	1.309	1.055	6.605	0.121	0.098
Criteria	E3	6.801	0.160	0.129	6.244	0.049	0.039
Criteria	E4	7.790	0.358	0.289	6.421	0.084	0.068
Criteria	E5	7.208	0.242	0.195	6.374	0.075	0.060
Criteria	E6	6.237	0.047	0.038	6.130	0.026	0.021
Criteria	E7	7.510	0.302	0.244	6.361	0.072	0.058
Alternatives	E1	11.052	1.513	1.351	5.365	0.091	0.081
Alternatives	E2	6.478	0.370	0.330	5.286	0.072	0.064
Alternatives	E3	5.517	0.129	0.116	5.143	0.036	0.032
Alternatives	E4	11.383	1.596	1.425	5.291	0.073	0.065
Alternatives	E5	5.993	0.248	0.222	5.218	0.055	0.049
Alternatives	E6	5.151	0.038	0.034	5.071	0.018	0.016
Alternatives	E7	6.112	0.278	0.248	5.200	0.050	0.045

3. Results and Discussion

Although the historical energy trends presented in Figures 1 and 2 conclude in 2019, the prioritization of energy-consumption drivers reflects current expert knowledge and incorporates evidence from recent studies published through 2026, thereby maintaining the relevance of the findings to Saudi Arabia's ongoing energy transition under Vision 2030. The results of the FAHP provide a clear prioritization of both the energy-consumption drivers and the alternative strategies to address them. By applying Buckley's fuzzy GMM, the aggregated judgments of the seven experts were transformed into defuzzified and normalized weights, ensuring that uncertainty in expert assessments was adequately captured. The reported priorities represent the aggregated judgments of a multidisciplinary panel of experts drawn from academia, government, consultancy, and industry, thereby incorporating multiple professional perspectives into the evaluation process.

3.1. Factors Influencing Energy Consumption

The analysis of energy-consumption drivers highlighted that industrial sector (0.382) and urbanization (0.210) carry the highest relative importance, followed closely by economic growth (0.142) and transportation sector (0.122) pressures (Table 6). These four energy-consumption drivers collectively accounted for the majority of the overall weight, underscoring their centrality in shaping urban sustainability outcomes. By contrast, residential sector expansion and climate conditions were rated lower with 0.098 and 0.046 respectively, suggesting that while these remain relevant, their direct impact is comparatively less significant when viewed through the lens of expert consensus. This finding aligns with broader regional research. For example, Brahmia and Mannai (2024) confirm that rapid industrialization and economic expansion in the Gulf Cooperation Council (GCC) countries significantly drive environmental degradation and carbon emissions, often exceeding the capacity of existing regulatory frameworks. Similarly, Amer et al. (2022) document how accelerated economic growth and urbanization in the GCC lead to higher consumption of natural resources, fueling unsustainable land-use trends and ecological strain.

The relatively low weight assigned to climate conditions (0.046) warrants careful interpretation because it appears counterintuitive for a country characterized by extreme temperatures, prolonged cooling seasons, and rapidly increasing electricity demand for air conditioning. Rather than suggesting that climate is unimportant, the finding indicates that, within the context of the FAHP pairwise comparisons, the expert panel perceived climate as exerting a more indirect influence on national energy consumption than structural drivers such as industrial activity, urbanization, and economic growth. One possible explanation is that the experts evaluated climate as a relatively stable background condition, whereas industrial expansion and urban development represent more immediate and policy-responsive determinants of energy demand. Another plausible explanation is familiarity bias, whereby experts working primarily in energy systems, urban planning, or industrial development may naturally emphasize anthropogenic drivers over environmental variables.

Furthermore, the broad criterion "climate conditions" may have combined several distinct influences, including cooling demand, seasonal variability, humidity, heatwaves, and long-term climate change, thereby reducing its perceived importance relative to more narrowly defined criteria. Future studies could therefore disaggregate climate into multiple sub-criteria to examine whether specific dimensions, particularly cooling degree days, projected temperature increases, or seasonal electricity demand, receive higher relative importance. This interpretation is consistent with previous studies demonstrating that although extreme temperatures substantially increase electricity consumption for cooling in Saudi Arabia, much of this demand is ultimately mediated through urban development patterns, building characteristics, and population growth (Howarth et al., 2020; Mehmood et al., 2023; Albalawi, 2025). Consequently, the low ranking should not be interpreted as evidence that climate is insignificant, but rather that experts regarded it as operating primarily through other structural drivers rather than as an independent determinant of energy consumption.

Prior to aggregating expert judgments, all pairwise comparison matrices were examined for consistency. Following minor revisions to matrices with CR values greater than 0.10, all matrices achieved acceptable consistency levels (CR < 0.10). The corrected matrices were subsequently aggregated using the geometric mean to obtain the fuzzy weights and rankings presented in Tables 6 and 7.

Table 6. FAHP weights, normalized priorities, and rankings of the energy-consumption drivers

Energy-consumption drivers	Fuzzy geometric mean	Fuzzy weights	Defuzzified normalized weights	%	Ranking
Economic growth	0.112,0.142,0.180	0.142	0.142	14	3
Urbanization	0.157,0.208,0.276	0.208	0.210	21	2
Industrial sector	0.304,0.384,0.481	0.385	0.382	38	1
Residential sector	0.075,0.098,0.127	0.097	0.098	10	5
Transportation sector	0.097,0.122,0.156	0.123	0.122	12	4
Climate condition	0.035,0.045,0.061	0.045	0.046	5	6

Moreover, comparative charts of the energy-consumption drivers and alternatives (Figures 4 and 5) provide a clear and accessible visual representation of the study’s findings. These figures not only highlight the relative weights derived through the FAHP process but also allow for straightforward comparison across categories. In Figure 4, the energy-consumption drivers’ chart visually demonstrates how energy-consumption drivers such as industrial activity, urbanization, and economic growth carry greater significance compared to climate-related conditions, reinforcing the quantitative results presented in the tables. The industrial sector received approximately 38% of the overall priority weight, suggesting that interventions targeting industrial energy efficiency are expected to generate substantially greater national energy savings than equivalent investments directed solely toward residential or climate-related measures. Consequently, policymakers should prioritize industrial modernization, cleaner production technologies, and process optimization while simultaneously supporting sustainable urban development and energy-efficient buildings.

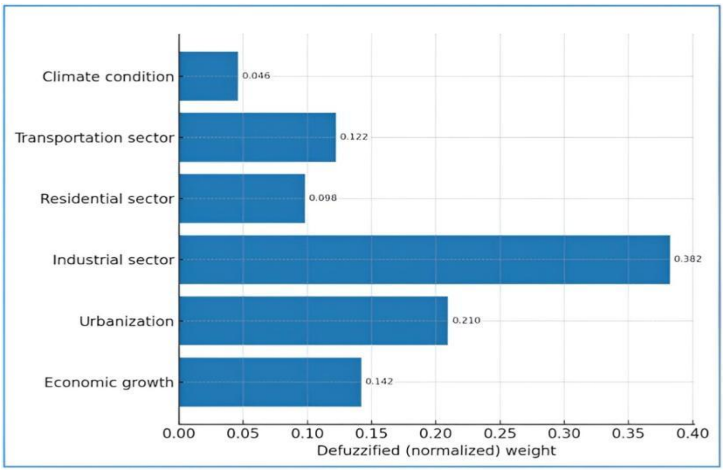

Figure 4. Defuzzified weights of energy-consumption drivers contributing to high energy consumption in Saudi Arabia

3.2. Sustainable Alternatives for Reducing Energy Consumption

The FAHP analysis of alternatives as illustrated in Table 7 revealed that sustainable urban form (0.324) and sustainable infrastructure (0.303) emerged as the top-ranked strategies, with nearly equal defuzzified weights. This indicates that experts view both building design and hard infrastructure development as the most impactful pathways to mitigate sustainability challenges. Energy-efficient buildings and urban greening followed in the ranking, while low-carbon transportation received a lower relative weight, although still considered relevant. These results align with global sustainability literature that positions infrastructure and building efficiency as foundational to resilient urban planning. For example, Rimi and Lawal (2020) and Kustova et al. (2024) emphasizes the pressing need for sustainable urban form and sustainable infrastructure development that aligns with the Sustainable Development Goals (SDGs), highlighting their critical role in transitioning urban systems toward environmental resilience.

Similarly, Konhäuser and Werner (2024) provide empirical evidence that energy-efficient building features such as improved insulation and systems deliver substantial financial and emission-reduction co-benefits across urban environments. The importance of sustainable urban form and greening is supported by Lefosse et al. (2025), who demonstrates how biophilic urbanism enhances livability and environmental health within dense urban contexts. Conversely, the relatively lower ranking of low-carbon transportation in this context stands in contrast to European policy trends, where decarbonizing transport has become a strategic priority, embedded in frameworks aimed at delivering energy-efficient, zero-emission mobility by 2030 and beyond (Nikolaidou et al., 2024). These references collectively substantiate the prioritization of infrastructure and buildings found in the FAHP analysis while illustrating how regional contexts may modify the role of transport in sustainability agendas.

Although low-carbon transportation received the lowest priority among the evaluated alternatives, this finding should not be interpreted as implying that transportation is unimportant in Saudi Arabia. Rather, it suggests that the expert panel perceived interventions in sustainable infrastructure and urban form as having broader and more immediate cross-sectoral benefits for reducing national energy consumption. Investments in energy-efficient buildings, integrated infrastructure, and sustainable urban development simultaneously influence residential, commercial, and industrial energy demand, thereby generating system-wide efficiency gains beyond the transport sector alone. In contrast, many transportation interventions primarily target mobility-related energy use and often require complementary investments in supporting infrastructure, regulatory reforms, and behavioural change before their full benefits can be realized. This interpretation is also consistent with Saudi Vision 2030, which places strong emphasis on sustainable infrastructure, urban transformation, energy-efficient buildings, and integrated city development as key pillars for improving energy efficiency and reducing carbon emissions. Consequently, the lower ranking of low-carbon transportation should be viewed as a relative prioritization within the FAHP framework rather than as an indication that transport decarbonization is of limited importance.

Table 7. FAHP weights, normalized priorities, and rankings of the sustainable alternatives

Alternatives	Fuzzy geometric mean	Fuzzy weights	Defuzzified normalized weights	%	Ranking
Energy-efficient buildings	0.110,0.146,0.195	0.152	0.147	15	3
Sustainable infrastructure	0.247,0.305,0.376	0.301	0.303	30	2
Low-carbon transportation	0.071,0.093,0.125	0.092	0.094	9	5
Sustainable urban form	0.256,0.326,0.410	0.322	0.324	32	1
Urban greening	0.102,0.130,0.167	0.133	0.130	13	4

Similarly, Figure 5 illustrates the prioritization of alternatives, showing that sustainable urban form, sustainable infrastructure, and energy-efficient buildings dominate as the most effective strategies, while options such as urban greening and low-carbon transport receive comparatively lower weights. Presenting the results in chart form enhances interpretability by enabling readers to quickly grasp both the magnitude and hierarchy of priorities, thus bridging the gap between numerical outputs and practical insights.

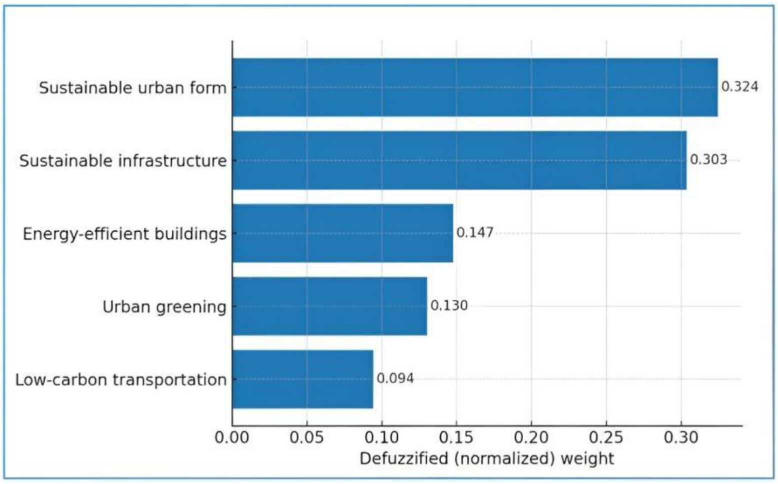

Figure 5. Defuzzified weights of alternatives for mitigating high energy consumption in Saudi Arabia

A notable observation is the alignment between high-ranked energy-consumption drivers and the corresponding alternatives. For instance, the prominence of industrialization and urbanization as key energy-consumption drivers is directly addressed by the prioritization of sustainable infrastructure and energy-efficient buildings, both of which can mitigate the environmental and resource stresses associated with rapid development. Similarly, transportation sector pressures are reflected in the inclusion of low-carbon transportation, albeit at a lower relative weight, suggesting that while recognized, transport interventions are currently seen as secondary compared to infrastructure and building-focused strategies.

From a policy perspective, the results suggest that urban sustainability in Saudi Arabia should be tackled primarily through integrated infrastructure planning and energy-efficient building regulations, supported by secondary initiatives in urban greening and sustainable spatial form. These interventions not only respond directly to the most pressing energy-consumption drivers but also align with Saudi Vision 2030, which emphasizes sustainable infrastructure and urban resilience as national priorities. The study therefore provides an evidence-based framework for urban planners and policymakers to strategically allocate resources to the areas of greatest impact.

3.3. Sensitivity Analysis

A sensitivity analysis was conducted to evaluate whether the FAHP rankings were overly dependent on the judgments of individual experts or on moderate changes in the leading criteria weights (Table 8). Two complementary tests were undertaken. First, a leave-one-out analysis was performed by sequentially excluding each of the seven experts and recalculating the aggregated weights and rankings. Second, the normalized weights of the industrial sector and urbanization, the two highest-ranked criteria, were individually increased and decreased by 10%. An additional scenario interchanged the weights of these two criteria. The leave-one-out analysis demonstrated that the two leading criteria were highly stable. The industrial sector retained the first position and urbanization retained the second position in all seven expert-exclusion scenarios. The ranking of the lower-weight criteria was generally stable, although some changes occurred when Experts E1 and E7 were excluded. In particular, excluding E1 altered the relative positions of economic growth, residential sector, and transportation sector, while excluding E7 affected the positions of economic growth and transportation sector.

The alternative rankings were also generally stable. Sustainable urban form remained the highest-ranked alternative in five of the seven expert-exclusion scenarios. However, when Expert E3 or E4 was excluded, sustainable infrastructure moved to the first position and sustainable urban form moved to the second. Energy-efficient buildings, urban greening, and low-carbon transportation retained their third, fourth, and fifth positions, respectively, in all seven scenarios. This indicates that the first two alternatives are closely ranked, whereas the positions of the remaining alternatives are highly robust.

The ±10% perturbations in the industrial-sector and urbanization weights did not change the criteria ranking. When the two weights were deliberately interchanged, urbanization became first and the industrial sector became second, while all remaining criteria retained their original positions. Because the alternatives were evaluated through a separate overall pairwise comparison matrix rather than under each individual criterion, perturbations in the criteria weights did not affect the alternative ranking. Hence, the sensitivity results confirm that the principal findings are robust, although the close competition between sustainable urban form and sustainable infrastructure warrants cautious interpretation.

Table 8. Summary of the sensitivity-analysis results

Scenario	Criteria-ranking result	Alternative-ranking result
Baseline	Industrial sector ranked first; urbanization second	Sustainable urban form ranked first; sustainable infrastructure second
Exclude E1	Top two unchanged; three lower criteria changed position	No change
Exclude E2	No change	No change
Exclude E3	No change	Sustainable infrastructure and sustainable urban form exchanged first and second positions
Exclude E4	No change	Sustainable infrastructure and sustainable urban form exchanged first and second positions
Exclude E5	No change	No change
Exclude E6	No change	No change
Exclude E7	Top two unchanged; economic growth and transportation changed position	No change
Industrial sector +10%	No change	Not affected
Industrial sector −10%	No change	Not affected
Urbanization +10%	No change	Not affected
Urbanization −10%	No change	Not affected
Industrial and urbanization weights swapped	Urbanization ranked first and industrial sector second; other rankings unchanged	Not affected

4. Conclusion

This study applied FAHP to evaluate the principal factors influencing energy consumption in Saudi Arabia and to prioritize sustainable alternatives for managing future demand. The results indicate that the industrial sector is the most influential driver, followed by urbanization, economic growth, and transportation. This study applied the FAHP to evaluate the factors influencing energy consumption in Saudi Arabia and to prioritize sustainable alternatives for managing future demand. The results indicate that the industrial sector is the most influential driver of energy consumption, followed by urbanization, economic growth, and transportation. The residential sector and climate conditions received comparatively lower weights, although both remain relevant to national energy planning, particularly because of the high electricity demand associated with air conditioning. On the policy side, sustainable urban form and sustainable infrastructure emerged as the two highest-ranked alternatives, followed by energy-efficient buildings, urban greening, and low-carbon transportation. These findings emphasize the urgent need for coordinated policies that balance growth with sustainability. However, this study is not without limitations. The focus on a limited set of energy-consumption drivers and alternatives may have excluded other important drivers, such as energy pricing, technological innovation, behavioral factors, and policy incentives. Moreover, the analysis is static and does not reflect dynamic changes in population growth, climate risks, or technology adoption over time. In addition, climate conditions were represented as a single aggregated criterion. This broad classification may not fully capture the diverse pathways through which climate influences energy consumption in Saudi Arabia, including cooling degree days, seasonal temperature variability, heatwave frequency, humidity, and projected long-term warming. Representing climate as a composite factor may therefore have contributed to its relatively low priority in the FAHP results. Future research should address these limitations by incorporating larger and more diverse expert panels, applying complementary modelling approaches such as system dynamics, econometric analysis, or machine learning, and conducting comparative studies across GCC countries. Future studies should also disaggregate climate into multiple sub-criteria to determine whether specific climate-related variables exert greater influence on energy consumption than indicated by the present analysis. Additional focus on renewable energy, smart grids, demand-side management, and behavioural interventions would further strengthen the framework.

The findings hold important implications for practice and policy. Investments in high-efficiency building technologies and stricter building codes could reduce residential energy use, while cleaner industrial processes and fuel diversification policies would mitigate industrial emissions. Expanding sustainable public transport and managing urban growth could ease pressure on the transport sector. Integrating climate-sensitive planning into energy policy is essential to account for rising cooling demand under warmer conditions. Anchoring these strategies within Saudi Vision 2030 will ensure that energy efficiency and sustainability remain central to the country's transformation. In conclusion, this study shows that FAHP is a powerful decision-making tool for prioritizing energy drivers and solutions. By highlighting the interplay between structural and environmental factors, it provides policymakers with actionable insights to strengthen energy security and sustainability in Saudi Arabia, offering a pathway to balance economic growth with environmental stewardship.

Ethical Approval and Informed Consent

This study employed an expert-elicitation approach based on structured pairwise comparison questionnaires and did not involve clinical interventions, vulnerable populations, or the collection of sensitive personal information. In accordance with the applicable institutional research policies, formal ethical approval was not required for this type of low-risk expert consultation. Participation was entirely voluntary, and informed consent was obtained from all experts before they completed the questionnaires. To protect participants' privacy, all responses were anonymized, no personally identifiable information was reported, and the data were used solely for academic research purposes.

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