UP4652

Exploring Energy Efficiency in Historical Urban Fabrics for Energy-Conscious Planning of New Urban Developments

Pardis Akbari[1] and Abbas Ziafati Bafarasat[2]

Abstract

The global rise in urban energy demand poses severe environmental and economic health challenges. We need adaptive policies in urban planning to reduce the need for urban energy. This has become a prominent agenda in urban planning, encompassing social (education and innovation in consumption), economic (real pricing), and physical (urban morphology) aspects. This research aims to investigate the influential role of urban form, particularly the physical environment, on energy performance. The methodological approach is centered on conducting analytical-comparative research to examine how urban form influences theoretical energy requirements. Yazd City is selected as a case study because of its distinctive features and traditional approaches to urban sustainability, which have been largely overlooked in previous energy consumption investigations. In a broader comparative context, five tissue types (morphological units) have been selected from Rome, Barcelona, Madrid, and Venice and used as the analytical basis of the study. The research categorizes urban forms into three levels: macro (fabric), medium (block), and micro (building patterns). Heating, cooling, and total energy consumption were computed at each level. The findings indicate that, at the macro scale, Barcelona fabric offers the highest potential for

---

[1] Virginia Tech University, School of Public and International Affairs, Blacksburg, Virginia, United States (corresponding author). Pardisa@vt.edu

[2] Oxford Brookes University. aziafati-bafarasat@brookes.ac.uk

adaptation in the hot, dry climate of Yazd City. Moreover, the paper analyzes the most recurring morphological indices in the tissues and proposes guidelines for new developments tailored to Yazd City's unique climatic conditions. By focusing on urban form's impact on energy performance, this research contributes to the broader understanding of sustainable urban planning. It offers valuable insights for energy-sensitive urban development in other contexts facing similar climate challenges.

Introduction

Climate change, greenhouse gas emissions, and air pollution have become pressing global concerns as cities expand and populations grow (Juaidi et al., 2019; Tong et al., 2019). Cities, which are hubs of social, cultural, and economic activities are responsible for 71% of the world's direct energy-related greenhouse gas emissions and two-thirds of its primary energy use (United Nations, 2015; Mostafavi et al., 2014). Among the urban sectors, buildings play a pivotal role which account the 60% of total energy use (IEA, 2016), making them a key target for energy efficiency strategies.

In the European Union, energy-saving strategies have predominantly focused on improving individual buildings since the 1980s, primarily centered on enhancing building structure compactness and optimizing envelope design parameters that influence heat transfer (Pacheco et al., 2012). However, Iran faces its own set of energy consumption challenges, with buildings accounting for about 40% of urban energy use, the highest proportion compared to other sectors (Esmaeili et al., 2010). With over 98% of building energy consumption in Iran derived from petroleum and gas production, buildings contribute significantly to air pollution (Nasrollahi, 2009). Urban form, which is determined by the physical characteristics of the built and natural surroundings significantly impacts how efficiently buildings use energy. (Rode et al., 2017; Bramley, 2009). Elements such as building orientation, street connectivity, land-use mix, and population density patterns all influence energy demand and carbon emissions (Wang et al., 2017; Crane, 2000). Studies have highlighted that urban form and building configuration can impact building energy consumption by up to 10% (Ratii et al., 2005). This underscores the significance of urban planning and design approaches in enhancing energy-efficient solutions to meet the concerns of global warming and climate change (Ramakreshnan et al., 2019).

Although there have been studies investigating the impact of urban form on fuel consumption in transportation, there is still a scarcity of comprehensive energy performance analyses conducted at an urban scale (Newman and Kenworthy, 1989; Vance and Hedal, 2007; Ewing et al., 2009). Furthermore, solely analyzing energy consumption at a single-building scale may not accurately represent real-world energy demands, as urban structures significantly influence building energy requirements, often overlooked in estimations (Pisello et al., 2012) For instance, in the hot-arid climate of Yazd, Khalili, and Amindeldar investigated particular traditional building components and discovered that features like the basement, Sardab, Hashti (vestibule), and wind catcher contributed reduce energy usage (Khalili & Amindeldar, 2014) On the other hand, Gupta demonstrated that buildings' energy consumption on a single-building scale may differ significantly from the energy consumption at a larger scale (Gupta, 1984).

To address the knowledge gap in evaluating energy demand at an urban scale, this paper seeks to identify key morphological indicators across macro, medium, and micro scales that can contribute to energy efficiency. By focusing on Yazd, a city known for its historical texture, and comparing it with urban fabrics like Madrid, Venice, Rome, and Barcelona, the study attempts to shed light on the direct connection between urban shape and the need for heating and cooling energy demand. By keeping non-morphological factors constant, such as insulation, materials, and building age, the research utilizes a sophisticated energy estimation program, the Energy Plus engine, to conduct a robust analysis of energy performance based on specific urban geometry and climatic conditions. The findings aim to inform the development of sustainable urban environments that address the challenges of urbanization and foster a greener, more resilient future.

In this study, the following questions will be addressed:

1. What are the determinative indicators of urban morphology that influence energy consumption?

2. Is the urban morphology of Yazd city the most efficient regarding its hot and dry climate?

3. How can the research findings be translated into urban planning guidelines for future developments?

Review of the Literature

Based on studies, a city's form and design significantly affect how much energy it consumes. Mostafavi et al. (2021) suggest a correlation between urban density and energy-use intensity (EUI). Nevertheless, the effect of urban density on EUI differs among various metropolitan areas. According to the study's findings, the distance between buildings at which urban form factors have the greatest impact on EUI varies from city to city and decreases as urban density increases. In other words, the relationship between urban form and energy-use intensity is not the same in all cities, and the distance from buildings that significantly affects EUI changes negatively with increasing urban density. Mutani et al. (2022) utilized a Geographic Information

System (GIS)-based engineering model to evaluate fluctuations in cooling energy demand within five separate blocks of buildings constructed during different periods in a continental-temperate climate. The analysis provided insights into how building attributes and urban form influence cooling energy demand, enabling the identification of optimal building block shapes in Turin for reduced energy consumption during the cooling season, irrespective of building types. Building coverage ratio, building density, primary street and building orientation, aspect ratio (height-to-width ratio), sky view factor, green area ratio, and normalized difference vegetation index were the main urban metrics used to define the urban morphology.

Zhang and Gao (2021) characterized various cases using form indices, including the floor area ratio (FAR), surface area ratio (SAR), and mean sky view factor (SVF). The research findings indicated a negative correlation between air temperature and direct shortwave radiation with surface ratio. Furthermore, the floor area and surface ratio showed an adverse relationship with cooling and heating loads, indicating that cooling and heating loads rise when these ratios fall. On the other hand, a positive correlation was observed between cooling and heating loads and average sky visibility, suggesting that higher cooling and heating loads are associated with increased average sky visibility. Vartholomaios et al. (2021) conducted a study investigating the geometric parameters that influence building energy balance. They noted a number of significant factors, such as dwelling shape, compactness, adjacencies, and shading that influence energy use at the urban scale. Leng et al. (2020), found that specific geometric factors affect the amount of heating energy consumption directly. Specifically, higher building site coverage (BSC), floor area ratio (FAR), building height (BH), road height-width ratio (RHR), and wall surface area (WSA) values were specifically linked to lower heating energy usage. FAR was picked out as one of these parameters that had the most detrimental effect on reducing the amount of energy used for heating.

Javanroodi et al. (2018) focused on analyzing the cooling loads of various urban forms in buildings. Their proposed solution involved creating denser neighborhoods with narrower streets surrounding the buildings. Additionally, they recommended using a height-to-width ratio (H/W) of 12 or higher for new neighborhoods. By implementing these urban planning strategies, the researchers observed a significant reduction in cooling loads, ranging from 2.3% to 17%, depending on the specific urban patterns considered. According to Morganti et al. (2018), the interaction between sunlight and urban form is significant. In their research, they studied fourteen different urban contexts in Rome and Barcelona, focusing on seven Urban Morphological Indices (UMI). These indices included the building's dimensional proportion, average building height, volume-to-area ratio, facade-to-site ratio, view-to-sky index, and floor space index.

In a study by Wei et al. (2016), the researchers identified several key indicators that play a significant role in determining urban morphology and influencing the microclimate. Among these, critical indicators are sky view indicators, floor area ratio, occupied area ratio, and the number of floors in buildings. Martins et al. (2016) found that certain indicators play a crucial role in their study. Specifically, the indicators of aspect ratio (referring to the height-to-width ratio of buildings), the distance between buildings, and the surface reflection coefficient were identified as the most important factors. In the research conducted by Rode et al. (2014), they found that certain urban design characteristics have a significant impact on heating energy efficiency. Specifically, dense buildings, compact blocks, and high-rise buildings contribute to increased heating energy efficiency in urban areas. In addition, they observed that canyons with a northeast-southwest (NE-SW) orientation tend to consume less energy in hot climate areas compared to other orientations. On the other hand, canyons with a northwest-southeast (NW-SE) orientation were found to consume the most energy. Moreover, they noted that for sky view factors (SVF) ranging from 0.71

to 0.34 and height-to-width ratios (H/W) between 0.5 to 2.0, the reduction in energy consumption can reach as much as 9.5%.

Martili et al. (2014) found that compact cities have the potential to reduce space heating and cooling demands, especially in mid-latitudes and hot, dry climate regions. This is achieved by maintaining low face-to-volume ratios (S/V) in the urban form. Wong et al. (2011) conducted a study examining the impacts of 32 separate urban setting scenarios on the energy performance of a three-story office building in Singapore. Their research highlighted that the height of neighboring buildings has a substantial impact on the air-conditioning energy consumption of the studied building.

Specifically, they found that certain urban configurations, such as taller surrounding buildings, have the potential to reduce air-conditioning energy consumption in the office building by up to 5%. In the research conducted by Krüger et al. (2010), they observed that increasing the height of adjacent buildings has a positive impact on reducing cooling demands. Additionally, they found that this effect is similar to the impact of having deeper streets in the urban environment. Arboit et al. (2008) introduced morphological parameters such as street width, building shape, and block direction and analyzed their impact on thirty-two low-density urban residential blocks. The research findings indicated that building shape and orientation play significant roles in absorbing solar energy in these urban settings. Specifically, the shape and direction of buildings influence their ability to capture solar energy effectively. On the other hand, the width of the street was found to have little to no effect on solar energy absorption in some cases.

Ratti et al. (2003) introduced the central courtyard as the best model from the perspective of thermal performance by simulating different models in hot and dry climates. Also, interior proportions were considered a fundamental factor in energy consumption. Among the groundbreaking investigations in the literature are those by Olgyay (1963) and Martin (1967), who used geometric approaches to building form and fundamental scientific concepts, supported by experimental findings, to predict energy consumption at a micro-scale. Gupta's study in 1984, following Martin's work, further explored the impact of building form at a macro scale. Gupta's research demonstrated that factors such as the distance between buildings, orientation, and form significantly influence thermal performance. Newton et al. (2000) conducted a study focusing on the operational energy consumption of several housing types in various climate zones in Australia. Based on their findings, they concluded that apartment buildings tend to consume less energy compared to detached houses. Based on the literature review, Table 1 indicates morphological factors that should be used to examine the urban morphology of a context at three different scales for study of urban energy efficiency.

As demonstrated earlier, despite extensive research about the influence of urban morphology on building performance, there remains a gap in studies focusing on the block and urban scales. Understanding the energy efficiency of urban morphology at different scales presents a promising avenue to mitigate energy consumption in the heating and cooling sector (Troy et al., 2003). In this paper, the researchers focus on analyzing the most repetitive indexes that play a crucial role in shaping urban energy performance. These key indexes include:

- Building pattern (building form): refers to the general layout and design of buildings in an urban setting, which influences thermal comfort and energy use.
- Surface-to-volume ratio (S/V): represents the ratio of the external surface area of buildings to their enclosed volume, affecting heat exchange with the surrounding environment.

- Orientation: relates to the direction that buildings face, which affects how much sunshine and shading they get as well as how much energy is consumed for heating and cooling as a result.
- Floor space index (FSI): describes the proportion of a building's total floor space to its total land area, which affects building density and the potential for energy efficiency.
- Density: refers to the population or building density within an urban area, which can influence energy demand and infrastructure requirements.

Through the examination of these indexes, the study seeks to acquire a more profound comprehension of how urban morphology affects energy efficiency, especially concerning heating and cooling requirements. These parameters are essential in determining how buildings interact with their surroundings and how the urban layout affects energy consumption patterns.

Case Study

Yazd is both a UNESCO World Heritage Site and the winner of a worldwide sustainability award which is known for its unique architectural style and urban texture. (Energy Globe, 2018). In addition, as the world’s second oldest city, is strategically located in the middle of Iran's plateau, east of the Zagros Mountains, among the latitudes of 29-34N and 52-56E. The Dasht-e Kavir and Dasht-e Lut deserts border the city on its northern and eastern sides, respectively. With an average elevation of 850 m above sea level and a population of 1,300,000, approximately 80% of which live in urban areas, Yazd faces arid conditions, experiencing merely 23 rainy days per year, making it one of the driest cities in Iran (Ziafati, 2021). The province of Yazd accounts for 6.3% of the country's total area (Mostafaeipour, 2010). The region exhibits a wide temperature fluctuation during summer and winter, with typical maximum temperatures reaching around 45°C and minimum temperatures dropping to −20°C (Dehghan, 2011). Figure 1 illustrates the positioning of Yazd city within Iran and its respective province.

Methodology

Depending on the study objectives, the research approach could be categorized as simulation research utilizing computer-aided tools or documentary-applied research based on historical data (Leng et al., 2020). This research studied the effective morphological indicators of energy consumption using exploratory and analytical approaches. To identify factors of urban morphology affecting the amount of energy consumption, peer reviewed literature available in Google Scholar and Web of Science were reviewed along with hard library literature, and the most repeated indicators were introduced as the indicators used in this research.

The Energy Plus analysis engine was utilized to conduct the simulation method. This energy analysis engine is located within the Honeybee plugins and Grasshopper software. The components that influence the building's shape were incorporated into the Grasshopper environment as a model, and the parameters impacting the building's energy performance were formulated as a parametric model. Subsequently, considering the morphological and climatic background information, the software commenced the simulation process and provided the energy demand for heating and cooling.

This method also facilitated easy modification of any parameter. The validation of the output information from this software was strongly supported by the utilization of the Energy Plus simulation engine, recognized as the most powerful energy calculation and analysis engine globally, developed by the US Department of Energy. Other software, such as Design Builder, also utilizes this engine. One of the most significant attributes of this software is its ability to calculate multiple parameters simultaneously. The choice of this software was based on its precision and widespread application in various researches within this field (Wetter et al., 2015)

As the empirical basis of this research, six scenarios were identified, including the historical context of Yazd city and five other contexts with different morphological patterns. These tissues were from Rome, Barcelona, Madrid, and Venice. Although the weather conditions in these cities were different, the energy consumption of these tissues was evaluated based on Yazd weather conditions. The selection of these cities ensured a wide range of textures was covered, representing diverse national building cultures that had led to apparent differences in the typology of textures over the centuries. Another reason for using these tissues was their repeated use in the field of morphology as a superior experience (Salvati et al., 2017; Gherri et al., 2021) After selecting the studied cities, their morphologies were first scanned. A qualitative approach was utilized in the initial step of this procedure, which mostly relied on speaking with specialists regarding historiological styles and the composition of buildings and urban areas. The snowball sampling helped to find relevant researchers and those familiar with the historical context of cities. A snowball sampling process built a sample of potential participants in the research inquiry by referring them to other acquaintances who could potentially contribute to the study (Biernacki et al., 1981). Eventually, in order to select the desired textures, interviews were conducted with experts skilled in the field of historical textures.

In the next stage, Google Earth was used to explore the cities through satellite images. The scale of urban texture representations was chosen from a spectrum with a checkered grid of one kilometer by one kilometer (Theurer, 1999), 400 meters by 500 meters (Adolphe, 2001), 100 meters by 100 meters (Cionco and Ellefsen, 1998), 500 meters by 500 meters (Rode et al., 2014), and 4 km x 4 km (Long et al., 2003). For the analytical phase of the research, a 150m x 150m spatial unit area was selected. This choice was made to align with the geometric simulation process of each tissue and to establish a suitable scale that corresponds to the inherent complexities of a basic tissue. This tissue encompasses diverse elements at different morphological levels, including street configurations, plot layouts, and building patterns.

Eventually, all six tissues were analyzed in three different scales. The simulation method is described in detail below:

First, the desired tissues were simulated based on morphological indicators and techniques. The models varied depending on different species and indicators, such as differences in density or grain arrangement within a tissue.

Subsequently, the algorithm necessary for conducting an energy analysis of the model was formulated and created. The first part of the algorithm involved entering the file containing climatic characteristics and the 3D-model. Weather files were downloaded from the internet based on geographic coordinates, providing information on radiation intensity, humidity, temperature, and more, obtained from weather stations or satellite data.

Other factors influencing the energy demand of the urban fabric, such as roof and wall materials, facade materials, floor types, and window insulation, were also considered (Kampf & Robinson, 2009). To ensure analytical and comparative validity, all non-morphological factors were kept constant for the six morphological scenarios. Thus, variables like user behavior, land use, green space coverage, air exchange rate, material reflection coefficient, insulation coefficient, heat transfer coefficient, wall, and facade materials remained consistent, with the only varying factor being the geometry and configuration of the city shape in the environmental functions.

The second part involved providing information about the number of openings and transparent walls on different physical levels (fronts) to enable the software to analyze the amount of penetrating light and energy, as well as energy loss in different months. A standardized ratio of the amount of opening, used in most studies, was applied to maintain comparability across scenarios.

The third part focused on natural ventilation, a critical input in the simulation model to determine the range of thermal comfort during hot and cold seasons. A minimum comfort temperature of 20 degrees Celsius in the cold seasons and 26 degrees Celsius in the hot seasons was taken into consideration for the building interiors based on international research and Iran's national building requirements (Changalvaiee et al., 2017).

The subsequent step involved providing information about materials and consumables, considering their general characteristics affecting building energy consumption, including heat capacity, reflection, etc. The materials' characteristics were aligned with section 19 of climate buildings related to Yazd. The Honeybee plugin allowed the researcher to choose the most appropriate materials for the physical models based on weather and relevant information. Various settings were adjusted in the following stages of the energy simulation algorithm, such as the length of the energy calculation period (monthly, daily, hourly) and the specific seasons (hot or cold). Additionally, north direction relative to the model and other settings were considered. The outputs were then presented in two modes: energy demand for heating and energy demand for cooling models, presented in selected units (e.g., kWh). Figure 2 presents a sample depiction of the simulated fabrics alongside the algorithms utilized for energy demand analysis.

The primary purpose of this research was to gain insight into the impact of morphological variables on improving energy efficiency in the climate of Yazd city, introducing a novel approach to address planning and design challenges.

Findings

In this research, fabric of Yazd city and five other fabrics including Rome, Barcelona, Madrid and Venice are modeled and simulated in the software as outlined in Figure 3. After simulation, the heating, cooling, and total energy demand are computed in three macro, medium and micro scales. Table 2 demonstrates that at a large scale, the Barcelona fabric exhibits the highest degree of responsiveness in the hot, and dry climate similar to Yazd city. Figure 4 also illustrates this comparison of the energy demand for heating, cooling, and the sum of heating and cooling.

To explore the medium (block) scale, sixteen rectangular buildings were strategically placed in diverse configurations to analyze their respective effects, as outlined in Table 3. Initially, the analysis focused on the first seven patterns, each having the same height and area. Among these patterns, pattern number 4, featuring a linear arrangement of two rows of eight adjacent north-south buildings, exhibited the lowest energy demand proportion. This outcome was attributed to the pattern's lower volume-area ratio, as demonstrated by a thorough examination of morphological indicators affecting energy efficiency. Consequently, reducing the volume-area ratio at both the building and block scale contributed to decreased energy demand.

Further analysis was conducted on patterns number 8, 9, and 10, which revealed that pattern 8 had the lowest energy demand, while pattern 10 had the highest. This observation indicated that buildings with lesser height, higher floor space index, and lower volume-area ratio resulted in lower energy demand. An exploration of the volume-area ratio indicator in the block scale indicated that pattern number 10, comprising four 4-story buildings, had the lowest volume-area ratio. However, pattern number 4, with a higher volume-area ratio, demonstrated lower energy demand. This was attributed to the more optimal floor space and density indexes in pattern number 4 compared to pattern number 10. The findings emphasize the need to consider multiple indicators when designing and segmenting buildings or blocks, as focusing solely on one indicator may not lead to the most optimal solutions.

In the small-scale (building pattern) analysis, five common building patterns were studied: central courtyard, cross-shaped pattern, north-south rectangular building, east-west rectangular building, and square building, which are presented in Table 4. The findings revealed that central courtyard and cross-shaped patterns exhibited the highest energy demand, while square and east-west rectangular patterns demonstrated the best energy efficiency. Additionally, Figure 5 illustrates the total, cooling, and heating energy demand across three distinct scales, ranging from macro to micro scale, with corresponding demonstrations in the software.

Furthermore, the research delved into analyzing indicators such as geographical orientation, floor space index, density, and volume-area ratio. The results highlighted the significant impact of geographical orientation on the energy demand.

Analyzing of Indexes: Building and Block Pattern

The central courtyard, although a dominant building pattern in Yazd city, was found to be not the morphologically optimal model for Yazd's climate, contrary to public opinion (Khalil and Amindeldar, 2014). Interestingly, the city of Barcelona, with its texture of rectangular buildings, exhibited the lowest cooling, heating and sum of cooling and heating energy demand among all textures. Despite not being an efficient form on a single scale, at the urban block scale, these rectangles displayed a lower surface ratio when attached from a longer front, resulting in a reduced surface-to-volume ratio index and energy demand.

Similarly, in other patterns, the linear texture chosen from the city of Madrid, which is also a common construction pattern in Iranian cities, ranked second after Barcelona in terms of energy demand. Like the rectangular pattern in Barcelona, these textures comprised rectangular structures joined together from longer facades, reducing surface exposure to radiation, and subsequently lowering energy demand as the surface-to-volume ratio decreased. Thus, the rectangular pattern emerged as the most optimal option at scales higher than a single building.

Surface-to-Volume Ratio

The reduced surface-to-volume ratio evident in the textures of Barcelona and Madrid is attributed to their rectangular building patterns, row blocks, and larger land areas. As this ratio is directly linked to the amount of energy demand, it could serve as a key factor contributing to the high energy demand in Yazd and the comparatively low energy demand in Madrid and Barcelona. The more favorable surface-to-volume ratio in the latter two cities results in reduced energy consumption, highlighting the significance of this index in shaping energy demands across different urban contexts.

Orientation

The behavior of the orientation index depends on the building pattern being analyzed. The findings demonstrate that for square and rectangular building patterns, the most desirable orientation is along the east-west axis. On the other hand, in the central courtyard pattern, the preferred orientation is north-south which is aligning with the construction pattern in old fabric of Yazd city (Kasmaie, 2016). However, the overall impact of this indicator on energy demand has diminished due to other indicators not being in favorable condition.

Floor Area Ratio (FAR), or Floor Space Index (FSI)

The reduction in Floor Space Index (FSI) within buildings and urban blocks corresponds to a rise in energy demands, as depicted in Figure 6. Both Yazd and Venice have what is known as fine-grained textures, which means that the amount of construction on each plot of land is relatively small compared to the total area of the plot.

Density

The density index in Yazd's historical texture aligns with its optimal state of energy efficiency. Building density, or the number of floors, causes a rise in the need for cooling energy but a decrease in the need for heating energy. However, as can be seen in Figure 7, there is a modest increase in overall energy demand because the increase in cooling energy demand surpasses the decrease in total energy demand. Considering the Yazd's climate, cooling energy demand is a primary concern, accounting for a significant portion of functional energy demand. Consequently, the low building density in Yazd's climate fosters a more responsive approach to functional energy demand, taking into account the critical role of cooling energy requirements in the region.

Thus, it is crucial to consider the combined influence of multiple factors to holistically assess energy demand in the city. Considering all relevant indicators is essential for gaining a comprehensive understanding of energy efficiency in various urban contexts.

Broader Findings and Urban Development Guidelines

After investigating the strengths of Yazd's morphology (Kasmaie., 2016; Khalili and Amindeldar, 2014), and combining them with the results of this paper, the following guidelines can be presented for use in new urban developments:

1. Compactness: Buildings should be closely situated to minimize open spaces between them, promoting a compact urban form (Vartholomaios et al., 2021; Rode et al., 2014)

2. North-South Extension: Based on the findings regarding Madrid's energy demand patterns, it is recommended that attached buildings have a north-south orientation.

3. For separate buildings, the optimal orientation is an east-west extension. This implies that these buildings should ideally face south, with their front sides having the largest area oriented toward the south, as indicated in the Table 4.

4. As shown in the Table 3, for buildings with a north-south extension that feature an east-west front, it is advisable to minimize the number of openings to prevent energy loss. This is because these fronts tend to experience greater energy loss compared to other orientations. In addition, having more buildings parts placed together could decrease energy demand.

5. Surface Area to Volume Ratio: Lower surface area to volume ratios in building design result in reduced energy demand, making it an essential consideration (Martili et al., 2014).

6. Dome Roofs: Implementing dome-shaped roofs can reduce sunlight absorption, or alternatively, a smooth and bright surface can be used to absorb less heat (Kasmaie, 2016).

7. Night Ventilation: Due to Yazd's hot and dry climate, using massive structures with small holes that allow for night ventilation is recommended (Kasmaie, 2016).

8. Utilizing Basements: Using basements and underground tunnels can reduce heat during hot weather, taking advantage of the earth's stable temperature (Khalili and Amindeldar, 2014).

9. Light-Colored Materials: The use of light-colored materials reduces sunlight and heat absorption, reducing the need for cooling devices. Dark colors on east, south, and west-facing walls can be considered if they create shading during hot periods (Kasmaie, 2016).

Conclusion and Policy Implications

The simulation comparing the old fabric of Yazd city with other textures in its hot and dry climate indicates that Yazd fabric is not very energy efficient. However, there are different perspectives to consider, and merely focusing on statistics and quantities may not be enough; other aspects need investigation. Some scholars argue that, especially on a small scale, Yazd city fabric is energy efficient due to various reasons like using local materials with insulation, having separate spaces for summer and winter, and incorporating traditional elements like wind catchers, cellars, vestibules, halls, and central courtyards (Khalili and Amindeldar., 2014; Soflaee and Shokouhian., 2005). This has led to conflicting conclusions.

For instance, the energy efficiency of summer and winter spaces relies on people's behavioral patterns, allowing for adaptability and movement. This aspect cannot determine by the morphological efficiency of the buildings. On the other hand, some believe that using courtyards can create a microclimate in each building, resulting in energy efficiency. However, it's important to note that although the result of this paper may indicate that the courtyard building pattern is not energy efficient, if we consider it as a suitable pattern, we face other concerns.

One of these concerns is the increasing land prices today, making it impractical to build buildings in the same way as in the past when parcel areas were larger. Additionally, achieving balance in different seasons may require increasing residential space per person, leading to urban sprawl and greater energy consumption for commuting, thus shifting the energy burden to the transportation sector. This highlights the need for a comprehensive approach that considers all aspects simultaneously in this type of research. To truly understand energy efficiency and its implications, it is essential to consider both the architectural design and people's behavior, along with various external factors, to ensure sustainable and effective urban planning. It's important to note that this study kept non-morphological factors, such as user behavior, land use, green space coverage, insulation coefficient, material reflection coefficient, and heat transfer coefficient, constant across six morphological scenarios.

In summary, this research aimed to estimate energy consumption in the old fabric of Yazd city and five other morphological patterns, investigating energy use at macro, medium, and micro scales to identify the most efficient pattern in each category. The findings have significant implications for planning new urban developments, and the codes and guidelines derived from this study can be used to build more energy-efficient cities.

Suggestions and Limitations

Since the morphological indicators affecting energy consumption at different scales are very large, it is not possible to integrate and examine all the indicators at all scales due to the limited time of conducting the research. Also, considering other components such as humidity and wind in different internal and external spaces leads to a more stable form, which is impossible to do in this research due to the lack of a comprehensive software to consider all cases. This gap gives an opportunity to interested programmers and researchers to create a link between components and produce comprehensive software by developing plugins and programming in the Python environment. Such software creates buildings, blocks, and textures compatible with the climate along with thermal energy efficiency, which will bring comfort to the residents. It is suggested that the internal division of spaces should also be considered in future research. Furthermore, the demand for lighting energy has not been investigated in this research and could be consider in the future investigation.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article

References

A. Martilli, An idealized study of city structure, urban climate, energy consumption, and air quality, Urban Clim. 10 (2014) 430–446.

Arboit, M., Diblasi, A., Llano, J. F., & de Rosa, C. (2008). Assessing the solar potential of low-density urban environments in Andean cities with desert climates: The case of the city of Mendoza, in Argentina. Renewable Energy, 33(8), 1733-1748

Biernacki, P., & Waldorf, D. (1981). Snowball sampling: Problems and techniques of chain referral sampling. Sociological Methods & Research, 10(2), 141–163. https://doi.org/10.1177/004912418101000205

Bramley, G.; Power, S. Urban Form and Social Sustainability: The Role of Density and Housing Type. Environ. Plann. B Plann. Des.2009, 36, 30–48.

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.

Changalvaiee, Y., Behzadfar, M., Mohammadi, M., & Zarabadi, Z. S. S. (2017). Urban Morphology and Energy Performances: Investigating the impacts of urban openness factor on theoretical energy demand, Case study: IsFahan Urban Morphological Types,147-133,18(10).

Cionco, R. M., & Ellefsen, R. (1998). High Resolution Urban Morphology Data for Urban Wind Flow Modeling, Atmospheric Environment, 32, 7-17.

Crane, R. The Influence of Urban Form on Travel: An Interpretive Review. J. Plan. Lit. 2000, 15, 3–23.

Delmastro, C., G. Mutani, M. Pastorelli, and G. Vicentini. "Urban Morphology and Energy Consumption in Italian Residential Buildings." 2015 International Conference on Renewable Energy Research and Applications (ICRERA), 2015. https://doi.org/10.1109/icrera.2015.7418677.

Energy Globe, 2018. Energy Globe World Awards 2018. Energy Globe.

Esmaeili, M., Asghari, A., Baziyar, M., Jalalzadeh, A., Rahaie, A., Somelo, A., Kazemi, A., Keramati, M., Golabchi, A., & Havaie, M. (2010). Iran's National Building Regulations, Department of Housing and Urban Development.

Ewing, R., & Dumbaugh, E. (2009). The built environment and traffic safety. Journal of Planning Literature, 23(4), 347–367. https://doi.org/10.1177/0885412209335553

Gherri, B., Maiullari, D., Finizza, C., Maretto, M., & Naboni, E. (2021). On the Thermal Resilience of Venetian Open Spaces. Heritage, 4(4), 4286–4303. https://doi.org/10.3390/heritage4040236.

Gropius, W., & Gropius, W. A. G. (1965). The new architecture and the Bauhaus (Vol. 21): MIT press.

Gupta, V. K. (1984). Solar radiation and urban design for hot climates. En- vironment and Planning B, 11 (4), 435-454.

Javanroodi, K., Mahdavinejad, M., & Nik, V. M. (2018). Impacts of urban morphology on reducing cooling load and increasing ventilation potential in hot-arid climate. Applied Energy, 231, 714–746. https://doi.org/10.1016/j.apenergy.2018.09.116

Juaidi, Adel, Fadi AlFaris, Faris Saeed, Esther Salmeron-Manzano, and Francisco Manzano-Agugliaro. “Urban Design to Achieving the Sustainable Energy of Residential Neighbourhoods in Arid Climate.” Journal of Cleaner Production228 (2019): 135–52. https://doi.org/10.1016/j.jclepro.2019.04.269.

Kämpf, J. H., & Robinson, D. (2009 (b)). Optimization of Urban Energy Demand Using an Evolutionary Algorithm. In Proceedings of the Eleventh International IBPSA Conference, Glasgow.

Kasmaie. M.(2016), Climate and Architecture, Iran Investment and House Construction Company.

Khalili, M., & Amindeldar, S. (2014). Traditional solutions in low energy buildings of hot-arid regions of Iran. Sustainable Cities and Society, 13, 171-181.

Krüger, E.; Pearlmutter, D.; Rasia, F. Evaluating the Impact of Canyon Geometry and Orientation on Cooling Loads in a High-Mass Building in a Hot Dry Environment. Appl. Energy **2010**, 87, 2068–2078.

Leng, Hong, Xi Chen, Yanhong Ma, Nyuk Hien Wong, and Tingzhen Ming. "Urban Morphology and Building Heating Energy Consumption: Evidence from Harbin, a Severe Cold Region City." Energy and Buildings 224 (2020): 110143. https://doi.org/10.1016/j.enbuild.2020.110143.

Li Z, Quan S, Yang P. Energy performance simulation for planning a low carbon neighborhood urban district: a case study in the city of Macau. Habitat Int 2016;53: 206–14.

Li, H., Chen, X., Ma, Y., Wong, N. H., & Ming, T. (2020). Urban morphology and building heating energy consumption: Evidence from Harbin, a severe cold region city. Energy and Buildings, 224, 110143. https://doi.org/10.1016/j.enbuild.2020.110143

Martins, Tathiane Agra, Luc Adolphe, Leopoldo Eurico Bastos, and Michele Agra Martins. "Sensitivity Analysis of Urban Morphology Factors Regarding Solar Energy Potential of Buildings in a Brazilian Tropical Context." Solar Energy 137 (2016): 11–24. https://doi.org/10.1016/j.solener.2016.07.053.

Morganti, Michele, Agnese Salvati, Helena Coch, and Carlo Cecere. "Urban Morphology Indicators for Solar Energy Analysis." Energy Procedia 134 (2017): 807–14. https://doi.org/10.1016/j.egypro.2017.09.533.

Mostafaeipoir, A. (2010). Feasibility study of harnessing wind energy for turbine installation in province of Yazd in Iran. Renewable and Sustainable Energy Reviews 15(3):1575-1592

Mostafavi, N., Heris, M. P., Gándara, F., & Hoque, S. (2021). The Relationship between Urban Density and Building Energy Consumption. Buildings, 11(10), 455. https://doi.org/10.3390/buildings11100455

Mostafavi, N.; Farzinmoghadam, M.; Hoque, S.; Weil, B. Integrated Urban Metabolism Analysis Tool (IUMAT). Urban Policy Res. 2014, 32, 53–69.

Mutani, G, V Todeschi, and S Santantonio. "Urban-Scale Energy Models: The Relationship between Cooling Energy Demand and Urban Form." Journal of Physics: Conference Series 2177, no. 1 (2022): 012016. https://doi.org/10.1088/17426596/2177/1/012016.

Nasrollahi, F. (2013). Green office buildings: low energy demand through architectural energy efficiency, Berlin: Universitatsverlag der TU Berlin.

Nasrollahi,F.(2009). Climate and Energy Responsive Housing in Continental Climates, Univerlagtuberli press.

Newman, P., & Kenworthy, J. (1989). Gasoline Consumption and Cities. Journal of the American Planning Association, 55(1), 24–37. https://doi.org/10.1080/01944368908975398.

Newton, P.; S. Tucker and M. Ambrose. (2000). Housing form, energy use and greenhouse gas emissions. pp. 74 - 84 in: Williams, K., E. Burton and M. Jenks. (2000). Achieving Sustainable Urban Form. Spon Press, Taylor and Francis Group, London.

Olgyay, V. (2015). Design with climate: bioclimatic approach to architectural regionalism-new and expanded edition: Princeton university press.

Pacheco, R., Ordóñez, J., & Martínez, G. (2012). Energy efficient design of building: A review. Renewable & Sustainable Energy Reviews, 16(6), 3559–3573. https://doi.org/10.1016/j.rser.2012.03.045

Pisello, A. L., Taylor, J. E., Xu, X., & Cotana, F. (2012). Inter-building effect: Simulating the impact of a network of buildings on the accuracy of building energy performance predictions. Building and Environment, 58, 37–45. https://doi.org/10.1016/j.buildenv.2012.06.017.

Ramakreshnan L, Aghamohammadi N, Fong C, Ghaffarianhoseini A, Wong L, Noor R, Hanif N, Azriyati Wan Abd Aziz W, Sulaiman N, Hassan N. A qualitative exploration on the awareness and knowledge of stakeholders towards Urban Heat Island phenomenon in Greater Kuala Lumpur: critical insights for urban policy implications. Habitat Int 2019;86:28–37.

Ratti, C., Baker, N., & Steemers, K. (2005). Energy consumption and urban texture. Energy and Buildings, 37(7), 762-776.

Rode, P., Keim, C., Robazza, G., Viejo, P., & Schofield, J. (2014). Cities and energy: urban morphology and residential heat-energy demand. Environment and Planning B: Planning and Design, 41(1), 138-162.

Rode, P.; Floater, G.; Thomopoulos, N.; Docherty, J.; Schwinger, P.; Mahendra, A.; Fang, W. Accessibility in Cities: Transport and Urban Form. In Disrupting Mobility: Impacts of Sharing Economy and Innovative Transportation on Cities; Meyer, G., Shaheen, S., Eds.;Lecture Notes in

Mobility; Springer International Publishing: Cham, Switzerland, 2017; pp. 239–273. ISBN 978-3-319-51602-8.

Salvati, A., Monti, P., Roura, H. C., & Cecere, C. (2019). Climatic performance of urban textures: Analysis tools for a Mediterranean urban context. Energy and Buildings, 185, 162–179. https://doi.org/10.1016/j.enbuild.2018.12.024.

Soflaee, F., & Shokouhian, M. (2005). Natural cooling systems in sustainable traditional architecture of Iran. Paper presented at the International Conference on Passive and Low Energy Cooling for the Built Environment.

Theurer, W. (1999). Typical Building Arrangements for Urban Air Pollutant Modeling, Atmospheric Environment, 33, 4057-4069.

Tong L, Hu S, Frazier A. Hierarchically measuring urban expansion in fast urbanizing regions using multi-dimensional metrics: a case of Wuhan metropolis, China. Habitat Int 2019;94:102070

Troy, P., D. Holloway, et al. (2003). Embodied and operational energy consumption in the city. Urban Policy and Research 21(1): 9-44.

United Nations (2015). Global initiative for resources efficient cities, Paris, France. France, Paris: United Nations Environment Programme. Retrieved from http://unep.org/.

Urban Database Analysis for Mapping Morphology and Aerodynamic Parameters: the Case of St. Jerome Sub- urban Area, in Marseille During Escompte.

Vance, C., and Hedal, R. (2007). “The impact of urban form on automobile travel: Disentangling causation from correlation.” Transportation, 34(5), 575–588.

Vartholomaios, Aristotelis, Angeliki Chatzidimitriou, and Konstantinos Ioannidis. “Estimating the Influence of Building and Urban Form on the Thermal Loads of Urban Dwellings in the Mediterranean Climate Using Machine Learning.” Energy Sources, Part B: Economics, Planning, and Policy 16, no. 8 (2021): 687–706. https://doi.org/10.1080/15567249.2021.1916796.

Vartholomaios, Aristotelis. “A Parametric Sensitivity Analysis of the Influence of Urban Form on Domestic Energy Consumption for Heating and Cooling in a Mediterranean City.” Sustainable Cities and Society 28 (2017): 135–45. https://doi.org/10.1016/j.scs.2016.09.006.

Wang, S.; Liu, X.; Zhou, C.; Hu, J.; Ou, J. Examining the Impacts of Socioeconomic Factors, Urban Form, and Transportation Networks on CO2 Emissions in China’s Megacities. Appl. Energy 2017, 185, 189–200.

Wei, Ruihan, Dexuan Song, Nyuk Hien Wong, and Miguel Martin. “Impact of Urban Morphology Parameters on Microclimate.” Procedia Engineering 169 (2016): 142–49 https://doi.org/10.1016/j.proeng.2016.10.017.

Wetter, M., Nouidui, T. S., Lorenzetti, D. M., Lee, E. A., & Roth, A. (2015). Prototyping the Next Generation EnergyPlus Simulation Engine. Conference Paper. https://doi.org/10.26868/25222708.2015.2419.

Wong, N.H.; Jusuf, S.K.; Syafii, N.I.; Chen, Y.; Hajadi, N.; Sathyanarayanan, H.; Manickavasagam, Y.V. Evaluation of the Impact of the Surrounding Urban Morphology on Building Energy Consumption. Sol. Energy **2011**, 85, 57–71.

Yang, Feng, Feng Qian, and Stephen S.Y. Lau. “Urban Form and Density as Indicators for Summertime Outdoor Ventilation Potential: A Case Study on High-Rise Housing in Shanghai.” Building and Environment 70 (2013): 122–37. https://doi.org/10.1016/j.buildenv.2013.08.019.

Yardımlı, S., Özer, D. G., & Shahriary, A. (2020). Sustainable street architecture and its effects on human comfort conditions: Yazd, Iran. İTÜ Dergisi A, 17(2), 113–122. https://doi.org/10.5505/itujfa.2020.70188.

Zhang, Mingjie, and Zhi Gao. “Effect of Urban Form on Microclimate and Energy Loads: Case Study of Generic Residential District Prototypes in Nanjing, China.” Sustainable Cities and Society 70 (2021): 102930.https://doi.org/10.1016/j.scs.2021.102930.

Ziafati Bafarasat, A. (2021). Is our urban water system still sustainable? A simple statistical test with complexity science insight. Journal of Environmental Management, 280, 111748. https://doi.org/10.1016/j.jenvman.2020.111748

Table 1. The three different scales of examining morphological factors in examination of urban energy efficiency

Morphological Scale	Variables
Macro level	Spatial Configuration
	Site Occupancy
	Density
	Urban Geometry
	Green plot ratio (GNPR)
	Perimeter-to-area ratio
Medium Level	Direction of roads
	Orientation of blocks
	Road surface
	Shadow area
	Street width
	Surface-to-volume ratio
	Density of blocks
	Height of blocks
	The number of external surfaces
Micro Level	Building height
	Building form
	Floor area ratio (FAR)
	Occupancy level
	Surface to volume ratio
	Sky view factor (SVF)

	Elongation of buildings
	Height-to-width ratio(H/W)
	Floor space index (FSI)

Table 2. Fabric patterns and energy demands in six different morphological contexts

Texture Name	Sum of Cooling and Heating Energy Demand (KWH/m^2)	Cooling Energy Demand (KWH/m^2)	Heating Energy Demand (KWH/m^2)
Yazd traditional texture	150.9578	87.08846	63.86935
Venice	101.158	67.7567	33.4013
Rome 1	94.51698	63.5985	30.91848
Barcelona	57.73963	50.63046	7.109166
Madrid	76.09255	59.31933	16.77323
Rome 2	144.6056	70.05906	74.54654

Table 3. Block patterns and energy demand in six different morphological contexts

Pattern Number	Block Pattern Type	Sum of Cooling and Heating Energy Demand (KWH/m^2)	Cooling Energy Demand (KWH/m^2)	Heating Energy Demand (KWH/m^2)
1	Linear pattern with east-west blocks	119.395873	88.312727	31.083146
2	Linear pattern with north-south blocks	94.500355	68.241051	26.259304
3	Linear pattern with 2 rows of 8 adjacent east-west buildings	94.598031	68.339873	26.258157
4	Linear pattern with 2 rows of 8 adjacent north- south buildings	83.548727	59.267807	24.632581
5	Linear pattern with central courtyard buildings	99.116091	70.48351	28.632581
6	Central courtyard block pattern	87.841259	62.34567	25.49559
7	Central courtyard block pattern(number2)	109.972563	80.29923	29.942639
8	1 building on 16 floors (16-storey building)	125.505752	107.3764434	18.129308
9	2 building blocks on 8 floors	101.034592	88.91372911	12.120863
10	4 4-storey buildings	90.158846	78.31568329	11.843163

Table 4. Building patterns and energy demand in six different morphological contexts

Building Pattern Type	Sum of Cooling and Heating Energy Demand (KWH/m^2)	Cooling Energy Demand (KWH/m^2)	Heating Energy Demand (KWH/m^2)
Central courtyard building	135.5256	97.21286	38.31277
Cross-shaped building	145.783188	105.810892	39.972297
North-south rectangular building	114.6696	84.46359	30.20597
East-west rectangular building	108.3141	79.0579	29.25622
Square building	108.2946	79.30629	28.98833

Fig. 1. Map of (a) Iran, (b) Yazd Province and (c) Historic city of Yazd (source: Esri, OpenStreetMap contributors, TomTom, Garmin, FAO, NOAA, USGS (2024)).

Fig. 2. 3D-modeling of Barcelona urban fabric with algorithm for energy demand analysis

Fig. 3. The satellite images and simulated models of six fabric patterns (source: Google Earth. (2024). Imagery ©2024 Google, Map data ©2024 Inst. Geogr. Nacional, United States. Retrieved from https://earth.google.com.

Fig .4. Cooling, heating and sum of cooling and heating energy demand in specified fabrics

Fig .5. Energy demand in different fabrics at three scales

Fig. 6. Heating energy demand with different floor area ratio

Fig. 7. Sum of heating and cooling, cooling, and heating energy demand in various densities