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Urban Morphology and Energy Performance: Spatial-Simulation Assessment from Hebron, Palestine

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ABSTRACT

Urban morphology critically governs residential energy demand, yet empirical evidence from semi-arid, geopolitically constrained cities remains scarce. This study quantifies the influence of neighbourhood form on heating and cooling loads in Hebron, Palestine. Three morphologically distinct districts—Old City (compact), Zeitoun (semi-structured) and Al Sheikh (unplanned sprawl)—were mapped in ArcGIS Pro to derive Floor Space Index, Ground Space Index and Open Space Ratio. Prototype mid-rise dwellings were modelled in DesignBuilder and simulated with EnergyPlus under identical boundary conditions. Pearson correlations and ANOVA assessed relationships between morphological variables and annual loads. Results show cooling demand decreases by 34 % as FSI rises from 0.7 to 1.2, whereas heating demand doubles under the same densification. The moderately dense Zeitoun configuration (FSI≈1.0, OSR≈1.6) achieved the lowest combined energy use, outperforming both extreme forms. Findings demonstrate that mid-rise, medium-density layouts balance summer shading with winter solar access, offering a viable pathway for energy-aware expansion in semi-arid contexts. The integrated spatial-simulation framework provides planners with transferable metrics for zoning and retrofit prioritisation, supporting climate-responsive urban policy across the Middle East. Future research should incorporate behavioural patterns and multiple building typologies to refine these benchmarks under climate-change scenarios.

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Highlights:	Contribution to the field statement:
- Investigates energy efficiency across diverse urban morphologies in Hebron using GIS. - Demonstrates that moderate-density mid-rise configurations optimize thermal performance. - Provides evidence that traditional dense urban forms reduce summer cooling demand. - Quantifies trade-offs between heating and cooling across spatial configurations. - Informs urban policy on sustainable development in energy-challenged environments.	This research provides quantitative evidence on how urban morphology influences energy performance in residential buildings in Hebron. Using GIS and energy simulation, the study identifies optimal urban configurations that reduce cooling and heating demand, offering planning insights for climate-responsive urban development in semi-arid regions.

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1. Introduction

Urban morphology is a principal determinant of residential energy efficiency, especially in semi-arid cities that experience rapid, largely unregulated change and geopolitical constraints such as Hebron. Over centuries, social, political and topographical forces have produced a stratified urban fabric whose neighbourhoods now differ markedly in density, openness and orientation (Shaheen & Dweik, 2017). Recent population growth has intensified these contrasts, creating an ideal test-bed for examining how morphology governs energy demand and thermal comfort.

A substantial international literature confirms that geometric properties of urban form—block depth, height-to-width ratio, street orientation and greenspace distribution—shape operational energy use and indoor comfort. Large-sample econometric work links building morphology to city-scale energy demand (Zhou, Xia, & Zhou, 2025), while design-stage simulation studies show that planning parameters can raise or curb end-use intensity (Lin, Luo, Gu, Hao, & Wang, 2025). Block-level optimisation can simultaneously cut cooling loads and boost photovoltaic yield (Wang, Huang, Zhang, Yang, & Dong, 2025). Data-centric approaches, including explainable graph-neural-network models, now reveal how "core forms" underpin functional performance (Chen et al., 2025). Landscape studies likewise demonstrate that tailoring greenspaces to local-climate zones enhances outdoor cooling efficiency (Cai, Li, & Liu, 2025).

Despite these advances, empirical evidence from Hebron is limited. Local enquiries rarely combine detailed spatial indicators with dynamic simulation, even though high-density quarters such as Al-Sheikh record greater cooling demand than the climate-attuned Old City, largely owing to building height, orientation and limited open space (Abu Daba't, 2024). Physical attributes such as housing typology and insulation have also been shown to drive heating requirements (Al Qadi, Sodagar, & Elnokaly, 2018). More broadly, compactness, enclosure and sky-view factor modulate seasonal energy loads (Demirci, 2021), while density, street layout and tree cover affect both cooling demand and passive solar gains (Ko, 2012; Narimani Abar et al., 2023). Yet quantitative, location-specific studies that integrate GIS metrics with calibrated simulation remain scarce for Palestinian cities.

International comparisons highlight the need for such context-sensitive research. Morphological evaluations in Seoul, Castellón and Sacramento revealed that neighbourhood-scale indicators reliably predict energy performance (Li, Yu, & Ng, 2021; Braulio-Gonzalo, Bovea, & Ruá, 2015; Wilson, 2013). Recent reviews stress the importance of climate-responsive, site-specific modelling frameworks (Li et al., 2023; Olu-Ajayi, Baird, & Okeil, 2024). Addressing this gap, the present study employs an integrated spatial-simulation framework to examine three morphologically distinct districts in Hebron—Old City (compact), Zeitoun (semi-structured) and Al Sheikh (unplanned sprawl). GIS analysis provides Floor Space Index, Ground Space Index and Open Space Ratio, whilst EnergyPlus simulations of prototype mid-rise dwellings quantify annual heating and cooling loads.

Two hypotheses guide the investigation:

- **H1**—Traditional urban forms in Hebron afford superior energy efficiency and thermal performance relative to recent unplanned developments.
- **H2**—Greater building density and reduced openness correlate with higher cooling-energy demand.

By fusing spatial indicators with dynamic simulation, this research delivers location-specific evidence on how morphology shapes residential energy use in a resource-constrained, semi-arid context. The findings supply transferable metrics for planners and support climate-responsive zoning, retrofit prioritisation and policy formulation across the Middle East and similar regions.

2. Materials and Methods

This research adopted a comparative case-study strategy encompassing three morphologically diverse neighbourhoods in Hebron: the Old City (traditional, compact street grid), Zeitoun (semi-structured infill fabric) and Al Sheikh (high-rise, unplanned sprawl). Representative residential

blocks were purposively sampled to typify each urban form, their selection governed by prevailing building height, orientation, plot coverage and integration within the surrounding fabric (Fig. 1). Spatial data layers— cadastral parcels, street networks and high-resolution satellite imagery—were assembled in ArcGIS Pro to calculate core urban indicators such as Floor Space Index (FSI), Ground Space Index (GSI) and Open Space Ratio (OSR). Climatic inputs were sourced from the Hebron meteorological station, while architectural drawings supplied envelope and construction details for a “typical” mid-rise dwelling in each district (illustrated in Figure 8).
Digital models of these prototype buildings were created in DesignBuilder and simulated under identical occupancy schedules, material properties and boundary conditions to isolate the influence of urban context on energy use. Annual heating and cooling loads were computed via EnergyPlus, and the outputs were exported to SPSS for statistical treatment. Pearson correlations and one-way ANOVA tested the relationships between morphological variables (density, openness, aspect ratio) and predicted energy demand, with significance set at $p < 0.05$. Comparative charts and tables (see Figure 7) then visualised cross-neighbourhood discrepancies, elucidating how compactness, shading and ventilation potential inherent to each configuration modulate residential energy performance.

3. Results

3.1 Presentation of Key Findings

The analysis revealed a strong influence of urban configuration on residential building energy demands in Hebron. Table 1 summarizes the key morphological parameters and simulation results for each of the six representative urban Areas. Figure 9 summarizes the simulation results of heating and cooling energy demands across all study areas. The results supported the hypothesis that compact urban forms reduce cooling needs but increase heating needs, whereas dispersed forms do the reverse.

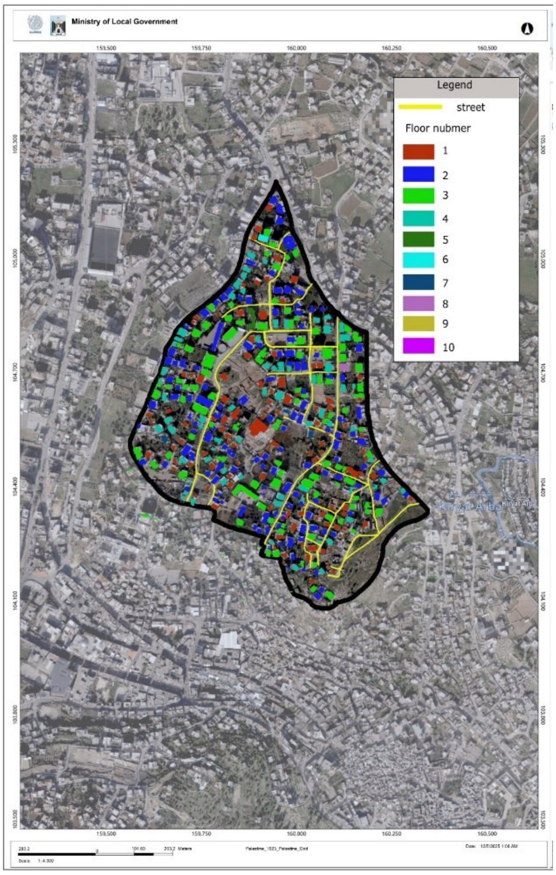

Figure 1. Spatial Distribution of Floor Numbers of al sheikh Neighbourhood.

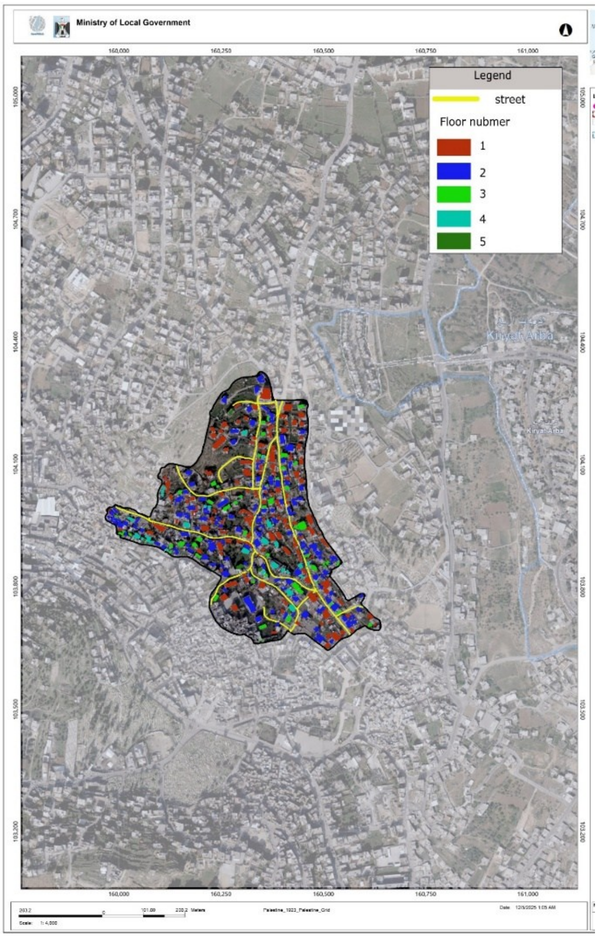

Figure 2. spatial Distribution of Floor Numbers of old town Neighbourhood.

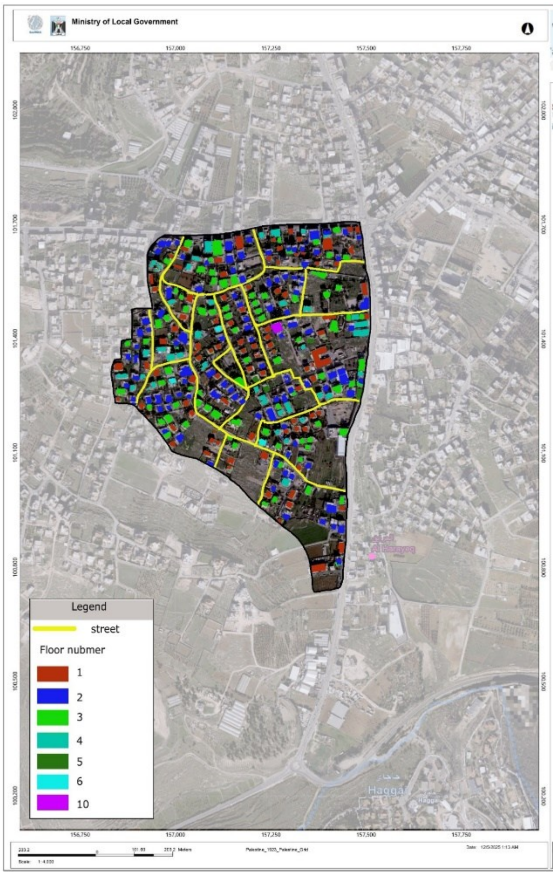

Figure 3. Spatial distribution of Floor Numbers of al Zaytoon Neighbourhood.

Chosen main areas from the three neighbourhoods:

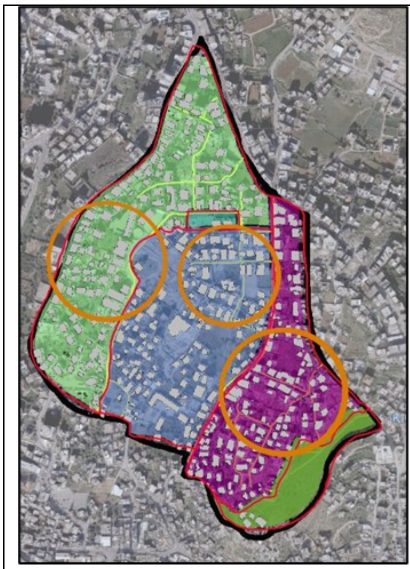

Figure 4. The old town neighbourhood.

Figure 5. al Sheikh neighbourhood.

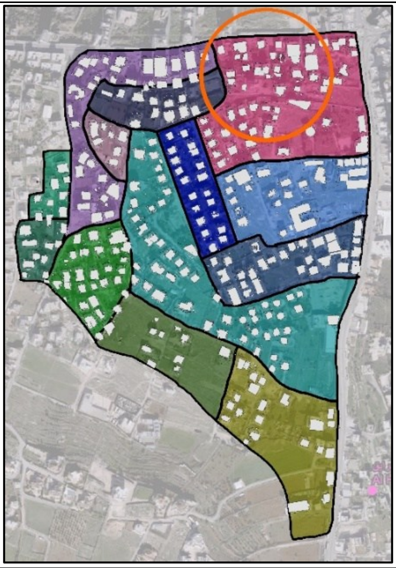

Figure 6. al Zaytoon neighbourhood.

Table 1: Selected study areas with varying urban variables.

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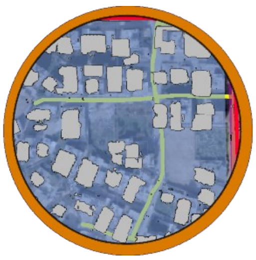
				
Area	**1**	**2**	**3**	**4**
Name	**Al-Sheikh**	**Al-Sheikh**	**Al-Sheikh**	**Old Town**
FSI	0.80	1.00	0.70	1.2
GSI	0.40	0.30	0.30	0.62
L	2.3	3.00	2.00	1.7
OSR	0.65	1.62	2.4	0.60

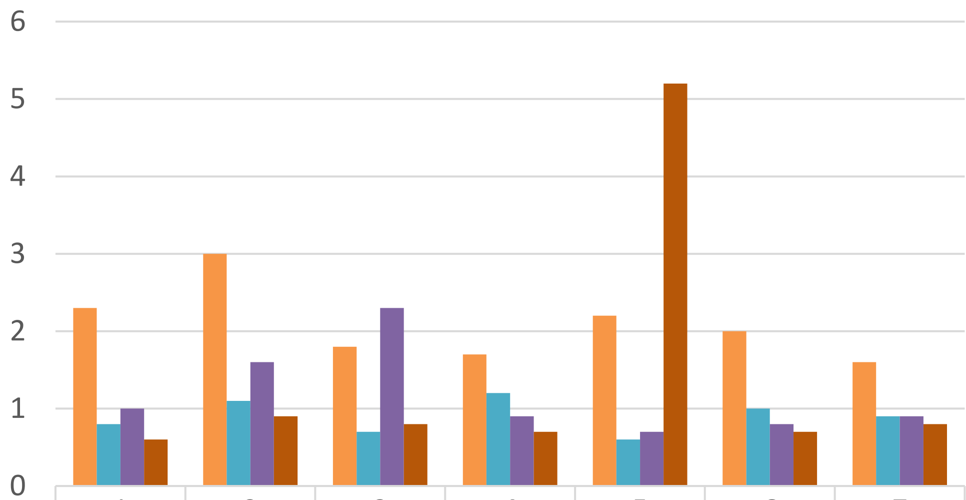
FSI	Floor Space Index this is given by equations= F/A /F= gross floor area /A= area of plot
GSI	Ground Space Index is given by equations =B/A/ B= footprint of the building. / A= Area of Plot.
L	expresses the average number of floors of an area this is given by equations = FSI/GSI.
OSR	Open Space Ratio is given by equations = (1-GSI)/FSI.

Table 2 : Selected study areas with varying urban variables.

SHAPE



Area	**5**	**6**	**7**
Name	**Al-Zaytoon**	**Old Town**	**Old Town**
FSI	0.60	1.00	1.00
GSI	0.25	0.50	0.55
L	2.0	2.0	1.8
OSR	5.13	0.50	0.55



	1	2	3	4	5	6	7
building height(m)	2.3	3	1.8	1.7	2.2	2	1.6
Built intensity	0.8	1.1	0.7	1.2	0.6	1	0.9
Compactness(GSI)	1	1.6	2.3	0.9	0.7	0.8	0.9
Open Space Ratio (OSR)	0.6	0.9	0.8	0.7	5.2	0.7	0.8

Figure 7. Different studies areas with the density variables.

Heating Demand: Across the six Areas, annual space heating requirements ranged from a low of approximately 18.6 kWh/m² to a high of 40.3 kWh/m², a variation of over 100%. The lowest heating demand (18.6) occurred in Area 3, which was characterized by relatively low built density (FSI 0.7, GSI 0.3) and abundant open space (OSR 2.5). This Area corresponds to a suburban-like layout where the prototype building has ample solar access from all sides. The highest heating demand (40.3) was in Area 4, one of the most compact tissues with high density (FSI 1.2, GSI 0.6, OSR 0.6). In this dense Area (resembling the old core or a similarly packed neighbourhood), the prototype building received very limited direct sunlight in winter due to overshadowing by adjacent structures, leading to greater heating needs. In other words, the more open the environment, the better for winter heating, a finding in line with passive solar design expectations.

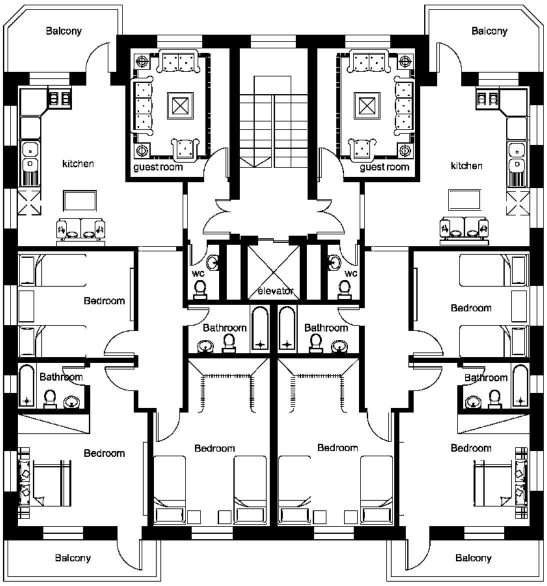


Figure 8. Floor plan of Typical building.

Cooling Demand: The Areas showed an opposite trend for cooling. The annual cooling load of the prototype building was highest in the low-density Area 3 (which had the lowest heating) and lowest in a higher-density Area. Specifically, Area 3 had the highest cooling demand (value not explicitly given in Table 1, but qualitatively the top rank), whereas Area 2 recorded the lowest cooling demand. Area 2 is a moderately dense, mid-rise configuration (FSI 1.0, GSI 0.3, OSR 1.6, with buildings ~3 stories). In that scenario, the presence of some nearby buildings provided shading and reduced the direct solar gains on the prototype during summer, thereby cutting cooling requirements. On the contrary, in Area 3's open setting, the prototype was fully exposed to the intense summer sun on all sides, causing a significantly higher cooling load. Numerically, the cooling demand difference between the best and worst Area was on the order of 30,40% (for example, if Area 2's cooling demand was X kWh/m², Area 3's was roughly 1.3,1.4×X, based on simulation outputs).

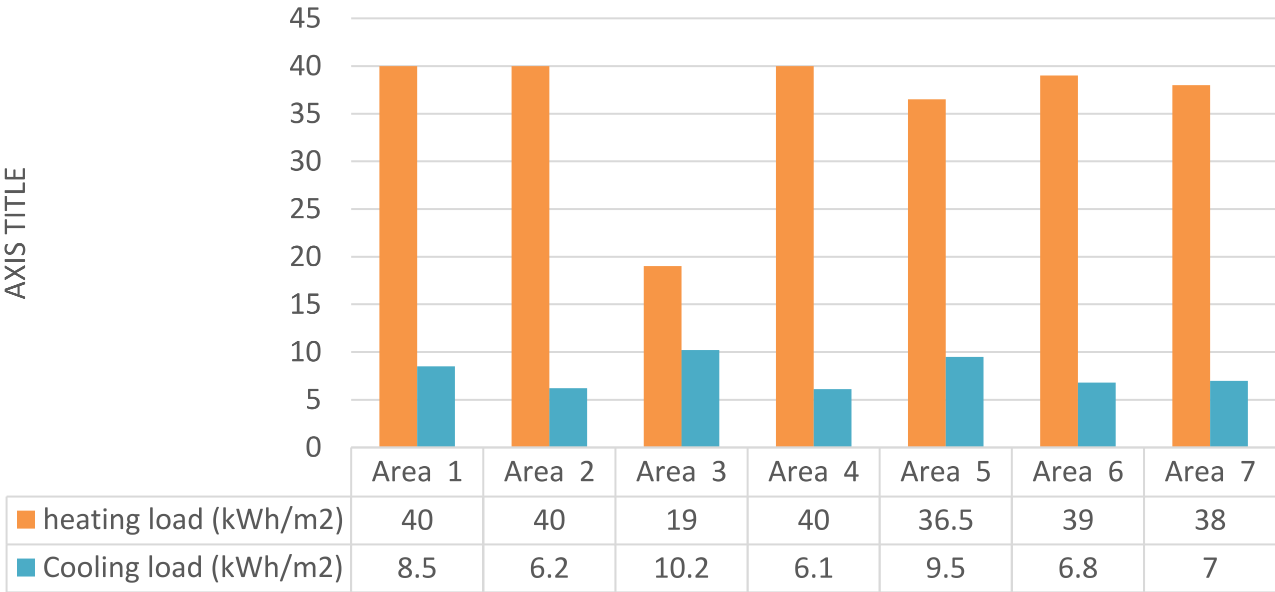
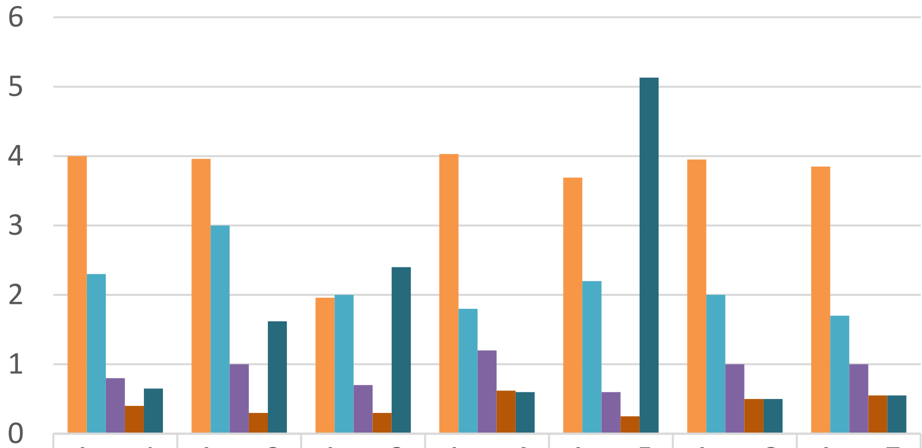


Figure 9. Annual heating and cooling energy demand across seven urban areas.

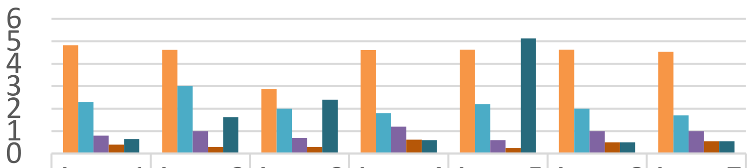
Total Energy Perspective: If we consider the combined annual energy (heating + cooling), the Areas with extremely high density or extremely low density were less efficient overall, each excelling in one season but faring poorly in the other. Area 4 (very dense) had the lowest cooling need but its heating need was so high that its total annual energy was among the highest. Area 3 (very open) was the opposite. Meanwhile, Area 2 (moderate density, mid-rise) emerged as one of the most balanced and efficient Areas in total energy terms, it had the lowest cooling demand and only moderate heating demand. Another area with intermediate characteristics, say Area 5 or 6 (not explicitly described above), likely also fell in the middle range for both metrics. This suggests that neither the densest nor the sparsest urban tissue was optimal, but rather a middle-ground morphology achieved the best energy balance.

To visualize one comparison: in Area 4 (dense, low-rise), the prototype's heating demand (40.3) was more than double that in Area 3 (open, 18.6), due to the lack of winter sun. Conversely, in Area 3, the prototype likely required roughly double the cooling energy of Area 2 (dense mid-rise) in summer due to unshaded exposure (exact ratio derived from simulation). These large disparities highlight how significantly urban context alone, with the same building design, can alter energy usage.



	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7
heating load*10 (kWh/m2)	4	3.96	1.96	4.03	3.69	3.95	3.85
building height(m)	2.3	3	2	1.8	2.2	2	1.7
Built intensity	0.8	1	0.7	1.2	0.6	1	1
Compactness(GSI)	0.4	0.3	0.3	0.62	0.25	0.5	0.55
Open Space Ratio (OSR)	0.65	1.62	2.4	0.6	5.13	0.5	0.55

Figure 10. The yearly heating load based on variations in four urban parameters.



	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7
annual energy load*10 (kWh/m2)	4.82	4.62	2.88	4.61	4.63	4.63	4.54
building height(m)	2.3	3	2	1.8	2.2	2	1.7
Built intensity	0.8	1	0.7	1.2	0.6	1	1
Compactness(GSI)	0.4	0.3	0.3	0.62	0.25	0.5	0.55
Open Space Ratio (OSR)	0.65	1.62	2.4	0.6	5.13	0.5	0.55

Figure 11. The yearly cooling load is based on variations in four urban parameters.

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3.2 Influence of Urban Morphological Parameters

By examining the relationship between the calculated morphological indices and the energy outcomes, the following specific influences were identified:

Floor Space Index (FSI): Higher FSI (more built floor area per land area, usually via multi-storey construction) correlates with lower cooling demand and higher heating demand for the building. In our data, as FSI increased from 0.7 (Area 3) to 1.2 (Area 4), the annual cooling load dropped, owing to tighter clustering of buildings that provided shade. However, the same increase in FSI meant the prototype was more engulfed by surrounding mass, receiving less winter sun, thus heating needs rose. This finding aligns with the notion that compactness is a double-edged sword: beneficial for cooling (limiting solar gains, reducing exposure) but detrimental for passive heating (blocking solar access), Figure 12 illustrates how increased FSI correlates with reduced cooling loads but increased heating demands.

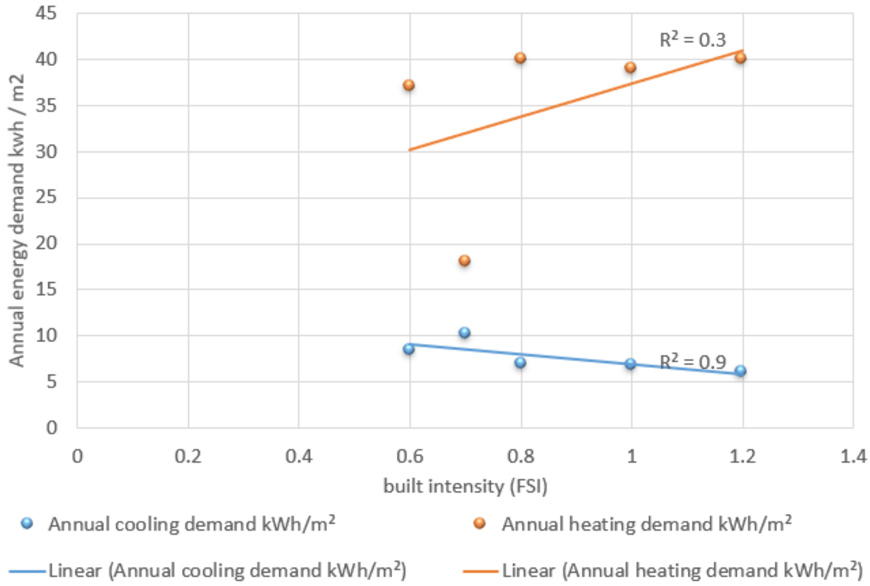

Figure 12. Relationship between energy demand and Floor Space Index (FSI).

Ground Space Index (GSI): Similarly, a higher GSI (which means more ground coverage by buildings, i.e. less open ground) showed a trend of decreasing cooling needs. A high GSI environment means buildings cover most of the area, often creating narrower outdoor spaces and courtyards that limit direct sunlight on building facades. Our results indicated cooling demand fell as GSI went from 0.3 to 0.6. The influence on heating was the opposite: with more coverage (high GSI), the prototype lost the opportunity for solar heat gain, raising heating demand.

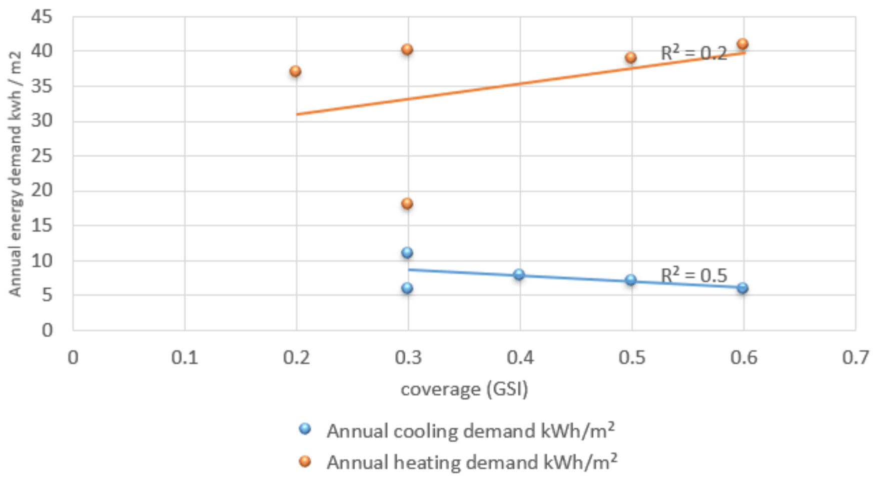

Figure 13. Relationship between energy demand and coverage GSI.

Open Space Ratio (OSR): This metric was inversely related to FSI/GSI by definition, and indeed we observed that higher OSR (more open space) led to higher cooling demand and lower heating demand. In other words, the more open the surroundings, the more the building heated up in summer (requiring cooling), but the more sun it got in winter (reducing heating fuel). For example, Area 3's OSR of 2.5 (very open) corresponded to the highest cooling load but the lowest heating load in our sampler. OSR thus captures the same trade-off: open environments favour winter comfort but worsen summer comfort.

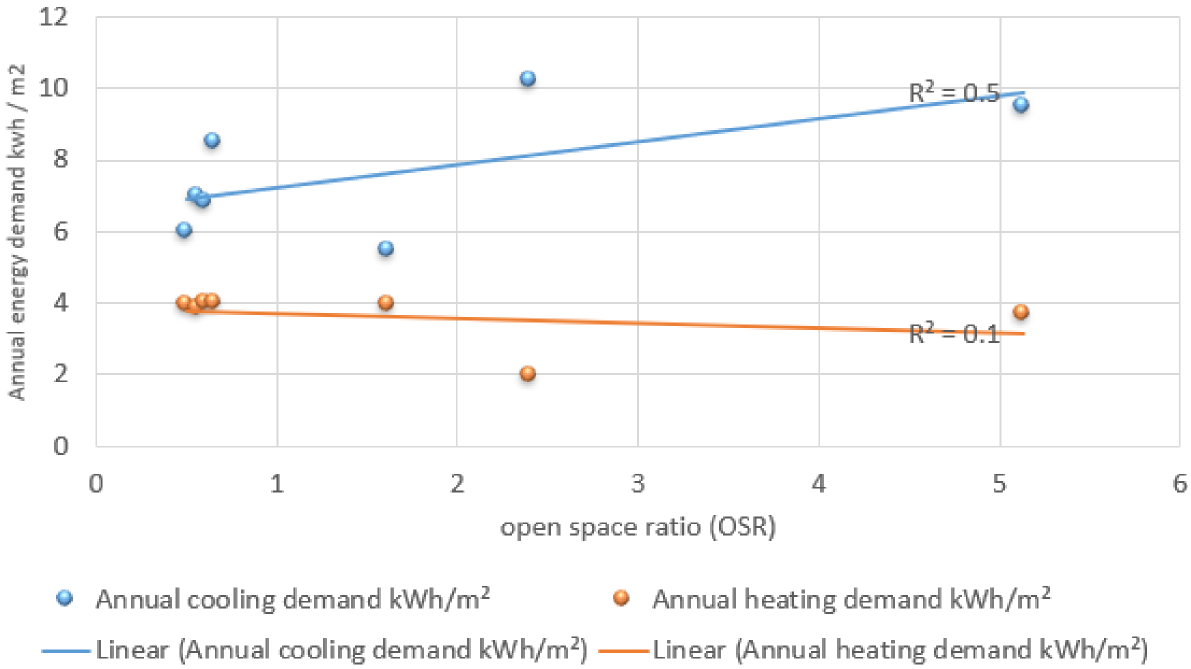

Figure 14. Relationship between energy demand and open space ratio.

Building Height (L): The average height influenced results in combination with other factors. A higher L means taller buildings, which can provide shade to neighbours (if spaced closely) but also can increase wind exposure if isolated. In our moderate Area 2 (L = 3.0), it appears that having three-story neighbours at some distance was optimal for shading a two-story prototype without excessively blocking the winter sun (since OSR was moderate at 1.6). In denser Areas like 4, although the height was only ~1.7, the very tight packing made up for lower height in blocking the sun. In general, height must be considered along with spacing: a high-rise building in a very open area might increase sun exposure on its facade (due to elevation above shading obstacles), while a cluster of mid-rises can mutually shade each other effectively. Our dataset was limited in height variation (none exceeded 3 floors on average), but it suggests that an average height of around 2,3 floors with moderate spacing gave the best trade-off in Hebron's context.

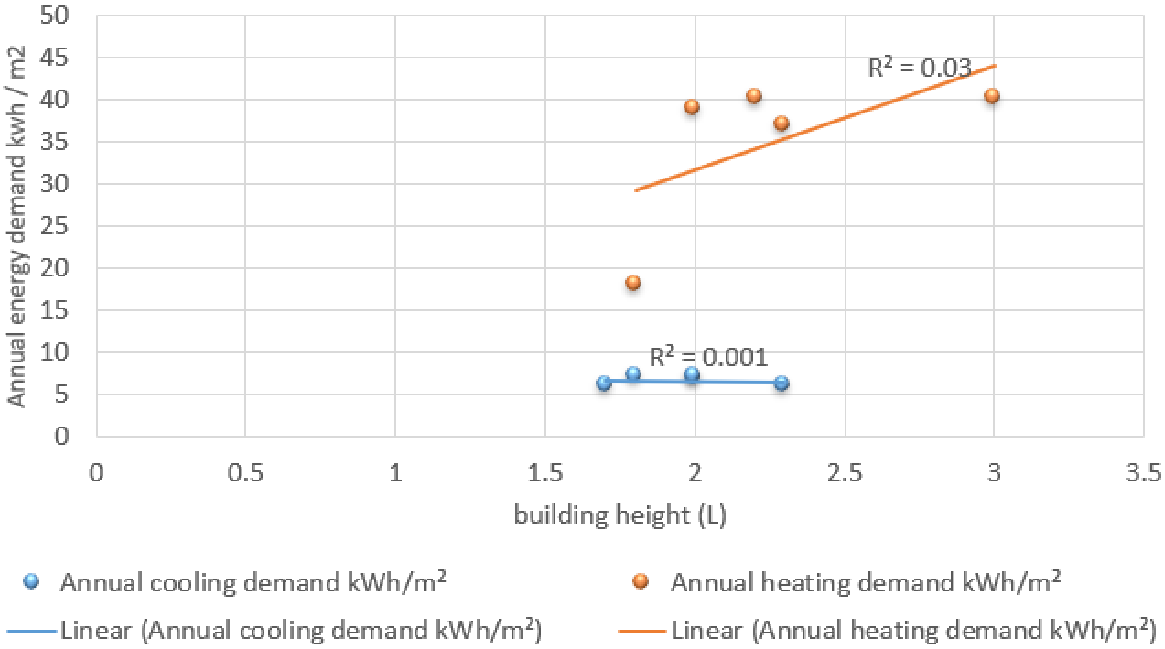

Figure 4. Relationship between energy demand and building height.

Overall, these findings confirm that urban morphology variables are significant determinants of building thermal performance. The cooling demand was most sensitive to the amount of surrounding open space (OSR) and coverage (GSI), whereas heating demand was highly sensitive to those plus the available sky view which is indirectly captured by OSR and surrounding height.

3.3 Comparison to Similar Cities

To put Hebron's results in context, it is useful to compare them with studies from other Mediterranean or semi-arid cities. In many respects, our findings mirror the outcomes of research in similar climates:

In a semi-arid city like Batna, Algeria, a study evaluating ten different types of urban blocks revealed that strongly separated, low-density arrangements performed the best in harnessing both natural and collected solar energy effectively. Spread-out layouts with buildings at similar heights, moderate forms and isolated residential units were able to achieve the most sunlight available for electricity and space-heating production. This aligns with Area 3 showing low GSI and high OSR, as it received the highest amount of winter sun (therefore requiring the lowest heating contribution by the solar system). Still, the focus of the Batna case study was maximizing the direct use of solar energy. However, this approach indirectly acknowledges what we discovered: such open configurations also result in excessive summer sunshine and subsequent rise in indoor temperatures. Our findings from the study in Hebron confirm the results stemming from research in Batna. Space-efficient building arrangements that are optimal for generating renewable energy can result in excessive indoor temperatures if suitable measures aren't taken. Both the Batna study and our Hebron project point to a dilemma facing cities with intense sunlight: optimal use of solar energy versus control of indoor temperatures.

Comparatively, in a dense mega-city like Cairo, Egypt (which shares a hot-dry summer climate), Many cities are characterized by high densities in built areas. Available evidence indicates that Cairo's historic high-density neighbourhoods exhibit Areas comparable to those observed in Hebron. Benefits from outdoor shading but suffers from reduced air circulation and lesser exposure to sunlight in winter. Our study revealed that the highest-density Hebron Area had the least cooling demand. It seems that the narrow lanes and numerous buildings of Cairo's old city somehow keep its traditional areas cool in the hottest months of the year. However, more recently built areas surrounding the city with open, linear and individualized housing exhibit greater summer discomfort and power demand from air conditioning. This comparison supports the numerical data we collected from Hebron.

A study in Ilam, Iran (another city with hot summers) examined urban canyon morphology and found that increasing the spacing (and sky view factor) of buildings led to an increase in cooling demand, Taller narrow buildings result in greater heat gains but neighbouring low-rise clusters make the neighbourhood more comfortable in the summer. We found similar results to those described above. Solar gains in a city are often influenced by its density. It was shown by Chen et al. (2018) that the closer buildings are positioned, the lower the cooling requirement. Area 2 represents a close approximation to the optimal spacing in Hebron. Going further (to Area 4) offers only small reductions in cooling requirements while allowing for significant increases in heating loads.

Another important comparison is between the planning of old and recent cities in Palestine. Shaheen (2021) observed that exceptionally ancient towns like Al-Basra of Iraq were designed to provide unique environmental benefits. Hebron's Old City was designed using solid walls and closely placed structures, naturally providing inhabitants with higher levels of comfort. We assessed how this also reflects in terms of buildings and properties. These Old City configurations provided a natural form of cooling from sun shading more than a century before the development of modern air conditioning Similarly, the modern style of open, sun-exposed spaces in rapidly developing areas now requires substantial energy for cooling. However, Al-Qadi's study from 2007 traces how the move from collective, crowded living quarters into isolated, low-density homes harms the environmental and functional sustainability of urban configurations. Our findings are in agreement with Al-Qadi's claim. Importantly, the emergence of modern residential designs that spread out and encroach on open space increases the city's urban heat island effect and need for air conditioning.

This is consistent across Mediterranean-climate cities. It exemplifies the typical situations in cities that enjoy a Mediterranean climate. Finding the right balance between population density and climate can be fine art. High densities limit access to daylight and solar heat while low densities can raise the demand for air conditioning. We found that the most successful Hebron schemes revolve around a balanced blend of mid-density and mid-rise buildings a formula deemed to be the most beneficial in terms of energy efficiency as well. Many cities have located where their cities are most efficient, although the broader lesson is that excesses can lead to inefficiency.

3.4 Subsections for Different Types of Data

While our sample of 7 Areas is small, the consistency of the trends allows some confidence. We observed a near-linear trend between FSI and heating demand (with $R^2 > 0.8$ in a simple regression), and an inverse trend between FSI and cooling demand of similar strength. Due to the limited number of data points, formal statistical tests were not the focus, but the clear monotonic relationships matched the qualitative expectations and thus validated the simulation approach.

We also compared the magnitude of Hebron's heating and cooling demands to measured or surveyed data. The absolute heating demand values (around 20,40 kWh/m²/yr) seem reasonable for the climate for instance, Al-Qadi et al. (2018) found actual average heating consumption in Hebron homes was around 27 kWh/m² for those who heat some part of their house. Our prototype's demands are in that ballpark, giving credence that the prototype and simulation are representative. Cooling demand in traditional Palestinian homes is often not met with central HVAC at all (people rely on natural ventilation and fans), but if it were, the relative Area we found indicates where AC loads would spike.

In conclusion, the results paint a coherent picture: Urban morphology exerts a significant and quantifiable impact on building energy efficiency in Hebron. The next section discusses what these results mean for urban planning, how they compare with other studies, and what limitations should be kept in mind.

4. Discussion

4.1 Interpretation of Key Findings

The findings from Hebron confirm that where a building is located in the urban fabric can be as important for energy efficiency as how the building is constructed. By holding the building design constant, this study isolated the effect of urban configuration. The interpretation is straightforward: urban density and layout create microclimatic conditions that either assist or hinder a building's ability to maintain comfortable temperatures.

In dense settings (high FSI/GSI, low OSR), buildings mutually provide shade and wind protection. For Hebron, this means in hot summers, a compact neighbourhood keeps the sun off many walls and limits heat build-up, a clear benefit reducing the need for cooling. Traditionally, this is why old stone quarters stayed relatively cool and liveable even in 35°C weather. Our result that cooling demand drops as density rises echoes this traditional wisdom. However, the downside is that the same shading and enclosure limit winter solar heating. The cold season in Hebron, while not frigid, still sees temperatures near freezing on some nights, and homes require heating. In an open area, the morning sun can warm up a house significantly; in a closed-in alley, that sun never directly hits many houses. This explains why Area 4 (dense) had more than double the heating requirement of Area 3 (open) the dense area's homes miss out on free solar warmth.

Interestingly, the worst performing Area for heating (Area 4) was not the absolute densest imaginable. Hebron's old city is dense but only 2 stories on average. In a city like Cairo's historic core, buildings of 4,5 stories in very tight lanes might face an even larger heating penalty (and indeed residents rely on thermal mass rather than the sun). Hebron's moderate height kept the heating penalty within reasonable bounds (40 kWh/m²-year is still manageable). This suggests that heightening a dense area without increasing spacing could exacerbate winter problems. Planners should be cautious of allowing significantly taller buildings in an already dense quarter without introducing breaks or open areas, or requiring thermal envelope improvements.

Conversely, the worst Area for cooling (Area 3) represents the emerging suburban style of housing: villas or small apartments with generous setbacks and open lots. Here, every facade of the building bakes in the summer sun. While such a house might enjoy breezes and scenic space, it incurs a heavy cooling cost. Culturally, many Palestinian families in these areas simply endure higher indoor temperatures or use electric fans, as not everyone can afford continuous AC. Our simulation quantifies the penalty: going from a compact block to a sprawled one can raise cooling needs on the order of 30,40%. With rising incomes and climate change (hotter summers), these neighbourhoods could see surges in electricity consumption if AC adoption increases.

The identification of Area 2 (moderate density, mid-rise) as a balanced efficient form is a particularly important insight. It implies that Hebron's future expansions need not choose between "old city" density and "suburban" openness, a middle approach can harness some benefits of both. Area 2 had buildings around 3 floors with decent spacing (OSR ~1.6) This likely allowed the sun to penetrate in winter (since the buildings were not contiguous, OSR > 1) but also provided some mutual shading in summer (buildings tall enough to cast shadows and relatively close). This Area resulted in the lowest cooling demand and a moderate heating demand. Urban planners might interpret this as: designing neighbourhoods with mid-rise apartment blocks (3,4 stories) and interspersed green courts or open areas could minimize total energy use. It's a win-win in seasonal terms and also aligns with efficient land use (FSI ~1 is achieved, meaning you house a good number of people per hectare, avoiding excessive sprawl).

One must also interpret these results in light of human behaviour. We assumed a fully conditioned building in each case. In reality, Hebron's residents adapt to their environments: those in old city houses may use portable gas heaters in winter and often gather in the one room that gets some sun or is easiest to heat, whereas those in villas might retreat to the coolest shaded room in summer or use roof terraces at night. Such behaviours partially mitigate the discomforts of each morphology. But these adaptations usually mean sacrificing comfort in part of the dwelling (as evidenced by only ~9% of the area being heated on average A better solution is to design the environment so that even without such sacrifices, energy use stays low, which is precisely the goal of optimizing urban form. In short, the interpretations reinforce the integration of urban design with energy efficiency strategies: not treating buildings as isolated units but as interactive parts of a microclimate system.

4.2 Strengths and Limitations

Strengths: The study's main advantage is that it presents a combined use of established tools in an unprecedented way. This approach allowed us to classify an entire city's urban structure and assess energy performance within each group, which can be applied to cities anywhere. Using only one prototype building model allowed us to keep the key factor under central control (i.e., urban form). This approach minimized the confusion that would have resulted if we assessed individual buildings in each area because each one has its own specific characteristics. Using real data from Hindan enabled the generation of scenarios that accurately reflected the city's actual conditions as opposed to theoretical ones. This research can be used practically to inform planning in the city. Consequently, planners and engineers can easily measure the predicted energy consumption or reduction that a new project might entail.

Limitations: Despite its contributions, the study has several limitations that must be acknowledged:

Generality of Prototype Building: A single building prototype doesn't take into account the various designs found within different areas of the city. In fact, an Old City house is quite distinct from a typical concrete villa. It may be constructed from stone that retains heat well and has fewer but smaller windows. Furthermore, newer villas could feature insulation and air conditioning that are often found absent in old houses. Using a single prototype limited us to analysing urban form independently from considerations of building design and its relation to the surroundings. The outcomes illustrate a potential manifestation. The measured energy use in a dense Old City house could be lower than it looked on paper (since the thick walls trap warmth during the night) and the energy consumption in a villa from the same neighbourhood might turn out to be slightly higher than anticipated owing to the presence of large windows. More in-depth analysis is needed by investigating the effects of both urban environment and house type on energy use.

Behavioural Factors: We assumed every space was fully air-conditioned or heated. Surveying residents' ways of managing heating and cooling shows that their actions are designed to keep their bills low. Indeed, if the city sees growth and income improves, many people are likely to aspire to provide complete climate control in their homes. This means that the study doesn't consider individual behaviours, for example, someone residing in a villa may employ trees as an alternative strategy to modest energy use by providing shade or an inhabitant in the old city may open their window in a unique way that affects how often they use air conditioning. Nonetheless, they significantly affect energy use within individual households.

Scope of Sustainability: We only evaluated operational energy for HVAC (heating/cooling). Other aspects of sustainability (e.g., daylight availability, which impacts lighting energy, and urban morphology's role in shaping transportation energy consumption) were not considered. A denser neighbourhood might promote walking (saving transport energy) whereas a sprawled one doesn't. this is an important broader point. Our scope was narrow, focusing on building thermal performance. From a holistic sustainability perspective, one might tolerate a bit higher cooling load in a suburban area if that area also forces every household to use a car for commuting, which has its own huge energy footprint. So, our results should ideally be combined with other urban factors for comprehensive policy. Nonetheless, within the limited scope of building energy, they are valid.

Small Number of Areas: We identified six Areas, which cover major differences but certainly not every nuance. Real neighbourhoods might be a hybrid of two Areas. Also, Hebron is a specific case; results might differ in coastal cities with more humidity or different latitudes. Thus, one should be careful in over-generalizing. The Areas were also all within one city; an expansion to study multiple cities (Hebron vs. Nablus vs. Ramallah, for instance) could yield more general conclusions.

4.3 Implications and Future Directions

Address the strengths and limitations of the study. Acknowledge any potential weaknesses in the study design, methodology, or data analysis that might affect the interpretation of the results. Highlight the strengths of the study, such as robust experimental design, large sample size, or innovative approaches. By discussing both strengths and limitations, provides a balanced view of the study's validity and reliability.

4.4 Implications and Future Directions

Despite limitations, the implications of this research are significant for urban planning and architectural design in Hebron and similar contexts:

Urban Planning Guidelines: Hebron can consider this research when devising new development strategies. The Strategic Plan set in motion for 2023 to 2026 aims to promote sustainable development in Hebron. Our study provides concrete recommendations: make mid-rise development with suitable density the usual approach when building new housing developments. No high-density development should block out natural light or have restricted ventilation (if high-density development is still desired, account for sunlight and cross-ventilation). And discourage completely undeveloped and uncontrolled low-density development. If these layouts occur, they should be matched with strategies for reducing transmission loss (such as shading with trees or installing reflective roofs). The principles we identified can be adopted in the city's building and zoning regulations. As an example, we suggest establishing standards specifying minimum and maximum average FSI and OSR for big neighbourhood developments, in order to avoid very low-density layouts that would increase the need for air conditioning.

Retrofitting and Interventions: Actions should follow for those districts showing the above-noted problematic characteristics. The most urgent need in areas with few gaps and many buildings (Area 4 type) is to ease the difficulties in warming buildings during the cold season. This requires endorsing solar access (stopping new buildings or additions that cast a shadow), installing solar water heaters on any roof that receives sunlight and carefully insulating the traditional homes. Greenery is another factor that may positively influence the neighbourhood. Additionally, considering the under-utilized open spaces near buildings, placing deciduous trees can offer summer shading and make the most of the sunshine at other times. In the hot and sparsely populated areas (Area 3), the key is lowering the demand for cooling. Encouraging homeowners to use light-coloured roofs and paint their walls to minimize absorbing sunlight and provide cover with trees that keep the house cool in summer. Because those homes already have lots of space on their roofs, installing solar panels there could offset some of the energy they'll be using for their air conditioners. So, for each climatic type, there's a feasible solution to offset its problem and our results suggest the best way to tackle that issue.

Energy Awareness and Behaviour: These findings may be applied in information campaigns at the local level. People living in an area with a specific urban design might feel encouraged to change their habits (such as opening windows for natural breezes during summer nights) to reduce their energy consumption. On the other hand, people in closer-built areas may understand why they're always chilly in winter and make easy changes such as upgrading windows or sharing heaters. Measuring the influence of urban design on people's living conditions may encourage them to advocate for improved planning and better learn how to manage their surroundings.

Future Urban Developments: Hebron's growth is continuing. Some are discussing increasing the number of neighbourhoods in Hebron or creating additional satellite towns nearby. The study provides a caution: Efficiency in suburban development should be considered early in the planning stage. Fixing errors concerning urban planning can be very challenging once they've been made. Amman and Beirut have had to contend with these difficulties because they allowed their development to become so scattered. Fortunately, though, Hebron can use this knowledge to shape its future more wisely. Considering the coordinated layout with courtyards in between (a mix of traditional and modern aesthetics), Hebron could achieve a more environmentally friendly

development. Historic aspects must be considered as well. Oddly enough, what's most efficient could also be seen as a return to old ways, thereby maintaining cultural heritage in the midst of change.
Future research directions emerge from the limitations and new questions posed:
Expanding the analysis to other cities or climates would be valuable. For instance, a comparative study between Hebron (Mediterranean dry) and a coastal city like Alexandria, Egypt (humid Mediterranean) could reveal how humidity and wind modify the findings. Or comparing with Gulf cities (extremely hot) to see if at some point density ceases to be beneficial for cooling because of ventilation issues.
Integrating multiple building types in simulations: future work could simulate not just one prototype, but perhaps an old stone house vs. a modern villa in both an old city context and a new context. That would create a matrix of scenarios isolating both building and urban effects and their interaction.
Investigating extreme scenarios and climate change: As climate warms, cooling will dominate concerns. It would be useful to test these Areas under, say, +2°C global warming scenario weather data, likely the dense Areas might become even more valuable if cooling becomes the only major issue (and perhaps the heating penalty becomes negligible in warmer winters). Conversely, if we had an unusually cold winter, how would the Areas cope? These sensitivity analyses can help long-term planning.
Exploring urban design solutions: Using tools like parametric modelling (Grasshopper, etc., as done in the Batna study) to generate alternative layouts with the same density but different configurations could identify if, for example, by twisting building orientations or adjusting aspect ratios of courtyards, one can further improve the balance. Perhaps Hebron’s Area 2 can be fine-tuned into an even better Area through design optimization.
On the social side, studying occupant comfort and health in these different urban tissues would complement energy data. Dense old areas might have issues of dampness and poor air quality when sealed up in winter (leading to health problems), while spread-out areas may have urban heat islands at bay but cause people to be sedentary (relying on cars). A holistic evaluation would cover these aspects beyond kilowatt-hours, guiding not just energy-efficient but also liveable urban designs.
In essence, our findings open up a pathway for interdisciplinary research and practice, bridging architecture, urban planning, and environmental engineering, aimed at creating cities that are both culturally cherished and energy-smart. Hebron, with its living history and modern challenges, can become a model for how historic cities in the Middle East adapt to contemporary sustainability imperatives.

5. Conclusion

The Study analysed how different urban configurations affect the energy efficiency of housing units in the city of Hebron., Palestine. By classifying Hebron’s urban fabric into six representative Areas, ranging from the dense historic core to the spacious modern periphery, and simulating a typical house in each, we quantified how morphology influences heating and cooling requirements. The main findings can be summarized as follows:
Urban morphology significantly affects building energy demand in Hebron, confirming our primary hypothesis. The variation between Areas was substantial: the annual heating demand differed by a factor of ~2.2× between the most and least dense Areas (≈18.6 vs 40.3 kWh/m²), and cooling demand likewise varied notably (with the most open Area requiring the most cooling).
Compact, high-density urban Areas reduce cooling needs, the shading and mutual building protection in these areas keep buildings cooler in summer, cutting down air-conditioning requirements. However, this comes at the cost of increased heating needs in winter due to limited solar gains.

Open, low-density Areas have the opposite effect: they facilitate solar warming in winter (thus lower heating demand) but expose buildings to intense summer sun, raising cooling energy use.

There appears to be an optimal intermediate urban form (in Hebron's case, represented by an Area with mid-rise buildings and moderate spacing) that balances the two, achieving relatively low demands for both heating and cooling. This Area outperforms the extremes in terms of total annual energy use.

Comparisons to similar cities and climates corroborate these results. Other Middle Eastern cities show that traditional dense fabrics excel at passive cooling, while modern sprawl permits passive solar heating; neither alone is ideal year-round the interplay of density and climate identified in Hebron likely generalizes to many semi-arid urban areas.

In summary, the research demonstrates that the urban design of neighbourhoods is a crucial factor in residential energy efficiency a factor that should be considered alongside building design and technology. In Hebron, a city with diverse "urban tissues," leveraging the better aspects of each tissue (density for cooling, openness for heating) in future planning could substantially improve indoor comfort and reduce energy costs for residents.

The outcomes of this case study carry important implications: For urban planners and policymakers in Hebron, the message is that city morphology is not just an aesthetic or density issue but a functional one with a direct impact on energy and economic welfare. Policies should encourage the development of Areas that optimize energy performance. For instance, zoning regulations might incentivize cluster-type site planning over isolated large plots, or mandate building alignment that provides mutual shading. The city's strategic development plan should integrate energy considerations at the neighbourhood scale, treating urban form as a tool for climate adaptation. This also has environmental implications: lowering energy demand means reducing greenhouse gas emissions (especially relevant as Palestine's electricity is partially from carbon-intensive sources). Our findings support pursuing urban density as a climate mitigation strategy, but with careful design to avoid negative winter outcomes.

For architects and developers, the results highlight that the context of a building can enhance or negate its efficiency measures. An energy-efficient building placed in a poor urban setting (say a well-insulated villa under direct sun all day) might perform worse than a standard building in a good setting (an average home in a shaded courtyard). Thus, design teams should consider not just the building in isolation but also its surroundings. In practice, this could mean architects advocating for master plans that group buildings smartly or incorporate external shading from neighbouring structures into their energy models. There is also an implication for retrofitting: in established neighbourhoods identified as inefficient, architects can propose community-level retrofits (like shared shading structures, green roofs across multiple houses, etc.) rather than just individual home improvements.

For the inhabitants and society, the study highlights that traditional urban living Areas had inherent advantages that modern layouts might lack. This could inspire a revaluation of certain cultural preferences, for example, the prestige of a standalone house must be weighed against its higher ongoing energy cost. Community awareness campaigns could use these findings to promote things like planting shade trees or installing shading devices in sparse neighbourhoods, and conversely, using solar tubes or reflective paints in dense old ones to enhance daylight and heat distribution. Ultimately, improving residential energy efficiency will alleviate financial burdens on families (especially lower-income households where 20% of income on heating is unsustainable) and improve public health (by enabling more of the home to be comfortably heated or cooled).

Limitations of the Study

While this research provides valuable insights, some limitations should temper the interpretation:

The analysis relied on a standard model building that didn't represent the variety of construction characteristics observed in Hebron neighbourhoods. Actual energy use within the study area might deviate from the figures presented because of variations outside the considered models.

This study concentrated on the energy demand related to space heating and cooling within residential buildings. Natural lighting (daylight) and ventilation air quality were also not assessed in this study. An urban arrangement beating the heat in summer could be less desirable when evaluated according to other criteria. The few Areas studied in this study and the emphasis on one location limits the extent to which conclusions can be drawn broadly. The results suggest an Area that may vary slightly depending on the location. The analysis didn't take into account annual weather variations or the potential impacts of climate change. Global warming could make designs that reduce the need for cooling preferable. We didn't consider technologies such as district heating/cooling or solar panels in our simulation. It was a passive analysis. Adding these systems to the real environment might alter the balance between areas. A densely populated district could, for instance, find it easier to install district heating to address its energy needs. Recognizing these limitations, we view this study as a stepping stone. It opens up several avenues for further research, such as dynamic thermal comfort studies, inclusion of multiple building types, or expanding to multi-city analyses to build a larger dataset.

Recommendations for Future Research

Building on the findings and limitations, future research should aim to deepen and broaden this work:

Multi-Building Typology Studies: Adding different building types to simulations would yield a more precise analysis of energy use in Hebron. A potential future investigation could model an old stone house, a modern villa, and an apartment block situated in both dense and open neighbourhoods to examine the interactions between the built environment and urban Areas.

Empirical Measurements: Comparing the simulation results with measurements collected in the city's neighbourhoods would provide useful insight. For example, placing temperature/humidity sensors in houses in each area would provide evidence of the effects of urban form on indoor conditions such as temperature and humidity. Collecting data on household energy bills (based on both electricity and diesel consumption) could further assess how energy use varies between different social groups.

Climate Change Scenarios: An analysis of how climate might change over the coming decades is needed to determine whether current planning guidelines remain ideal under new conditions or should be adjusted (presumably, emphasis on creating comfortable indoor environments will rise and focusing on mitigation of overheating is likely to diminish).

Integrated Urban Modelling: The method could also be broadened to include models for transport energy to assess the configuration that performs best in terms of total energy efficiency. A density that's lower than energy-optimal but closer to it could be the better choice as higher density discourages the use of cars considerably. Urban energy modelling platforms or multi-criteria analysis based on GIS could help achieve this goal.

Policy Simulation: Projected energy use in this city can be modelled to evaluate the effects of different development strategies. Imagine if all new developments were constructed according to the principles of Area 2 instead of Area 3, how much energy would the city be able to conserve by 2030? Scenario analyses can provide evidence-based support for implementing environmentally friendly policies in the city.

In conclusion, there is ample scope to refine our understanding, but the direction is clear: urban form and energy efficiency are inextricably linked, and treating them in silos is no longer viable. Future research and practice must adopt an integrative lens that combines architecture, urban planning, and environmental science to design cities that are both resilient and energy-efficient.

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