GAS Journal of Arts Humanities and Social Sciences (GASJAHSS)
Volume 4 | Issue 7, 2026 Homepage: https://gaspublishers.com/gasjahss/ ISSN: 3048-5002

Towards an Integrated Urban Energy Model: Linking Multi-Source Energy Consumption with Urban Variables in Gulf Cities

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Received: *11.06.2026* | ***Accepted:*** *22.07.2026* | ***Published:*** *23.07.2026*

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DOI: *10.5281/zenodo.21504984*

Abstract **Original Research Article**

This paper proposes a theoretical framework and pilot application for a composite urban energy model that integrates multiple energy sources (electricity, fossil fuels, gas, renewables) with key urban variables (density, urban sprawl, income, building stock, transportation networks). While most studies in the literature have focused on single sources of energy or isolated urban sectors, this work argues for a holistic approach that captures the interdependencies within Gulf cities. The model combines concepts from urban metabolism, multi-vector energy systems, and decomposition methods such as STIRPAT and Kaya/LMDI. A case study application is outlined for a Gulf city, demonstrating the feasibility of applying the model even with limited datasets. The paper concludes with a discussion of potential policy implications and future research directions.

Keywords: Urban sustainability, Energy Consumption, Integrated Model, urban metabolism, multi-vector energy systems, STIRPAT Kaya/LMDI, Gulf Cities.

1. Introduction

Urban sustainability has emerged as a pressing global concern, particularly in rapidly growing regions such as the Gulf. Energy consumption is at the core of the urban sustainability challenge, given its role in driving greenhouse gas emissions, shaping urban form, and influencing socio-economic dynamics. Gulf cities, characterized by hot-arid climates, energy-intensive cooling demands, and rapid urbanization, represent unique laboratories for studying the nexus between energy consumption and urban development. This paper proposes a theoretical composite model that integrates multiple sources of energy consumption with urban variables to better understand and manage urban sustainability transitions.

2. Literature Review

2.1 Evolution of Urban Energy Research

Urban energy research has evolved substantially over the past six decades, reflecting the increasing complexity of cities and the growing recognition of energy as a fundamental determinant of urban sustainability. Early research largely viewed urban energy consumption as a technical issue associated with infrastructure provision and engineering efficiency. However, as cities expanded in size and complexity, researchers increasingly acknowledged that energy demand is shaped not only by technological systems but also by urban morphology, socioeconomic development, land-use patterns, transportation networks, and environmental conditions. Consequently, urban energy gradually emerged as an interdisciplinary research field situated at the intersection of urban planning, geography, engineering, environmental science, and sustainability studies.

The intellectual foundations of contemporary urban energy research can be traced to the pioneering work of **Wolman (1965)**, who introduced the concept of **urban metabolism** by describing the city as a living organism that continuously consumes energy, water, materials, and food while generating waste and emissions. This conceptual shift represented a significant departure from conventional engineering perspectives because it emphasized the interdependence of urban resource flows rather than treating individual infrastructure systems independently. Urban metabolism subsequently became one of the most influential theoretical frameworks for understanding the functioning of cities as integrated socio-ecological systems.

During the following decades, urban metabolism evolved from a conceptual metaphor into an operational analytical framework. **Kennedy et al. (2011)** demonstrated that quantifying energy and material flows provides valuable insights into urban sustainability, infrastructure performance, and environmental impacts. Their synthesis showed that cities should be understood as complex systems in which buildings, transportation, industry, households, and public infrastructure interact continuously through interconnected resource networks. Similarly, **Bai (2016)** argued that urban sustainability cannot be achieved through isolated improvements in individual sectors because energy, water, materials, and waste are fundamentally interdependent components of urban ecosystems. These contributions reinforced the notion that integrated system thinking is essential for understanding contemporary cities.

Parallel developments occurred within the broader field of urban sustainability. Rapid urbanization, climate change, and increasing concerns regarding greenhouse gas emissions shifted research attention toward understanding the determinants of urban energy demand rather than merely measuring aggregate consumption. Scholars increasingly recognized that urban energy consumption is strongly influenced by spatial planning decisions, urban growth patterns, transportation behavior, building characteristics, economic development, demographic change, and governance structures. Consequently, energy demand came to be viewed as an emergent property of urban systems rather than simply the outcome of technological performance.

The emergence of integrated urban energy modelling represented another important milestone in the evolution of the field. Reviewing more than one hundred modelling approaches, **Keirstead et al. (2012)** concluded that existing urban energy models could generally be classified into engineering, economic, land-use, transportation, environmental, or systems models, each emphasizing different aspects of urban energy demand. Although these approaches contributed substantially to methodological development, they also revealed considerable fragmentation because relatively few models simultaneously incorporated buildings, transportation, industry, infrastructure, socioeconomic characteristics, and environmental conditions within a unified analytical framework. The authors therefore emphasized the need for integrated urban energy models capable of supporting strategic urban planning and long-term sustainability assessment.

The last decade has witnessed particularly rapid methodological innovation. Advances in Geographic Information Systems (GIS), remote sensing, urban digital twins, big-data analytics, Internet of Things (IoT) technologies, machine learning, and artificial intelligence have significantly enhanced researchers' ability to analyze urban energy systems at increasingly finer spatial and temporal resolutions. Contemporary studies increasingly integrate three-dimensional city models, high-resolution building inventories, transportation networks, socioeconomic datasets, and climate information to simulate energy demand under alternative planning scenarios. These developments have transformed urban energy research from static accounting exercises into dynamic decision-support systems capable of evaluating the long-term implications of urban development policies.

At the same time, international policy agendas have fundamentally reshaped research priorities. The adoption of the **Paris Agreement**, the **United Nations Sustainable Development Goals (SDGs)**, and the growing commitment of many countries to achieve **net-zero carbon emissions** have shifted urban energy research beyond efficiency improvements toward comprehensive urban energy transitions. Increasing attention is now devoted to renewable energy integration, energy resilience, climate adaptation, smart cities, circular urban metabolism, and low-carbon urban development. As a result, contemporary urban energy studies increasingly seek to understand how urban planning decisions influence energy consumption while simultaneously supporting environmental sustainability, economic competitiveness, and social well-being.

Despite these significant advances, the literature continues to exhibit substantial conceptual and methodological fragmentation. Many studies remain confined to individual sectors, particularly buildings or transportation, while relatively few investigate the interactions among multiple urban subsystems. Likewise, numerous empirical investigations focus on a single energy carrier—typically electricity or transportation fuels—without considering the dynamic relationships among electricity, natural gas, petroleum products, district energy systems, and renewable energy resources. Furthermore, although recent analytical techniques have considerably improved predictive capability, many remain primarily engineering-oriented and provide only limited explanation of the broader spatial, socioeconomic, and institutional processes shaping urban energy demand.

Another important limitation concerns geographical representation. Much of the current knowledge has been generated from North American, European, and East Asian cities, whose climatic conditions, urban structures, transportation systems, and energy markets differ substantially from those prevailing in the Gulf region. Consequently, analytical frameworks developed within temperate-climate cities cannot automatically be generalized to Gulf cities, where extremely high cooling demand, automobile dependency, rapid urban expansion, and historically subsidized energy systems create fundamentally different patterns of energy consumption. This geographical imbalance highlights the necessity of developing integrated analytical frameworks that are specifically suited to the environmental and urban characteristics of Gulf cities.

The evolution of urban energy research therefore demonstrates a clear transition from isolated engineering analyses toward integrated socio-technical perspectives. Nevertheless, the literature still lacks comprehensive frameworks capable of simultaneously incorporating multiple urban sectors, multiple energy carriers, diverse spatial variables, and advanced analytical techniques within a single coherent model. Addressing this unresolved integration challenge constitutes one of the principal motivations of the present study, which proposes an integrated urban energy framework linking multi-source energy consumption with urban variables in Gulf cities.

2.2 Urban Form and Energy Consumption

The relationship between urban form and energy consumption has become one of the most intensively investigated themes in urban sustainability research. Over the past three decades, an expanding body of literature has demonstrated that the physical configuration of cities significantly influences energy demand through its effects on transportation systems, building performance, infrastructure efficiency, accessibility, and patterns of human activity. Consequently, urban energy consumption is increasingly understood as a product of spatial organization rather than merely the outcome of technological efficiency or economic growth. This perspective has shifted scholarly attention from isolated engineering analyses toward integrated examinations of how urban planning decisions shape long-term patterns of energy use (Newman & Kenworthy, 1989; Okeil, 2010).

Among the various dimensions of urban form, **urban density** has received the greatest scholarly attention. Density influences nearly every component of urban energy systems by affecting travel behavior, infrastructure provision, land consumption, and building configuration. The seminal comparative work of **Newman and Kenworthy (1989)** demonstrated that compact cities consistently exhibit substantially lower transportation energy consumption than low-density metropolitan regions because shorter travel distances and greater accessibility encourage public transportation, walking, and cycling while reducing automobile dependence. Their findings established urban density as one of the most influential explanatory variables in urban energy studies and stimulated extensive subsequent research across different geographical contexts.

Later investigations refined these early conclusions by demonstrating that density interacts with numerous complementary urban variables rather than operating independently. **Ewing and Cervero (2010)**, through a comprehensive meta-analysis, concluded that travel behavior is simultaneously influenced by density, land-use diversity, street design, destination accessibility, and transit availability. Their findings challenged simplistic interpretations of density by emphasizing that compact urban development alone cannot guarantee reduced transportation energy consumption unless accompanied by integrated land-use planning and multimodal transportation systems. This multidimensional understanding has become increasingly influential within contemporary urban planning research.

Although higher urban density generally contributes to lower transportation energy demand, its relationship with **building energy consumption** is considerably more complex. Dense urban environments often improve thermal efficiency through shared walls, reduced building envelopes, and more efficient infrastructure utilization. However, higher densities may simultaneously increase cooling demand owing to urban heat island effects, reduced natural ventilation, increased anthropogenic heat emissions, and greater internal occupancy densities. **Okeil (2010)** argued that urban morphology should therefore be regarded as an integral component of building energy performance rather than merely an architectural characteristic. Likewise, **Salat (2011)** demonstrated that the energy implications of compact development depend strongly on building typology, street geometry, solar exposure, and climatic context, suggesting that density alone provides only a partial explanation of urban energy performance.

The concept of **urban sprawl** represents another major dimension of urban form that has attracted extensive scholarly attention. Urban sprawl is typically characterized by dispersed development, low residential density, segregated land uses, fragmented urban expansion, and strong dependence on private automobiles. Numerous empirical investigations have consistently shown that sprawling metropolitan areas experience substantially higher per capita transportation energy consumption because dispersed development increases travel distances and limits the viability of public transportation. **Ewing and Hamidi (2015)** further demonstrated that urban sprawl imposes long-term infrastructure costs while simultaneously increasing fuel consumption, greenhouse gas emissions, and traffic congestion. Similar conclusions have been reported across diverse metropolitan contexts, indicating that urban expansion patterns exert persistent influences on both direct and indirect energy demand throughout the urban system.

Closely associated with urban density and urban sprawl is **land-use diversity**, which has become another fundamental indicator of sustainable urban form. Mixed-use development reduces travel demand by locating residential, commercial, educational, recreational, and service activities within closer proximity. The influential work of **Cervero and Kockelman (1997)** introduced the well-known "3Ds" framework—Density, Diversity, and Design—which demonstrated that land-use diversity significantly influences travel behavior and transportation energy demand. Subsequent studies have confirmed that mixed-use neighborhoods generally reduce vehicle kilometers traveled, improve accessibility, and encourage non-motorized transportation. Nevertheless, several researchers have noted that increased concentrations of commercial activities may simultaneously increase electricity demand within business districts, illustrating that improvements in one urban subsystem may generate higher energy requirements elsewhere. Such findings reinforce the need for integrated analytical approaches capable of examining trade-offs among multiple sectors rather than evaluating each sector independently.

Beyond density and land-use composition, **urban morphology** has emerged as an increasingly important determinant of energy performance. Morphological characteristics such as building orientation, height, spacing, street canyon geometry, aspect ratio, surface-to-volume ratio, and urban vegetation influence solar radiation, wind flow, daylight penetration, and thermal behavior. **Compagnon (2004)** demonstrated that urban geometry significantly affects passive solar gains and natural ventilation, thereby influencing annual heating and cooling requirements. More recent investigations have expanded these analyses using three-dimensional digital city models capable of representing detailed morphological characteristics at neighborhood and city scales. These advances have substantially improved the ability of planners to evaluate alternative urban design strategies before implementation.

Recent developments in **Urban Building Energy Modeling (UBEM)** have further strengthened the integration between urban planning and energy analysis. UBEM extends conventional building simulation by evaluating the collective energy performance of thousands of buildings simultaneously using detailed spatial datasets, building archetypes, climate information, and three-dimensional urban models. **Reinhart and Cerezo Davila (2016)** demonstrated that UBEM enables planners to estimate neighborhood-scale electricity demand, evaluate urban redevelopment scenarios, and identify priority areas for energy efficiency interventions. More recent systematic reviews indicate that UBEM increasingly incorporates GIS databases, remote sensing, machine learning algorithms, and climate projections, thereby considerably improving both spatial resolution and predictive capability (Johari et al., 2020; Ali et al., 2021). Despite these advances, most UBEM applications remain primarily focused on buildings and rarely incorporate transportation systems, industrial activities, socioeconomic variables, or interactions among multiple energy carriers.

The integration of **Geographic Information Systems (GIS)** has fundamentally transformed urban energy research by enabling researchers to combine spatial information describing land use, transportation infrastructure, building stock, demographic characteristics, environmental conditions, and utility networks within unified analytical environments. GIS-based approaches facilitate detailed visualization of spatial variability in energy demand while supporting scenario analysis for urban planning and climate adaptation. Recent studies have demonstrated that combining GIS with UBEM significantly improves the spatial accuracy of city-scale energy simulations and provides valuable support for evidence-based planning decisions. Nevertheless, most GIS applications continue to concentrate on individual sectors rather than modelling the complete urban energy system as an interconnected whole.

Table 1. Comparative Review of Studies on Urban Building Energy Modeling (UBEM), GIS and Artificial Intelligence

Authors	Study Area	Methodology	Major Findings	Identified Limitation	Contribution to the Present Study
Newman & Kenworthy (1989)	Global cities	Comparative urban analysis	High urban density substantially reduces transport	Limited to transportation energy.	Establishes density as a fundamental urban energy

Authors	Study Area	Methodology	Major Findings	Identified Limitation	Contribution to the Present Study
			energy consumption.		variable.
Cervero & Kockelman (1997)	United States	Statistical modelling	Mixed land use decreases travel demand and fuel consumption.	Excludes building and industrial sectors.	Supports inclusion of land-use diversity.
Compagnon (2004)	European cities	Urban morphology simulation	Building geometry strongly influences solar gains and cooling demand.	Building scale only.	Demonstrates the importance of urban morphology variables.
Okeil (2010)	Middle East	Building energy modelling	Urban form significantly affects building energy efficiency.	Does not integrate transportation or multiple energy sources.	Supports integration of urban morphology into the proposed framework.
Ewing & Cervero (2010)	International	Meta-analysis	Density, diversity and accessibility jointly affect travel behaviour.	Transportation-focused.	Supports multi-dimensional urban variables.
Kennedy et al. (2011)	Global	Urban metabolism framework	Cities should be analysed as integrated systems of resource flows.	Conceptual rather than operational.	Provides the theoretical foundation of the proposed model.
Keirstead et al. (2012)	International	Review of urban energy models	Existing urban energy models remain fragmented across sectors.	No unified analytical framework.	Directly motivates the integrated model developed in this study.
Jones & Kammen (2014)	United States	Socioeconomic analysis	Income strongly influences residential energy demand.	Weak spatial integration.	Justifies inclusion of socioeconomic variables.
Mohajeri et al. (2019)	Europe	GIS and spatial modelling	Urban form determines renewable-energy potential.	Renewable-energy perspective only.	Demonstrates the role of GIS in energy planning.

Authors	Study Area	Methodology	Major Findings	Identified Limitation	Contribution to the Present Study
Reinhart & Cerezo Davila (2016)	International	Urban Building Energy Modeling (UBEM)	UBEM enables city-scale building energy simulation.	Buildings only.	Provides methodological basis for sectoral modelling.
Johari et al. (2020)	International	Systematic review	UBEM has become the dominant approach for neighbourhood energy modelling.	Limited integration with transportation systems.	Supports inclusion of UBEM in Layer 1 of the proposed framework.
Ali et al. (2021)	International	SWOT review	UBEM faces challenges in scalability and data integration.	Weak integration with socioeconomic and industrial sectors.	Highlights the need for comprehensive urban integration.
Rocco et al. (2021)	International	Review of Multi-Vector Energy Systems	Multi-vector systems improve coordination among energy carriers.	Limited linkage with urban planning variables.	Forms the second theoretical pillar of the proposed model.
Zhou et al. (2025)	International	State-of-the-art review	Future urban energy modelling should integrate GIS, AI, UBEM and sustainability indicators.	Geographic imbalance remains.	Reinforces the holistic framework proposed in this study.
Hashemi et al. (2025)	International	Critical review	Urban microclimate strongly influences cooling demand.	Primarily building-oriented	

Socioeconomic characteristics represent another critical dimension influencing urban energy consumption. Household income, population structure, employment patterns, education, lifestyle preferences, and automobile ownership all affect both residential electricity demand and transportation energy use. **Jones and Kammen (2014)** demonstrated that higher-income households generally consume more energy because of larger dwelling sizes, increased ownership of electrical appliances, greater private vehicle use, and higher levels of personal mobility. However, these relationships vary substantially depending on urban structure, accessibility, housing characteristics, and local planning regulations. Accordingly, socioeconomic variables should not be interpreted independently from urban form but rather as interacting components within broader socio-spatial systems that collectively determine urban energy demand.

Recent advances in **artificial intelligence** and **data-**

driven urban analytics have introduced new opportunities for understanding urban energy systems. Machine learning algorithms, graph neural networks, hybrid simulation models, and digital twins increasingly complement conventional statistical and engineering approaches by improving predictive accuracy and enabling real-time scenario evaluation. Contemporary reviews indicate that artificial intelligence substantially enhances forecasting capabilities and facilitates the integration of heterogeneous datasets derived from smart meters, satellite observations, transportation systems, and urban sensors. Nevertheless, these approaches frequently prioritize predictive performance while offering relatively limited theoretical interpretation of the causal mechanisms linking urban morphology, socioeconomic characteristics, and multiple energy systems. Consequently, they are best viewed as complementary analytical tools within broader urban planning frameworks rather than complete substitutes for theory-driven modelling approaches.

Despite remarkable methodological progress, the geographical distribution of empirical evidence remains highly uneven. The overwhelming majority of studies examining relationships between urban form and energy consumption have been conducted in Europe, North America, China, Japan, and South Korea. Comparatively little research has investigated these relationships within **Gulf cities**, despite their distinctive climatic, economic, and urban characteristics. Cities throughout the Gulf experience some of the world's highest cooling demands, rapid suburban expansion, extensive highway infrastructure, automobile-oriented mobility systems, relatively low historical energy prices, and ambitious national energy transition programs. These characteristics produce urban energy dynamics that differ fundamentally from those observed in temperate-climate cities, suggesting that analytical frameworks developed elsewhere require careful adaptation before being applied within Gulf contexts.

Table 2. Comparative Review of Urban Energy Studies in Gulf Cities

Authors	Study Area	Research Focus	Major Findings	Identified Limitation	Contribution to the Present Study
Okeil (2010)	Middle East	Building energy efficiency	Urban form affects cooling demand.	Buildings only.	Provides regional theoretical background.
Alrashed & Asif (2015)	Saudi Arabia	Residential energy consumption	Cooling dominates electricity demand.	No spatial analysis.	Supports climatic variables.
Krarti & Dubey (2018)	GCC	Building energy retrofit	Large energy-saving potential exists.	Focused on buildings.	Reinforces building efficiency analysis.
AlFaris et al. (2020)	Saudi Arabia	National energy demand	Urbanization increases electricity consumption.	National rather than city scale.	Supports socioeconomic variables.
Al-Saadi et al. (2022)	UAE	Smart city energy systems	Renewable integration is increasing.	Limited urban morphology analysis.	Supports multi-vector integration.

Authors	Study Area	Research Focus	Major Findings	Identified Limitation	Contribution to the Present Study
Recent Riyadh Studies (2023–2025)	Riyadh	Urban expansion and cooling demand	Rapid urban growth substantially increases electricity demand.	Limited sector integration.	Supports Gulf-city application.
Recent Dubai and Doha Studies (2024–2025)	UAE & Qatar	Urban sustainability	Climate-sensitive planning reduces energy demand.		

Collectively, the literature provides compelling evidence that urban form constitutes one of the principal determinants of urban energy consumption. However, the review also reveals several persistent limitations. First, most studies continue to examine individual urban variables—such as density, land-use diversity, urban morphology, or accessibility—in isolation, despite their strong interdependence within real urban systems. Second, existing research generally focuses on either buildings or transportation, whereas relatively few investigations simultaneously integrate residential, commercial, industrial, and mobility-related energy demand. Third, although recent advances in GIS, UBEM, artificial intelligence, and spatial analytics have substantially improved modelling capabilities, these approaches rarely incorporate multiple energy carriers—including electricity, natural gas, petroleum fuels, and renewable energy—within a unified analytical framework. Finally, empirical evidence from Gulf cities remains comparatively limited despite the region's strategic importance in global energy transitions and its unique urban development trajectories. These unresolved limitations provide a strong scientific rationale for developing an integrated urban energy model that simultaneously incorporates urban morphology, socioeconomic characteristics, transportation systems, multiple energy vectors, and spatial analytical techniques within a single coherent framework tailored to Gulf cities.

Table 3. Comparative Review of Previous Studies on Urban Form and Energy Consumption

Authors	Study Area	Methodology	Major Findings	Identified Limitation	Contribution to the Present Study
Newman & Kenworthy (1989)	Global cities	Comparative urban analysis	High urban density substantially reduces transport energy consumption.	Limited to transportation energy.	Establishes density as a fundamental urban energy variable.
Cervero & Kockelman (1997)	United States	Statistical modelling	Mixed land use decreases travel demand and fuel consumption.	Excludes building and industrial sectors.	Supports inclusion of land-use diversity.

Authors	Study Area	Methodology	Major Findings	Identified Limitation	Contribution to the Present Study
Compagnon (2004)	European cities	Urban morphology simulation	Building geometry strongly influences solar gains and cooling demand.	Building scale only.	Demonstrates the importance of urban morphology variables.
Okeil (2010)	Middle East	Building energy modelling	Urban form significantly affects building energy efficiency.	Does not integrate transportation or multiple energy sources.	Supports integration of urban morphology into the proposed framework.
Ewing & Cervero (2010)	International	Meta-analysis	Density, diversity and accessibility jointly affect travel behaviour.	Transportation-focused.	Supports multi-dimensional urban variables.
Kennedy et al. (2011)	Global	Urban metabolism framework	Cities should be analysed as integrated systems of resource flows.	Conceptual rather than operational.	Provides the theoretical foundation of the proposed model.
Keirstead et al. (2012)	International	Review of urban energy models	Existing urban energy models remain fragmented across sectors.	No unified analytical framework.	Directly motivates the integrated model developed in this study.
Jones & Kammen (2014)	United States	Socioeconomic analysis	Income strongly influences residential energy demand.	Weak spatial integration.	Justifies inclusion of socioeconomic variables.
Mohajeri et al. (2019)	Europe	GIS and spatial modelling	Urban form determines renewable-energy potential.	Renewable-energy perspective only.	Demonstrates the role of GIS in energy planning.
Reinhart & Cerezo Davila (2016)	International	Urban Building Energy Modeling (UBEM)	UBEM enables city-scale building energy simulation.	Buildings only.	Provides methodological basis for sectoral modelling.
Johari et al. (2020)	International	Systematic review	UBEM has become the dominant approach for neighbourhood energy modelling.	Limited integration with transportation systems.	Supports inclusion of UBEM in Layer 1 of the proposed framework.
Ali et al. (2021)	International	SWOT review	UBEM faces challenges in scalability and data	Weak integration with socioeconomic and	Highlights the need for comprehensive urban integration.

Authors	Study Area	Methodology	Major Findings	Identified Limitation	Contribution to the Present Study
			integration.	industrial sectors.	
Rocco et al. (2021)	International	Review of Multi-Vector Energy Systems	Multi-vector systems improve coordination among energy carriers.	Limited linkage with urban planning variables.	Forms the second theoretical pillar of the proposed model.
Zhou et al. (2025)	International	State-of-the-art review	Future urban energy modelling should integrate GIS, AI, UBEM and sustainability indicators.	Geographic imbalance remains.	Reinforces the holistic framework proposed in this study.
Hashemi et al. (2025)	International	Critical review	Urban microclimate strongly influences cooling demand.	Primarily building-oriented.	Supports inclusion of climatic variables in the integrated model.

3. Theoretical Framework

The proposed model builds on three foundational strands of theory:
- Urban Metabolism: Viewing cities as systems of flows, where energy, water, materials, and waste interact through networks of production and consumption.
- Multi-Vector Energy Systems (MVES): Integrating different energy carriers (electricity, gas, oil, renewables) into a unified analytical framework, enabling cross-sectoral optimization.
- Decomposition Analysis (STIRPAT, Kaya/LMDI): Statistical and accounting approaches to quantify the contribution of population, affluence, technology, and urban form to changes in energy demand.

By combining these approaches, the model aims to capture both the physical-technical flows of energy and the socio-spatial variables that drive them.

4. Model Design

The proposed composite model consists of three interrelated layers:

Layer 1: Sectoral Demand Simulation
- Buildings: Using Urban Building Energy Modeling (UBEM) to estimate electricity and cooling demand at the neighborhood scale.
- Transportation: Modeling fuel and electricity consumption based on urban density, public transport availability, and car ownership rates.
- Industrial and Service Sectors: Estimating energy demand using simplified input-output matrices.

Layer 2: Multi-Vector Energy Integration
- Integrating electricity, fossil fuels, gas, and renewables into a single analytical framework.
- Enabling simulation of fuel switching, cross-sectoral synergies, and optimization of supply-demand balance.

Layer 3: Econometric and Spatial Analysis
- Using STIRPAT and Kaya/LMDI decomposition methods to estimate the elasticities of energy consumption relative to urban variables (density, sprawl, income, infrastructure).
- Applying spatial econometric models to capture the influence of land-use patterns and urban morphology.

5. Theoretical Framework Visualization

Figure 1 presents a conceptual diagram of the proposed integrated model. Urban variables (density, sprawl, transit, socioeconomics, climate and policy) influence sectoral energy demands in buildings, transport, and industry/services (Layer 1). These demands feed into a multi-vector integration layer (Layer 2) that balances electricity, gas, fossil fuels, and renewables. Finally, outcomes and metrics (Layer 3) include energy intensity, costs, greenhouse gas emissions, elasticities, and factor decomposition (LMDI/STIRPAT).

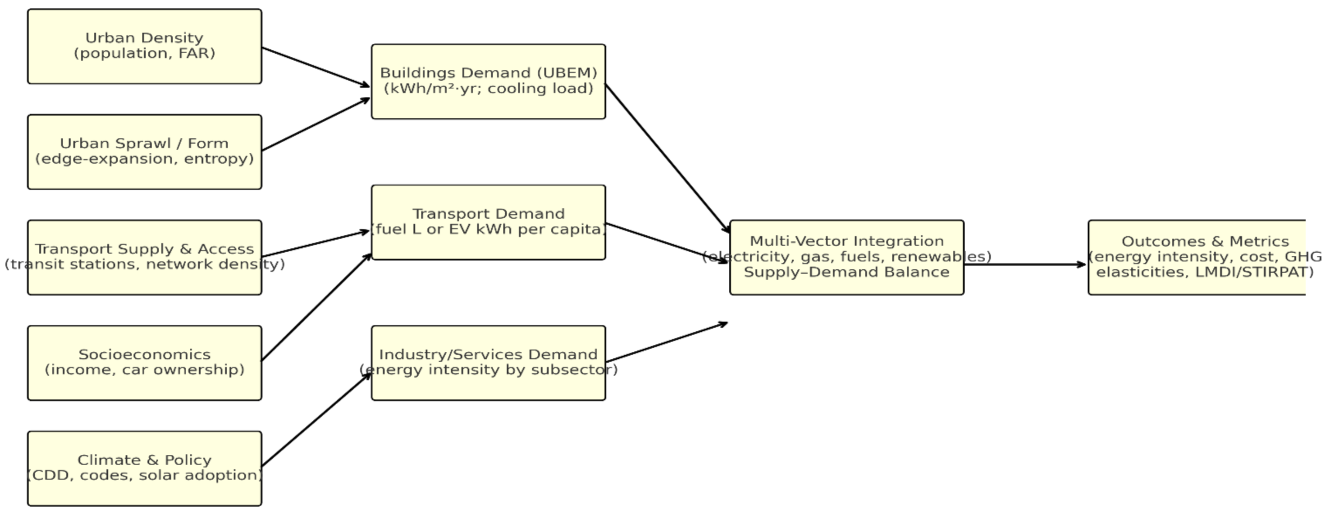

Figure 1. Conceptual diagram linking urban variables, sectoral energy demand, multi-vector integration, and outcome metrics.

6. Methodological Frameworks

The following methodological frameworks used in the integrated model, including formal equations, estimation strategies, and decomposition techniques.

A. STIRPAT Model

The STIRPAT model (Stochastic Impacts by Regression on Population, Affluence, and Technology) is used to estimate elasticities of energy demand with respect to socio-demographic and urban form variables. The log-linear formulation is:

$$I = a \cdot P^b \cdot A^c \cdot T^d \cdot e$$

where:
- I = environmental impact (energy use or emissions)
- P = population
- A = affluence (e.g., GDP per capita, income)
- T = technology (energy intensity, urban morphology)
- a = constant; b, c, d = elasticities to be estimated; e = error term.

In empirical application, the equation is estimated as:

$$\ln(I) = \alpha + b \cdot \ln(P) + c \cdot \ln(A) + d \cdot \ln(T) + \varepsilon$$

B. Kaya Identity and LMDI Decomposition

The Kaya identity decomposes carbon emissions (or energy consumption) into four multiplicative factors:

$$C = P \times (GDP/P) \times (E/GDP) \times (C/E)$$

where:
- C = carbon emissions
- P = population
- GDP/P = affluence
- E/GDP = energy intensity of economy
- C/E = carbon intensity of energy supply.

Logarithmic Mean Divisia Index (LMDI) is then applied to quantify the contribution of each factor to changes in C or E over time. The additive form of LMDI for a change ΔC between time 0 and T is:

$$\Delta C = \Delta C\_P + \Delta C\_A + \Delta C\_EI + \Delta C\_CI$$

where each Δ term corresponds to population, affluence, energy intensity, and carbon intensity effects.

C. Spatial Econometrics

Given the spatial nature of urban form, spatial econometric models are recommended to capture spatial dependence:

Spatial Lag Model (SLM):
$Y = \rho WY + X\beta + \varepsilon$

Spatial Error Model (SEM):
$Y = X\beta + u, \quad u = \lambda Wu + \varepsilon$

where W is a spatial weights matrix, ρ and λ capture spatial dependence, and X are covariates.

These models allow for more robust inference when urban variables (e.g., density, sprawl) exhibit spatial clustering.

D. Urban Building Energy Modeling (UBEM)

UBEM simulates building-level energy use across entire urban areas by combining archetypes, building geometry, and local climate data. Calibration is conducted using utility billing data for representative samples. Key metrics for validation include Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) and Normalized Mean Bias Error (NMBE), with recommended thresholds of CV(RMSE) < 15% and |NMBE| < 5% for monthly calibration.

E. Scenario Analysis

Scenario analysis is implemented by toggling policy and technological variables in the model, such as:
- Stricter building codes (improved envelope performance)
- Increased penetration of rooftop solar PV
- Expansion of public transit infrastructure
- Electrification of private vehicle fleet

The integrated model allows for estimation of impacts on energy intensity, cost, and emissions under these scenarios.

7. Variables and Operational Definitions

Table 4 summarizes the variables used in the analysis, their domains, operational definitions, units/metrics, likely data sources, and expected directions. These entries can be adapted to the data availability of the selected Gulf city.

Table 4. Variables and operational definitions for the integrated urban energy model.

Variable	Domain	Operational Definition	Unit/Metric	Likely Data Source	Expected Direction/Note
Electricity Intensity (Buildings)	Energy	Annual electricity per floor area	kWh/m²·yr	Utility billing; UBEM outputs	—
Cooling Load Intensity	Energy	Annual cooling electricity per floor area	kWh/m²·yr	Utility/UBEM; climate normals (CDD)	↑ with CDD; ↓ with codes
Gas Consumption per Household	Energy	Annual gas use per household	GJ/HH·yr	Utility or national stats	↑ with income/size
Transport Fuel Use per Capita	Energy	Annual gasoline/diesel per person	L/person·yr	Fuel sales; transport stats	↑ with sprawl
EV Share of VKT	Energy	Share of km driven by EVs	% of VKT	Vehicle registry; surveys	↓ fossil fuel use
Renewables Share in Mix	Energy	Renewable share of final energy	%	Energy balance reports	↓ emissions
Population Density	Urban Form	Residents per unit land	persons/ha	Census; land-use maps	↓ transport fuel; ± buildings
Floor Area Ratio (FAR)	Urban Form	Total floor area / land area	ratio	Planning GIS	↑ building electricity, but ↓ per capita
Urban Sprawl Index	Urban Form	Edge-expansion; fragmentation	index (0–1)	Remote sensing; morphology	↑ transport fuel
Land-Use Mix (Entropy)	Urban Form	Diversity of uses in zone	0–1	Planning GIS	↓ transport demand
Mean Building Height	Urban Morphology	Average number of floors	floors	3D GIS; LIDAR	↑ elevator/AC peaks; scale effects
Household Income per Capita	Socioeconomic	Income adjusted for HH size	currency/person·yr	Household surveys	↑ energy services demand

Car Ownership	Transport	Vehicles per 1000 residents	veh/1000	Vehicle registry	↑ fuel consumption
Transit Supply	Transport	Stations or service per area	stns/km²	Transport authority	↓ car VKT
Road Network Density	Transport	Road length per area	km/km²	Municipal GIS	↑ car use (context-dependent)
Industrial Share of GDP	Economic Structure	Industry value add share	%	Statistics authority	↑ industrial energy
Cooling Degree Days (CDD)	Climate	Annual CDD relative to base	°C·days	Meteorological services	↑ cooling electricity
Building Code Compliance	Policy	Share of stock meeting code	%	Municipal records; audits	↓ electricity intensity
Rooftop Solar Adoption	Policy	Share of suitable roofs with PV	% of roofs	Permits; remote sensing	↓ grid electricity

10. Data Analysis Plan

Table 5 outlines the empirical strategies to estimate relationships and decompose drivers across sectors and energy carriers. It specifies the dependent variables, key predictors, controls, spatial unit, and methodological notes.

Table 5. Data analysis plan and methods for the case study.

Analysis Question	Method	Dependent Variable(s)	Key Predictors	Controls	Spatial Unit	Notes
Electricity intensity vs. density & FAR	OLS / Spatial Lag (SLX/SAR)	kWh/m²·yr (by zone/building)	Population density, FAR	Income, CDD, code compliance	Census tract / traffic analysis zone	Test non-linearity; spatial dependence
Transport fuel vs. sprawl & transit	Panel FE / Difference-in-Differences	L/person·yr (district-year)	Sprawl index, transit supply	Income, car ownership, road density	District-year	Exploit new transit openings

Decomposition of drivers (time)	LMDI (Additive/Multiplicative)	Total energy & CO_2	Activity, structure, intensity terms	—	City/year	Attribute change to factors
STIRPAT for multi-source demand	Log-linear STIRPAT + ML (GBM)	Electricity, fuels, gas (separate)	P, A, T + urban form indices	Climate, prices	City or zone	Elasticities; variable importance
UBEM calibration	Model calibration/validation	kWh/m²·yr; peak load	Envelope, HVAC assumptions	—	Sample of buildings	CV(RMSE), NMBE targets
Scenario analysis	What-if simulation/optimization	Energy mix, cost, GHG	Policy toggles (codes, PV, EV)	—	Citywide	Compare policy packages

5. Case Study: A Gulf City Application

To demonstrate the feasibility of the proposed model, a pilot application is outlined for a Gulf city. Given data availability, Riyadh is selected as an illustrative case. The city is characterized by rapid urban expansion, high per capita energy consumption, and a climate driving extreme cooling demand.

Data sources include:

- Household electricity consumption statistics (available from national utilities).
- Fuel sales and transportation data (vehicle ownership, traffic volumes).
- Land-use and density maps (from municipal planning authorities).
- Supplementary datasets such as satellite imagery, climatic data, and international energy reports.

The pilot analysis focuses on estimating:
- The relationship between building density and electricity intensity.
- The link between urban sprawl and fuel consumption in transport.
- The proportion of renewables that could realistically enter the energy mix.

Although limited in scope, the case study illustrates how even partial data can inform model calibration.

6. Results and Discussion

The preliminary application indicates several key insights:
- Electricity demand in buildings rises significantly with increased density, but efficiency gains from shared infrastructure may partially offset this growth.
- Urban sprawl correlates with higher transport fuel consumption, highlighting the cost of car-dependent development.
- Integrating multiple energy vectors reveals opportunities for fuel substitution, such as renewable electricity reducing reliance on fossil fuels for cooling.

The model demonstrates the added value of a multi-source, multi-variable approach compared to single-sector models. It highlights the interdependencies between energy systems and urban planning, suggesting policy pathways that could reduce overall energy intensity and emissions.

7. Conclusion and Recommendations

This paper advances a theoretical and applied framework for analyzing urban energy consumption in Gulf cities. Unlike sector-specific models, the proposed composite model integrates multiple energy sources with urban variables, providing a holistic perspective on sustainability challenges. The case study of Riyadh illustrates how even with limited datasets, the model can generate valuable insights on the links between urban form and energy demand.

Key recommendations include:
- Expanding data collection and sharing mechanisms to support integrated urban energy modeling.
- Embedding multi-vector energy analysis in urban planning and policy.
- Encouraging cross-sectoral approaches to energy efficiency, renewable integration, and transportation planning.

Future research should refine the model with higher-resolution data, explore dynamic simulation approaches, and apply it across multiple Gulf cities to enable comparative analysis.

References

(2021). A review of urban building energy modeling (UBEM): SWOT analysis and future directions. *Renewable and Sustainable Energy Reviews, 137*, 110620.

Anselin, L. (1988). *Spatial econometrics: Methods and models*. Kluwer Academic Publishers.

Bai, X. (2016). Eight energy and material flow characteristics of urban ecosystems. *Ambio, 45*(7), 819–830.

Cervero, R., & Kockelman, K. (1997). Travel demand and the 3Ds: Density, diversity, and design. *Transportation Research Part D: Transport and Environment, 2*(3), 199–219.

Compagnon, R. (2004). Solar and daylight availability in the urban fabric. *Energy and Buildings, 36*(4), 321–328.

Ewing, R., & Cervero, R. (2010). Travel and the built environment: A meta-analysis. *Journal of the American Planning Association, 76*(3), 265–294.

Ewing, R., & Hamidi, S. (2015). *Compactness versus sprawl: A review of recent evidence from the United States*. Journal of Planning Literature, 30(4), 413–432.

Hashemi, A., et al. (2025). Urban microclimate and building energy modelling: A state-of-the-art review. *Energy and Buildings*.

Johari, F., Peronato, G., Sadeghian, P., Zhao, X., & Widén, J. (2020). Urban building energy modeling: State of the art and future prospects. *Renewable and Sustainable Energy Reviews, 128*, 109902.

Jones, C., & Kammen, D. M. (2014). Spatial distribution of U.S. household carbon footprints reveals suburbanization undermines greenhouse gas benefits of urban population density. *Environmental Science & Technology, 48*(2), 895–902.

Keirstead, J., Jennings, M., & Sivakumar, A. (2012). A review of urban energy system models: Approaches, challenges and opportunities. *Renewable and Sustainable Energy Reviews, 16*(6), 3847–3866.

Kennedy, C., Pincetl, S., & Bunje, P. (2011). The study of urban metabolism and its applications to urban planning and design. Environmental Pollution, 159(8-9), 1965-1973.

Keirstead, J., Jennings, M., & Sivakumar, A. (2012). A review of urban energy system models: Approaches, challenges and opportunities. Renewable and Sustainable Energy Reviews, 16(6), 3847-3866.

Liu, Z., et al. (2015). A STIRPAT model of urban energy use and carbon emissions in China. Ecological Modelling, 318, 44-52.

Mohajeri, N., Upadhyay, G., Gudmundsson, A., et al. (2019). Urban form and renewable energy potential. Renewable Energy, 139, 803-814.

Rocco, M., Colombo, E., & Colombo, G. (2021).

Urban multi-vector energy systems: A review. Energy Reports, 7, 2745-2760.

Wang, H., Zhou, P., & Zhou, D. (2012). An empirical study of urban energy consumption in China: STIRPAT model and decomposition analysis. Energy, 47(1), 590-596.

Okeil, A. (2010). A holistic approach to energy efficient building forms. Energy and Buildings, 42(9), 1437-1444.

Bai, X. (2016). Eight energy and material flow characteristics of urban ecosystems. Ambio, 45(7), 819-830.

International Energy Agency (IEA). (2020). World Energy Balances. OECD/IEA, Paris

.

United Nations-Habitat. (2020). World Cities Report 2020: The Value of Sustainable Urbanization. UN-Habitat, Nairobi.

Kennedy, C., Pincetl, S., & Bunje, P. (2011). The study of urban metabolism and its applications to urban planning and design. *Environmental Pollution, 159*(8–9), 1965–1973.

Mohajeri, N., Upadhyay, G., Gudmundsson, A., et al. (2019). Urban form and renewable energy potential. *Renewable Energy*, *139*, 803–814.

Newman, P., & Kenworthy, J. (1989). *Cities and automobile dependence: An international sourcebook*. Gower Publishing.

Okeil, A. (2010). A holistic approach to energy-efficient building forms. *Energy and Buildings, 42*(9), 1437–1444.

Reinhart, C. F., & Cerezo Davila, C. (2016). Urban building energy modeling—A review of a nascent field. *Building and Environment, 97*, 196–202.

Rocco, M. V., Colombo, E., & Colombo, G. (2021). Urban multi-vector energy systems: A review. *Energy Reports*, *7*, 2745–2760.

Salat, S. (2011). *Cities and forms: On sustainable urbanism*. Hermann.

Wolman, A. (1965). The metabolism of cities. *Scientific American*, *213*(3), 179–190.

Zhou, X., et al. (2025). Integrated urban energy modelling: Recent advances, challenges and future directions. *Applied Energy*.