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Electrical energy reduction based on residential densification for passive heating and cooling load reduction in Jordan

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In Jordan, housing is one of the largest consumers of electricity due to total heating and cooling requirements. This research looks at how populated spaces impact energy consumption. The case study is mid-rise apartments, and it takes a cross-disciplinary approach by merging the fields of electrical engineering and architectural design. The study, through simulation and the national building code of Jordan, especially the 2018 building code and its code regarding urban density, considers the effect on energy consumption of increasing building height by adding floors in categories A, B, and C. The aim is to identify passive design. Such a goal, inspired by low energy building schemes, looks at how to reduce electricity demand without active systems. Key factors like the number of floors, building height, and shade coverage also matter. The simulations indicated that increasing the residential density to 6 floors, the mean values of the spent electricity per square meter of floor area decreased considerably. The averages were down 26% for category A, 28.6% for category B, and 28.3% for category C. Overall, these findings capture the essence of the strategic civil and architectural design needed to really understand the abstraction of energy demand and offer the basis for energy efficient construction to be adopted in Jordan, especially concerning the national electrical grid.

Keywords Electrical energy conservation, Electrical load management, Residential building densification, Electrical energy efficiency, Design optimization, Energy simulation, Sustainable electricity

Jordan contends with a crisis in the energy sector due to rapid population growth, the instability of energy supply, and limited natural energy resources[1–3]. To address this, numerous studies have suggested and implemented conservation strategies and developed and used renewable energy sources, as in[4,5]. Consumption trend analysis, however, shows that despite these manifold efforts and studies, the largest share of energy demand in the economy continues to be the residential sector. For instance, globally the residential sector accounts for approximately 43% of energy use and 33% of the total greenhouse gas emissions[4,6–9]. In 2018, residential buildings in Jordan contributed 22% to the total energy consumption of the country, as illustrated in Figure 1.

Data from the Jordanian Electric Power Company (JEPCO) further underscores this trend. Among all sectors, residential use consistently ranks highest, followed by industrial and water pumping sectors, as in Figure 2.

In 2021, electricity consumption in Jordan hit almost 19,500 GWh, with the residential sector consuming about 45% of this consumption[10,11]. This calls for an increased focus on energy efficiency in the residential sector. Research indicates that the potential for reducing electricity consumption due to increased building density is significant, going as far as 50% for single-family houses, 18% for multi-family dwellings, 17% for commercial buildings[12]. Such findings characterize urban densification as an opportunity for sustainable development in Jordan, which is much needed. Economically thriving urban centers offering higher standards of living have long been established as resource densification zones. This is the case for land, as well as for utilities and services like electricity, water, and transport that provide services for lower emissions. However, the energy implications of densification are of a paradoxical nature. While shared walls and reduced surface exposure can lower heating and cooling demand, close building spacing typically limits airflow, traps heat, and blocks cooling[13–15]. To elaborate on this point, urban planning approaches building orientation, setbacks, and ventilation corridors[16,17]. This is of particular interest in Jordan, where the population increased 87% from 2004 to 2014[18]. Urban sprawl, informal housing, and increasing urban energy infrastructure strain are consequences of sprawl. The city ordinances

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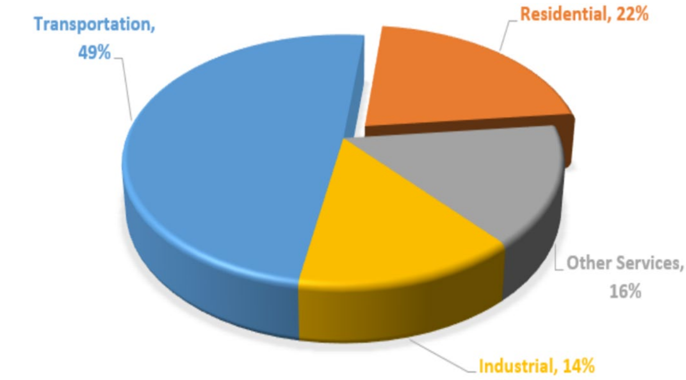

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Fig. 1. Jordan energy consumption per sectors in 2018, source[10].

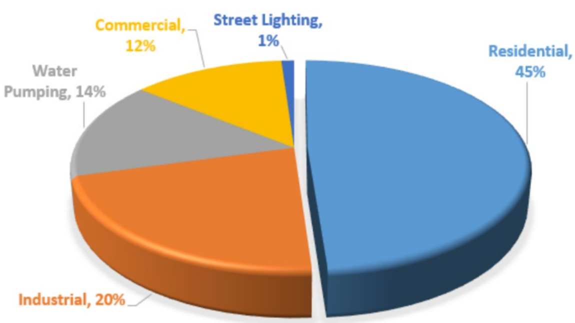

Fig. 2. Jordan electrical power load consumption, source[10].

must strategically manage policies and evaluative eng growth to make sure densification offers sustainable and efficient outcomes. Energy-related challenges in the built environment have been tackled by a significant portion of the scholarly community by improving energy efficiency in current structures and incorporating alternative energy sources (e.g., renewables, micro-grids)[5,10]. Numerous studies have zeroed in on building performance enhancement[4,9,19–21] by targeting changes to external and internal components, which include increased insulation, HVAC system and appliance upgrades, double-glazing, addition of shading devices, and accounting for occupant behaviour.

For instance, in[22], research conducted in the United Arab Emirates demonstrated that passive design measures, such as optimal building orientation and effective thermal insulation, could yield energy savings of up to 20% in hot climates. Meanwhile, however, unlike the climate in Jordan with an average of 25 °C in summer and 8 °C in winter, extreme heat in the UAE makes passive measures less comfortable and less impact in summer. In Abu Dhabi, a study was conducted by[23] with an average mean temperature reaches 36 °C in August. The study found a significant reduction in electrical energy consumption as density increases, and solar heat gains were reduced by 50% resulting in a 10% reduction in total electrical energy consumption. However, this research only investigated detached villas, distance variable between units without considering density increasing by stacking the units. A study in[24], in Dallas, TX., found that increasing building density reduces wall exposure and surface area per person, which helps lower heating and cooling demand. The study also noted that overall energy performance depends greatly on building design and strategies such as green roofs. However, Dallas is a large city with abundant land, allowing densification to occur both horizontally and vertically, and it is characterized by relatively high-income residents.

Jordan has notably smaller urban areas and its densification of built environments mostly takes the form of vertical growth. Given the lower socioeconomic status of inhabitants around the world and relative unprofitability of investments, the affordability and provision of basic housing become more pressing in these settings, as noted in reference[25]. Urban overheating resulting from the urban heat island effect was shown to increase cities' cooling demands, and, whilst expending little energy on meeting heating demands, cities were shown to incur greater cooling losses. The focus on the energy balance in the built environments cooling season during hot and humid climates, and recommended the use of vegetation, reflective surfaces, and other greener architectural improvements to building envelopes. However, the research failed to consider densification as one of the meaningful, potentially efficient urban and energy policy integrated solutions with probable large results on urban overheating. Jordan, and particularly the city of Irbid, has a unique climate with four defined and relatively lower temperature and dry seasons. Given the increase in energy prices, large population growth, and limited land available around cities, this research proposes vertical densification to resolve some of the urban issues. In reference[26], the author and other co-identified several metrics to describe integrated energy and urban form of the built environments with vertical greening systems in China. The potential for vertical greening systems to contribute to energy savings was demonstrated whereby EnergyPlus building performance simulations showed VGS established in the buildings, energy consumption on a yearly basis could be reduced by as much as 8.7% in building energy consumption. The study has gaps related to how optimizing core design elements, such as the number of shared walls, building height, substrate thickness, and so on, to maximize energy savings, is crucial. Overall, the research indicated to some extent the potential of VGS on building energy efficiency, but did not sufficiently account for available households or the growth of the population to support it. Another approach as in[27] using 2D and 3D thermal simulation, indicated window insulation could cut energy by 68%. This approach, however, is highly processing intensive, which makes the time spent on modelling and analysis lengthy. In the case of China, the application of passive house principles which entailed using airtight windows and thick insulation, was shown to slash heating and cooling energy demand by as much as 62%[28]. Consequently, the use of sophisticated modelling software such as EnergyPlus, DesignBuilder, and PHPP, to improve the energy efficiency of building envelopes and HVAC systems has become common. Even so, retrofitting older building remains a real challenge. Structural constraints of many of these older buildings make it hard to add thick insulation or contemporary ventilations systems without compromising usable space. DesignBuilder simulations indicate that other building envelope materials could curb energy used in Jordan by 24%[1] but, due to practical retrofitting challenges, this potential remains largely untapped. Research on renewable and smart energy alternatives has also proliferated. Households can have almost 29%[29] less electricity every month with rooftop solar systems, and off-grid solar PV systems with batteries ensure self-sufficiency[30,31]. Still, many of these studies do not consider passive solar strategies, like insulation and shading, that help to reduce the baseline demand. In multi-unit buildings, rooftop constraints can make solar panels much less effective[32]. While smart energy systems, particularly meshed micro-grids[5,33], have potential, their cost and technical sophistication can preclude many households.

Given these constraints, this study takes the initiative to concentrate on policy and planning. It advocates a revision of building regulations to stimulate vertical residential increase. With higher, multi-story structures, the compact form can reduce energy per unit while minimizing urban sprawl. While high-rises do pose challenges, particularly the energy cost of complex mechanical and electrical systems, heating and cooling alone account for almost 50% of total household energy use in Jordan[34]. This study splices together knowledge from engineering and architecture. While electrical engineers devise novel power system and control technology and advances control technologies that automate power usage within buildings, engineers shift the focus of their passive design approaches on insulation, ventilation, and natural light improvements. Integration of these design approaches yields buildings that are high performing from an operational cost, comfort, and sustainability standpoint. Enhanced performance of buildings, in terms of cost and comfort, and increased sustainability are reinforced by simulation results. Raising building heights to six floors was found to cut heating and cooling demand by 26%, 28.6%, and 28.3% in Residential Categories A, B, and C, respectively. These results highlight vertical densification as an effective and affordable passive strategy for reducing energy demand. They also provide strong evidence to guide updates to building codes and inform sustainable urban planning in Jordan.

Methodologies

As the relation between urban density and building energy consumption has received increasing attention in recent literature, this study investigates electrical energy consumption with respect to building vertical densification. In fact, densification methodologies can be categorized into.

a. Statistical Studies: Such studies analyze energy consumption data in locations of different densities (sometimes taking into account other variables such as topology), aiming to find a significant correlation between them. In[35], a study of three urban typologies in one Greek city concluded a negative correlation at lower densities and a positive correlation at higher densities. On the other hand,[36] studied 145 Spanish cities and found that electrical and "thermal" consumption per household increases as density increases, except in the cities with the highest density. Similarly, consumption per inhabitant was lowest in the cities with the lowest density. Some studies, such as[37], conducted in Seoul found no significant impact and concluded that other morphological variables have a more prominent effect on energy consumption. Another study of 140 Italian cities has been conducted by[38], which also accounted for per capita income and GDP. While the study has shown a positive correlation with electrical energy consumption, a negative correlation between density and consumption was found. Hence, the samples are mainly dense clusters of smaller towns where the density does not exceed that of a metropolitan area; therefore, the range of densities studied is limited.
b. Simulation: Several studies have employed simulation software to assess the effect of different residential density variables on energy consumption. In[17], an iterative simulation was conducted to assess the impact of the number of floors across four typologies: detached houses, row housing, low-rise apartments, and high-rise apartments. They simulated buildings with 1 to 4 levels in each typology, considering both north–south and east–west orientations. For each category, the normalized load (kWh/m^2) and average normalized energy consumption were calculated using Ecotect and DesignBuilder software. These tools, powered by the EnergyPlus engine, provided a comprehensive evaluation of thermal performance alongside other parameters like shading design, lighting control, mean radiant temperature, mean operative temperature, humidity, CO_2 generation, façade heat transmission, and total/normalized energy consumption. The software's graphical output enabled clear and accessible analysis. Similarly,[23] investigated the effects of building height and separation (compactness) using Rhino, EnergyPlus, and the Honeybee plugin. They modelled a 1- to 3-story villa situated in the centre of eight identical masses and analyzed how varying the distance between the buildings influenced energy performance.[39] Also explored the relationship between building height and en-

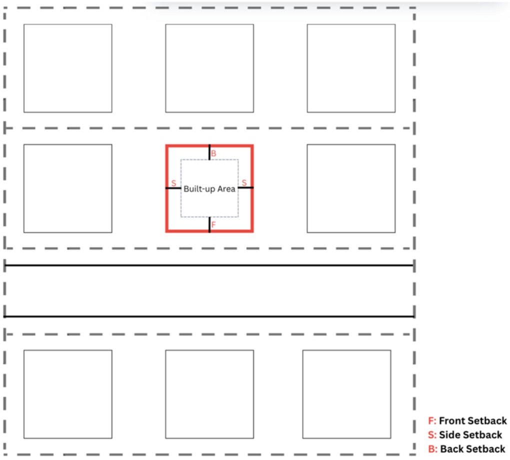

Fig. 3. Controlled depth, width, and setbacks based on the specified Jordan Building and Regulations Code for Cities and Villages.

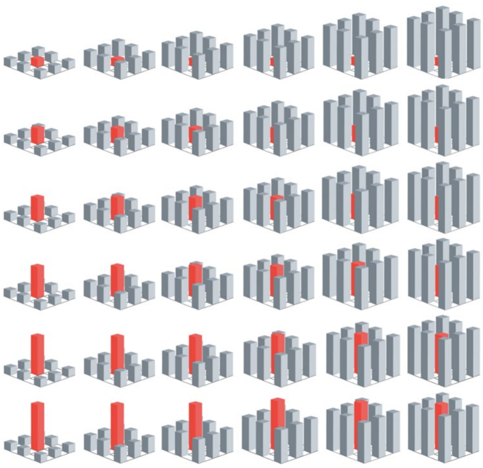

Fig. 4. Residential blocks' height adjustments throughout simulation testing.

ergy consumption, focusing on office buildings in Shanghai. They simulated the energy use of a hypothetical representative commercial building with floor area ratios corresponding to increasing heights (15, 20, and 25 floors). Their study examined the performance of three distinct building forms to understand the impact of height and design on energy efficiency.

c. Traditional experiments, which are very rare in urban-scale studies[40].

This study aims to investigate the effect of residential building density in Jordan on electrical energy consumption in terms of building cooling and heating, based on DesignBuilder Simulation software, using variables testing parameters such as setbacks, building height, and shading as shown in Figure 3.

Urban density is affected by many interrelated urban form variables that directly affect electrical energy consumption, such as building height, setbacks, building geometry, site geometry, and building-to-plot ratio. Therefore, this relationship can be studied using the 2022 Jordan Building and Regulations Code for Cities and Villages (JBRCCV), which regulates all the aforementioned variables. By doing so, an urban configurable neighbourhood will be constructed in accordance with the JBRCCV. Density will be adjusted throughout various simulations while other urban form variables are controlled to isolate and record the effects of densification on electrical consumption in terms of cooling and heating. That is, depth, width, and setbacks will be controlled as specified by the JBRCCV. In addition, the height of the residential blocks will be adjusted throughout the simulation (within the ranges specified by the code), where electrical consumption will be a dependent variable as shown in Figure 4. It is important to note that in this study, the primary variable tested was building height as a proxy for vertical densification. Other factors that can strongly influence energy consumption, such as building orientation, street width, and occupant behaviour, were kept constant. While these variables are equally important in shaping energy performance, they were excluded to isolate the effect of height within the constraints of this research and discussed as limitations.

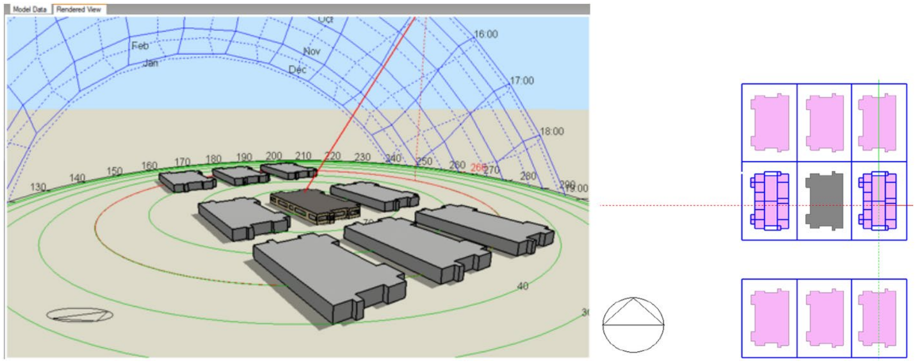

Fig. 5. Solar incidence and gains reductions based on neighborhood density.

Element	Material	Thickness (cm)	Total U-value (W/m^2-k)
Exterior Walls	Stone	5	0.61
	Concrete	10	
	Insulation	3	
	Block	10	
	Plaster	2	
Internal Walls	Plaster	2	1.955
	Block	10	
	Plaster	2	
Internal ceiling	Ceilings tiles	0.3	1.405
	Mortar	3	
	Sand	7	
	Water insulation	0.5	
	Reinforced concrete	20	
	Plaster	2	
Roof	Gravel	2	1.248
	Inclined concrete	5	
	Water insulation	0.5	
	Reinforced concrete	25	
	Plaster	2	
Windows	Aluminum frame, single glazing	0.6	5.70

Table 1. Construction Materials Specifications.

In categories A, B, and C, as density increased, the cooling loads dropped more. The cooling loads in these low density categories not dropping as much or even increasing slightly can be explained through the absence of co-shading. At these lower densities, increases in building density do little in terms having an impact to block and scatter solar radiation, as the reduction in shading is minor. That is, as shadow coverage increases, less solar radiation is likely to hit the façades, leading to a reduction in the heat transfer through the envelope and a reduction in heat gains through the glazing during the periods of overheating, especially during the glazing periods of overheating. That lower solar exposure will lower the electrical energy needed to cool the building. There is a strong relationship between solar incidence, solar gains, and total energy demand, specifically cooling loads. More density within compact neighborhoods led to a greater reduction in solar incidence and gains, as illustrated in Figure 5, which corresponded with the significant reductions in observed cooling loads.

Study specifications

Building materials and geometry

In order to gather more information on the situation of residential buildings in Jordan, an extensive study was undertaken to understand the most prevalent structural and spatial characteristics in the local context. Findings showed builders practiced a considerable degree of uniformity in the choice of construction practices, materials, and design features. Consequently, the construction materials chosen for the simulation reflect the most commonly used and most prevalent materials in Jordan's residential sector. To facilitate comparability, these specifications were kept uniform across different building classifications and simulation cases.

Table 1 presents the main components of buildings, the corresponding materials, thicknesses of each layer, and the U-values used in the simulation.

Input data	Value
Family size	6 members
Metabolic rate	0.8 met
Summer clothing	0.5 clo
Occupancy time	All day
Air exchange	2 ach -1
Heat gain	80 W/person
Lighting	5 W/m^2

Table 2. Simulation input parameters and assumptions.

Area classification	Min. land property size	Min. street facing length	Setback (Front, Side, Back)	BCR (%)
A (أ)	1000 m^2	25 m	F = 5, S = 4, B = 5	39%
B (ب)	750 m^2	20 m	F = 4, S = 3, B = 4	45%
C (ج)	500 m^2	18 m	F = 3, S = 2.5, B = 3	51%

Table 3. Jordanian building & regulation code 2022.

These specifications were constant for all simulation scenarios based on typical thermal performance for Jordanian residential construction. Three representative floor plans were created for each of the residential classifications (A, B, and C) based on national building regulations. Also, single-glazed windows and the conventional wall and ceiling assemblies were included in the model to reflect the reality of Jordanian residential building stock, where such construction methods are still prevalent. While there are more advanced materials of construction, their use is still rather limited. This understatement provides a more realistic overview of the performance of the majority of the existing housing units, even though it could result in a slight underestimation of the potential energy savings permitted by modern construction methods.

Simulation software and environmental settings

In order to guarantee technical precision and reproducibility of the simulations, the research employed DesignBuilder V7.0 using Energy-Plus as the simulation engine. DesignBuilder is intuitive and comprehensive with the ability to perform 3D construction and energy performance simulation, encompassing thermal comfort and HVAC performance, daylighting and natural ventilation, and other components of energy performance evaluation. His parametric simulation function is especially useful in assessing design alternatives in an organized and logical manner. The simulations incorporated Typical Meteorological Year (TMY3) climate data for Irbid, Jordan, and to capture the local weather realities.

For all simulation scenarios, the HVAC system was set to be the Ideal Load Air System provided by EnergyPlus to isolate the impact of building form on heating and cooling demand without the variability introduced by system-specific efficiencies. While approach is widely used in simulation-based research to ensure that observed energy differences result solely from architectural or urban design parameters, it was added as a limitation. Internal loads were standardized using the residential occupancy template from EnergyPlus, with the assumptions presented in Table 2.

These assumptions reflect typical Jordanian household conditions and were derived from official data and national standards. Family size and occupancy schedules were based on the Jordanian Department of Statistics (DOS, 2018). Construction practices and material properties were selected according to the Jordan Building and Regulations Code (2022) and field surveys of residential housing stock. The HVAC and internal load assumptions follow standard and ready EnergyPlus templates and align with practices commonly applied in Jordanian buildings. Table 2 summarizes the key input parameters used in the simulation.

These baseline conditions were applied uniformly across all study cases to ensure comparability and to isolate the impact of these variables on heating and cooling energy consumption.

Neighborhood's configuration

By reviewing JBRCCV for building setback and ventilation ability, the residential categories to be studied throughout this research were identified as A, B, and C. In addition, the representative neighbourhood has been designed based on the local regulations specified for each category in terms of property minimum size, neighbourhood street width, and number of lots served, as in Table 3.

Simulation results and discussion

The analysis of the data sets extracted from the simulation began with plotting the annual energy consumption of each neighbourhood (series) against residential units' density. In the A category, higher density leads to lower energy consumption per square meter, as indicated in Table 4. Density played a significant role in energy consumption reductions, with maximum decreases of 21.8%, 27.6%, 28.9%, 28.2%, 26.3%, and 23.7% respectively, per group observed in the iteration combination of building and surrounding density height.

Category	Group	Case	Annual Heating Load (kW)	Saving % Heating Load	Annual Cooling Load (kW)	Saving % Cooling Load	Total Heating and Cooling Consumption (kWh)	Heating and Cooling Consumption per m^2 (kWh)	Total Saving% (within the group)
A	Group 1	B_1S_1	5499.9	0	8428.2	0	13,928.1	35.7	0
		B_1S_2	5779	-5.1	7437	11.8	13,216	33.9	5.1
		B_1S_3	5854.5	-6.4	6607.1	21.6	12,461.6	32	10.5
		B_1S_4	6026.4	-9.6	5774.9	31.5	11,801.3	30.3	15.3
		B_1S_5	6109.6	-11.1	5129.8	39.1	11,239.4	28.8	19.3
		B_1S_6	6229.3	-13.3	4667.8	44.6	10,897.1	27.9	21.8
	Group 2	B_2S_1	8920.8	0	14,488	0	23,408.8	30	0
		B_2S_2	8923.9	-0.04	13,086	9.7	22,009.9	28.2	6
		B_2S_3	8964.5	-0.5	11,310.7	21.9	20,275.2	26	13.4
		B_2S_4	8997.3	-0.9	9888.8	31.7	18,886.1	24	19.3
		B_2S_5	9048.2	-1.4	8705.1	39.9	17,753.3	22.8	24.2
		B_2S_6	9075.6	-1.7	7867.7	45.7	16,943.3	21.7	27.6
	Group 3	B_3S_1	13,506.7	0	20,473	0	33,979.7	29	0
		B_3S_2	13,310.2	1.5	19,054	6.9	32,364.2	27.7	4.8
		B_3S_3	13,047.2	3.4	16,875.8	17.6	29,923	25.6	11.9
		B_3S_4	12,937.7	4.2	14,545.9	28.9	27,483.6	23.5	19.1
		B_3S_5	12,875.8	4.7	12,751.6	37.7	25,627.4	22	24.6
		B_3S_6	12,771.7	5.4	11,381.9	44.4	24,153.6	20.6	28.9
	Group 4	B_4S_1	18,702.9	0	26,378.5	0	45,081.4	28.9	0
		B_4S_2	18,408.5	1.6	24,980	5.3	43,388.5	27.8	3.6
		B_4S_3	17,958.3	4	22,782	13.6	40,740.3	26.1	9.6
		B_4S_4	17,538.7	6.2	20,051.9	23.9	37,590.6	24.1	16.6
		B_4S_5	17,234.9	7.8	17,382	34.1	34,616.9	22.2	23.2
		B_4S_6	16,965.8	9.3	15,395	41.6	32,360.8	20.7	28.2
	Group 5	B_5S_1	24,020.8	0	32,230.2	0	56,251	28.8	0
		B_5S_2	23,835.5	0.8	30,839.9	4.3	54,675.4	28	2.8
		B_5S_3	23,300.7	3	28,664	11.1	51,964.7	26.6	7.6
		B_5S_4	22,740.1	5.3	25,903.6	19.6	48,643.7	25	13.5
		B_5S_5	22,055.8	8.2	22,827	29.2	44,882.8	23	20.2
		B_5S_6	21,491.6	10.5	19,971.8	38	41,463.4	21.3	26.3
	Group 6	B_6S_1	29,531.4	0	38,025.7	0	67,557.1	28.9	0
		B_6S_2	29,537.4	-0.02	36,649.2	3.6	66,186.6	28.2	6.6
		B_6S_3	28,923.5	2.1	34,493	9.3	63,416.5	27.1	13
		B_6S_4	28,190.9	4.5	31,744.3	16.5	59,935.2	25.6	17.7
		B_6S_5	27,373.6	7.3	28,662	24.6	56,035.6	23.9	21.5
		B_6S_6	26,636.8	9.8	25,388	33.2	52,024.8	22.2	23.7

Table 4. Category A—Annual heating and cooling loads (kW).

As seen from Table 4, while the cooling load has steeply decreased moving from S1 to S6 per group, the heating load has slightly increased for groups 1 and 2 only, given higher overall electrical power savings, particularly from S3 and up, as shown in Figure 6.

In group 2, a slight increase was observed in heating, while substantial drops were observed in cooling. As a result, the gradual increase in total savings as the cooling load decreases. In group 3, the heating load decreases slightly, while the cooling load decreases significantly, leading to the highest savings, especially in cases of (S6). Similarly, in groups 4 and 5, heating load reduction is less significant, while cooling load and total savings progression among groups see a steady improvement from S1 to S6. Lastly, a notable savings in cooling load and the total consumption was observed in group 6, with a slight drop from groups 2, 3, and 4 as the shading factor decreased with building elevation increases. Yet, savings grow as the cases progress. In general, while the heating load has increased slightly across the cases, with Group 1 showing the highest starting heating load and the smallest changes, the cooling load decreases in all cases, with direct savings. The savings become more pronounced as shown in Figure 7, tracking how energy savings have improved over six different scenarios (S1 to S6) for each group in Category.

As a result, with higher residential building units' densification, electrical consumption per unit m^2 has dropped significantly by an average of 7.75 kWh per m^2 to illustrate higher savings and less electrical consumption, as shown in Figure 8.

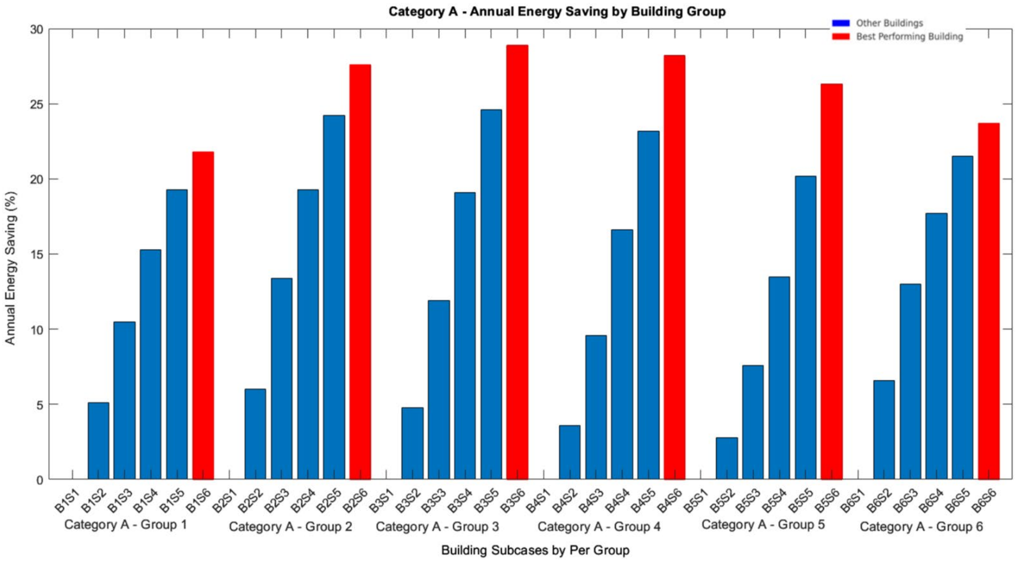

Fig. 6. Category (A) building annual electrical energy savings – six cases in six groups, with red bar indicating building with the highest saving case in each group.

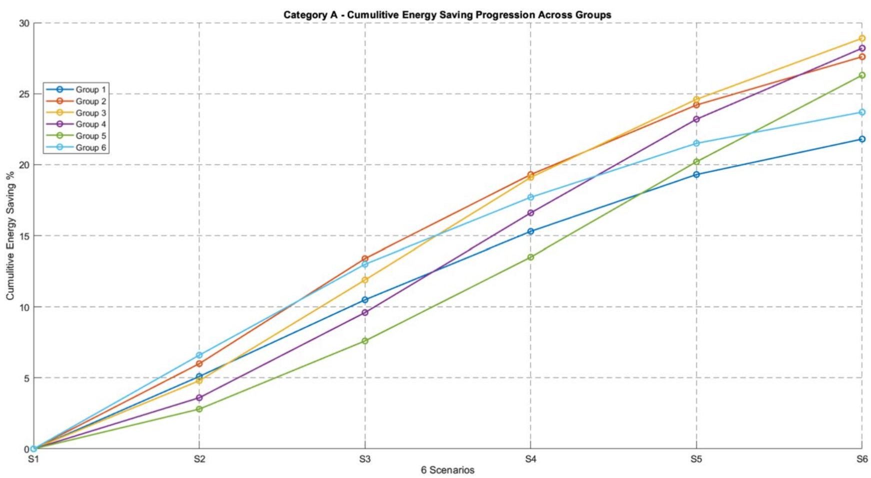

Fig. 7. Category A –cumulative electrical energy saving percentage over six cases with steady increase in energy saving.

The regression analysis for Category A, Figure 9 and Table 5, reveals a strong positive relationship between building height and annual energy saving percentage. The slopes of the regression lines are steep, and the R^2 values are comparatively high, indicating that height explains a large share of the variance in savings. This result can be linked to the zoning parameters of Category A, which is defined by large land parcels (minimum 1000 m^2), wide setbacks, and a low building coverage ratio of 39%. As a result, adding floors substantially reduces exposure envelope area per unit and offer efficiency gains. Statistically, this makes Category A the most responsive to vertical densification, with savings improving markedly as building height increases.

Meanwhile, simulation results in the B category indicate a negative correlation between density and electrical consumption, as well as in terms of cooling and heating. The higher vertical floor density leads to lower energy consumption per square meter. That is, electrical consumption decreased by 23.6%, 28.8%, 31.1%, 31.3%, 31.1%, and 27.3% as height density combination increases in the building and surrounding as shown in Table 6.

Moving from S1 to S6 per group, electrical power savings have achieved a major electrical power in category B as well. As shown in Figure 10, total savings for heating and cooling load have gradually increased as approaching S6 with an average of more than 30% electrical savings.

The saving progression for category B, as shown in Figure 11, has shown approximately similar results to category A. A slight increase was observed in group 1 due to heating load increases and considerable drops in cooling load. That is, a gradual increase in total savings was observed in groups 3, 4, and 5 due to significant cooling load decreases. Meanwhile, a notable savings progression was observed in group 6 as it approached S6.

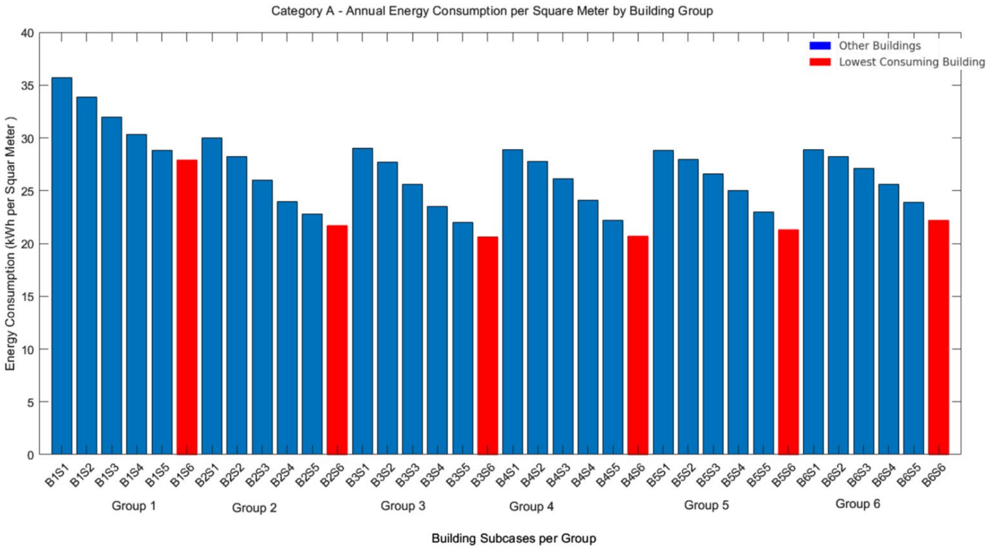

Fig. 8. Category A building annual energy consumption per square meter—six cases in six groups, with red bars indicating building with less consumption in each group.

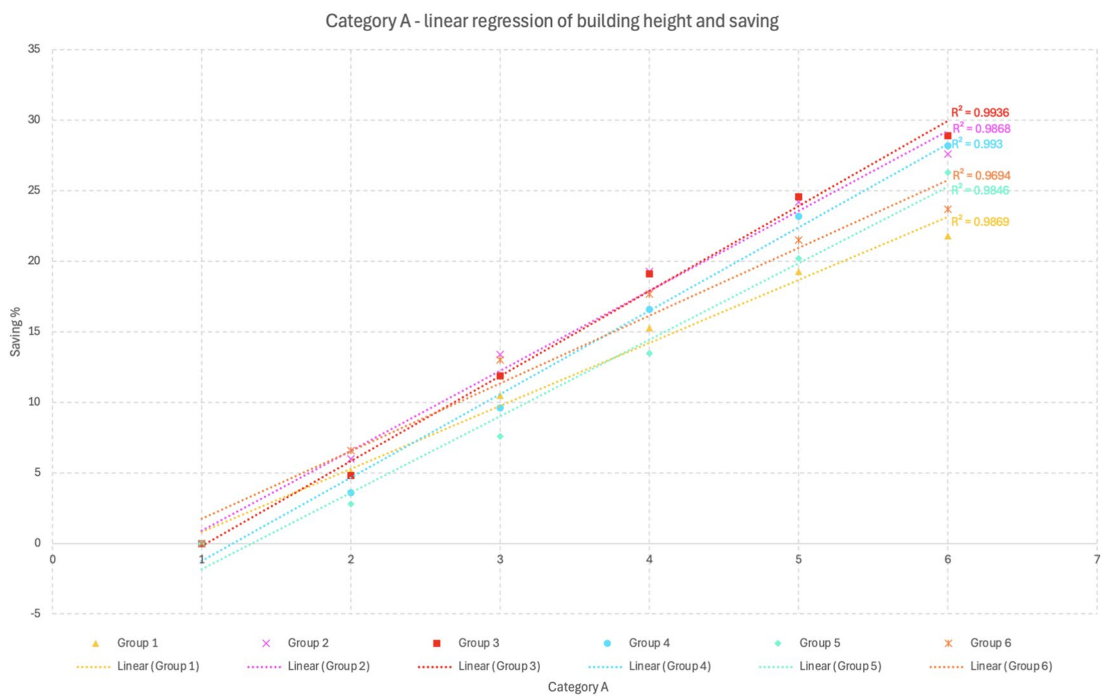

Fig. 9. Category A: linear regression of building height and annual saving percentage.

As a result, the saving progression rose from S1 to S6 to illustrate the heating and cooling load drop in all cases for direct electrical power savings.

Furthermore, the proposed densification method has shown a significant drop in electrical consumption per unit m^2. That is an average of 5.5 kWh per m^2 drop in electrical consumption was obtained by increasing building occupancy in vertical means, as shown in Figure 12.

In Category B, Figure 13 and Table 7, the regression results also show a clear positive association between building height and annual savings, though the slopes are less steep than in Category A. The R^2 values remain significant, but they indicate moderate rather than strong explanatory power, suggesting greater variability in the relationship. This outcome reflects the intermediate zoning conditions of Category B, with minimum lot sizes of 750 m^2, medium setbacks, and a building coverage ratio of 45%. The higher ground coverage compared to Category A means that the efficiency gains from additional floors are somewhat diluted, though still evident. From a statistical perspective, Category B represents a transitional condition: vertical densification continues

Category	Group	Case	Power Saving Regression Predicted Y	Power Saving Regression Fit quality R^2
A	Group 1	B_1S_1	1.42	0.9869
		B_1S_2	5.52	
		B_1S_3	9.62	
		B_1S_4	13.72	
		B_1S_5	17.82	
		B_1S_6	21.92	
	Group 2	B_2S_1	2.17	0.9868
		B_2S_2	7.40	
		B_2S_3	12.63	
		B_2S_4	17.86	
		B_2S_5	23.09	
		B_2S_6	28.32	
	Group 3	B_3S_1	2.19	0.9936
		B_3S_2	7.54	
		B_3S_3	12.89	
		B_3S_4	18.24	
		B_3S_5	23.59	
		B_3S_6	28.94	
	Group 4	B_4S_1	1.96	0.993
		B_4S_2	7.30	
		B_4S_3	12.64	
		B_4S_4	17.98	
		B_4S_5	23.32	
		B_4S_6	28.66	
	Group 5	B_5S_1	2.35	0.9846
		B_5S_2	7.53	
		B_5S_3	12.71	
		B_5S_4	17.89	
		B_5S_5	23.07	
		B_5S_6	28.25	
	Group 6	B_6S_1	1.75	0.9694
		B_6S_2	6.23	
		B_6S_3	10.71	
		B_6S_4	15.19	
		B_6S_5	19.67	
		B_6S_6	24.15	

Table 5. Category A – combined power consumption and saving regression in 6 groups.

to deliver meaningful savings, but other factors such as envelope geometry and compactness ratios may also influence performance.

Lastly, in category C, simulation has also indicated similar results with a negative relation between vertical floor density and electrical consumption in terms of cooling and heating load. That is, as provided in Table 8, the electrical load (consumption) dropped by 22.8%, 32.2%, 31.4%, 30.9%, 28.1%, and 24.6% as building density increases to accommodate higher electrical load efficiency and fewer losses.

As shown in Table 8, the heating load has also gradually increased as the cooling load decreased, moving from S1 to S6 to indicate higher power saving, particularly in group 2 and up, as shown in Figure 14.

Saving progression for category C, as in Figure 15 for tracking energy savings improvements over Category six scenarios (S1 to S6), has shown higher trends in group 2, followed by the other groups. Yet, saving progression rose from S1 to S6 for all groups to illustrate the heating and cooling load drop in all cases, providing an average of 28% electrical power savings.

As a result, the electrical consumption per unit m^2 for the C category has dropped by an average of 6.6 kWh per m^2 to illustrate less electrical consumption per unit, as shown in Figure 16, by approaching the surrounding building of S6.

Category C, Figure 17 and Table 9, demonstrates the weakest statistical relationship between building height and annual energy savings. The regression lines still have positive slopes, confirming that taller buildings achieve greater efficiency, but the distribution of points is more scattered and the R^2 values are comparatively low. This outcome is closely tied to the zoning features of Category C, which permits small parcels (minimum 500 m^2),

Category	Group	Case	Annual Heating Load (kW)	Saving % Heating Load	Annual Cooling Load (kW)	Saving % Cooling Load	Total Heating and Cooling Consumption (kWh)	Heating and Cooling Consumption per m^2 (kWh)	Total Saving% (within the group)
B	Group 1	**B_1S_1**	3297.8	0	5497.4	0	8795.2	26.1	0
		B_1S_2	3729.4	-13.1	4482.6	18.5	8212	24.3	6.6
		B_1S_3	4032.6	-22.3	3619.3	34.2	7651.9	22.7	13
		B_1S_4	4148.3	-25.8	3093.1	43.8	7241.4	21.5	17.7
		B_1S_5	4165.9	-26.3	2736.4	50.2	6902.3	20.5	21.5
		B_1S_6	4187.9	-27	2525.3	54.1	6713.2	19.9	23.6
	Group 2	**B_2S_1**	3865.3	0	9740.6	0	13,605.9	20.2	0
		B_2S_2	4323.5	-11.9	8308	14.7	12,631.5	18.7	7.1
		B_2S_3	4864.1	-25.8	6538.1	32.9	11,402.2	16.9	16.2
		B_2S_4	5189.6	-34.3	5371.5	44.9	10,561.1	15.6	22.4
		B_2S_5	5316	-37.5	4726.7	51.5	10,042.7	14.8	26.2
		B_2S_6	5357.4	-38.6	4336.3	55.5	9693.7	14.4	28.8
	Group 3	**B_3S_1**	4762.2	0	14,030	0	18,792.2	18.6	0
		B_3S_2	5035.9	-5.7	12,569	10.4	17,604.9	17.4	6.3
		B_3S_3	5654.9	-18.7	10,372.9	26.1	16,027.8	15.8	14.7
		B_3S_4	6179.1	-29.8	8288.4	40.9	14,467.5	14.3	23
		B_3S_5	6504.1	-36.6	7015.1	50	13,519.2	13.4	28
		B_3S_6	6613.1	-38.9	6331.7	54.9	12,944.8	12.8	31.1
	Group 4	**B_4S_1**	5887	0	18,214.5	0	24,101.5	17.9	0
		B_4S_2	6143.7	-4.7	16,843.6	7.5	22,987.3	17	4.6
		B_4S_3	6492	-10.3	14,620.5	19.7	21,112.5	15.6	12.4
		B_4S_4	7095.2	-20.5	12,110	33.5	19,205.2	14.2	20.3
		B_4S_5	7626.2	-29.5	9903.3	45.6	17,529.5	13	27.2
		B_4S_6	7959.6	-35.2	8590.5	52.8	16,550.1	12.6	31.3
	Group 5	**B_5S_1**	7109.4	0	22,391.3	0	29,500.7	17.5	0
		B_5S_2	7336.5	-3.2	21,093.4	5.8	28,429.9	16.8	3.6
		B_5S_3	7764.6	-9.2	18,898.2	15.6	26,662.8	15.8	9.6
		B_5S_4	8078.5	-13.6	16,356.4	27	24,434.9	14.5	17.2
		B_5S_5	8684.7	-22.2	13,690.4	38.9	22,375.1	13.3	24.1
		B_5S_6	9174.6	-29	11,460.3	48.8	20,634.9	12.2	30.1
	Group 6	**B_6S_1**	8251.4	0	26,538.5	0	34,789.9	17.2	0
		B_6S_2	8564.7	-3.8	25,242.3	4.9	33,807	16.7	2.8
		B_6S_3	8906.9	-7.9	23,130.8	12.8	32,037.7	15.8	7.9
		B_6S_4	9307.2	-12.8	20,613.8	22.3	29,921	14.8	14
		B_6S_5	9659	-17.1	17,906.8	32.5	27,565.8	13.6	20.8
		B_6S_6	10,121.6	-22.7	15,215.1	42.7	25,336.7	12.5	27.1

Table 6. Category B—annual heating and cooling loads (kW).

reduced setbacks, and the highest building coverage ratio (51%). In this compact form, density is already maximized at the ground level, and while adding height does improve efficiency, the marginal gains are less pronounced. Statistically, this results in greater dispersion of outcomes and weaker model fit. Thus, in Category C, vertical densification remains beneficial, but its impact is less dominant compared to Categories A and B.

As a result, to accomplish a comprehensive saving analysis based on categories, groups (BnSn), heating and cooling electrical load consumption per m^2, the focus will be on identifying trends in energy savings across the simulated dataset.

That is, in terms of heating and cooling trend across the three categories, a structured breakdown analysis combining heating and cooling load saving is presented in Figure 18. With 6 groups in each category representing various building configurations to test energy efficiency improvements, it was clear that overall savings increase gradually, with larger savings in the later cases of surrounding (S6) by increasing building height. In[41], a scale of heights (in terms of building number of floors) constitutes optimal energy savings in heating and cooling.

The findings highlight a strong potential for improving energy efficiency in residential buildings. In many cases, cooling savings exceeded 50%, while heating demand consistently decreased toward B6S6. A 0.67 correlation involving annual heating and cooling loads reveals an opposite trend: an increase in heating load correlates with a decrease in cooling load, consistent with[42] regarding dwelling unit density and energy use[42]. After stage S3, significant savings of 15-20% in S4, and 25-32% in S6 were achieved. Among the three residential

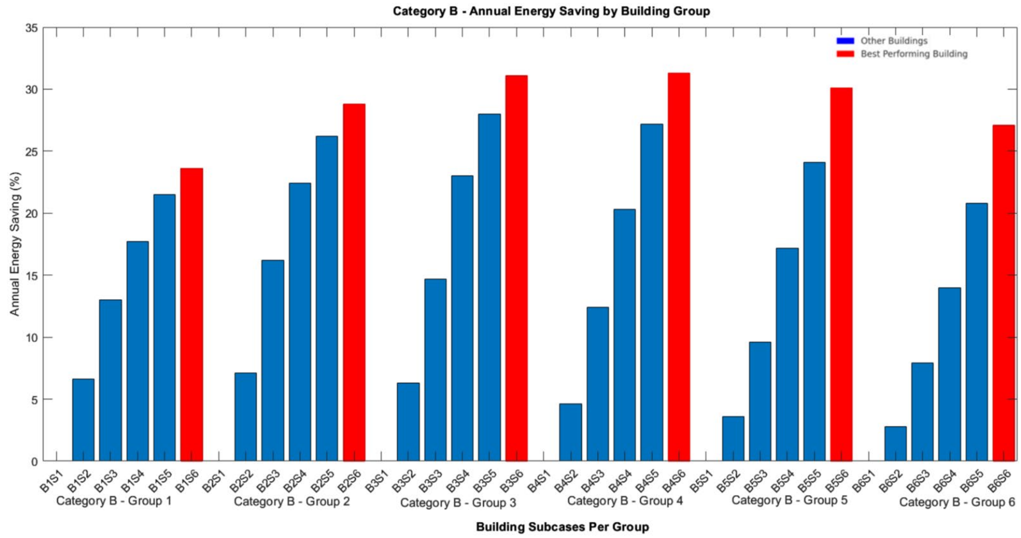

Fig. 10. Category (B) building annual electrical energy savings – six cases in six groups with red bar indicating building with highest saving case in each group.

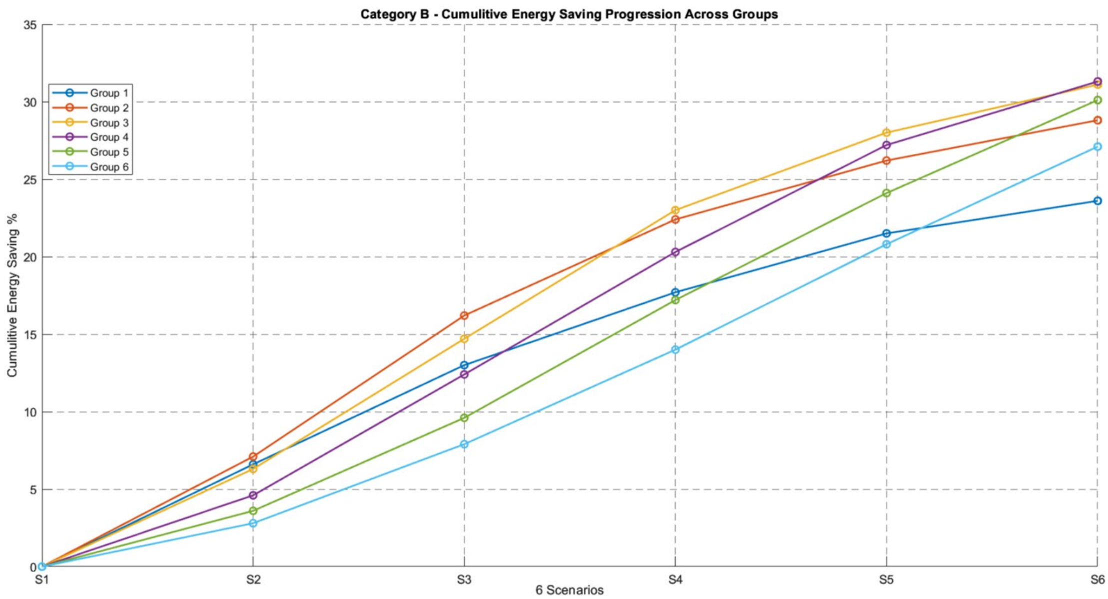

Fig. 11. Category B –cumulative electrical energy saving percentage over six cases with steady increase in energy saving.

categories, residential category B achieved the highest average savings of 28.67% S6, which was due to smaller property size and restrictive easement areas. Following closely, category C attained 28.33% while category A, with larger properties and lower density, achieved the least savings of 23.7%. This indicates that in savings average 27% in electricity use per household in the evaluated categories. Applying this to the 2.44 million households in Jordan with 8.77 TWh of residential electricity use in 2021 translates to 968 kWh per household each year, approximately 2.36 GWh at the total level. This aligns with studies in Montreal[43] in which energy savings of 30% were achieved by densifying single-family houses, and in Egypt[44] where solar shadings provided savings of 33% in a climate similar to Jordan.

Applicably, these findings provide a basis guidance for energy policy, urban planning, and building regulations in Jordan:

- Urban planning: Cooling loads can reduced and improve energy efficiency per unit area by promoting vertical densification, specifically in dense neighbourhoods.
- Building codes: Easement limits, solar shading, and property size can enhance energy savings in both existing and new buildings.

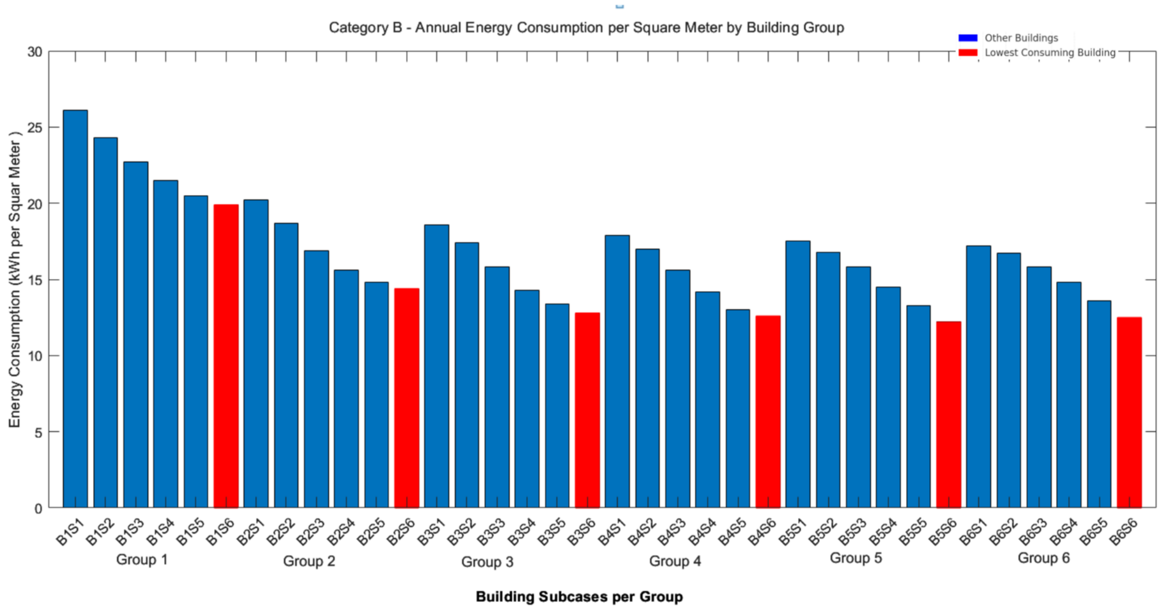

Fig. 12. Category **B** building annual energy consumption per square meter—six cases in six groups with red bars indicating building with less consumption in each group.

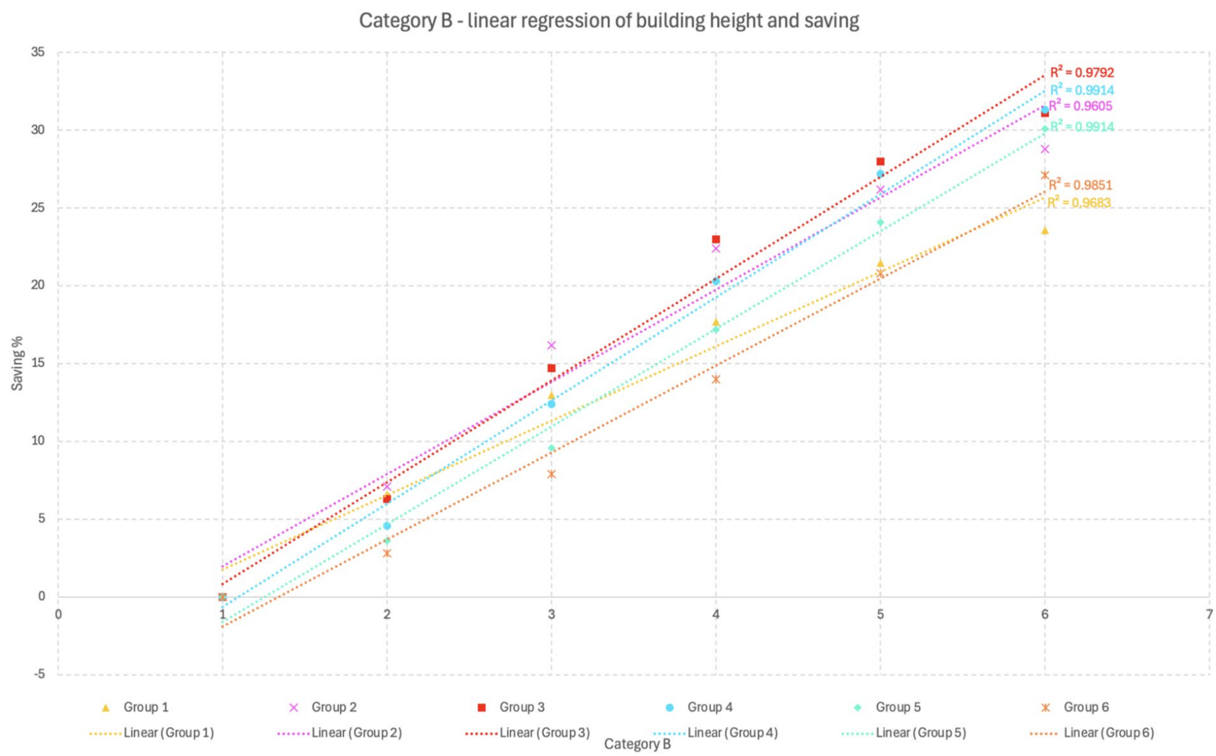

Fig. 13. Category B: Linear Regression of Building Height and Annual Saving Percentage.

- Energy policy: Extensive implementation could significantly lower residential electricity demand, reduce grid loads, delay expensive infrastructure growth, and enhance nationwide sustainability goals.

To enable adequate comparisons across building category, simulations was used to provide annual heating and cooling loads (kWh/year) normalized by floor area (kWh/m^2/year) and examined under consistent urban form conditions. As a result, a clear trend was revealed: both heating and cooling demands decline as density increases.

Category	Group	Case	Power Saving Regression Predicted Y	Power Saving Regression Fit quality R^2
B	Group 1	B_1S_1	1.92	0.9683
		B_1S_2	6.27	
		B_1S_3	10.62	
		B_1S_4	14.97	
		B_1S_5	19.32	
		B_1S_6	23.67	
	Group 2	B_2S_1	1.65	0.9605
		B_2S_2	7.35	
		B_2S_3	13.05	
		B_2S_4	18.75	
		B_2S_5	24.45	
		B_2S_6	30.15	
	Group 3	B_3S_1	2.15	0.9792
		B_3S_2	8.13	
		B_3S_3	14.11	
		B_3S_4	20.09	
		B_3S_5	26.07	
		B_3S_6	32.05	
	Group 4	B_4S_1	2.22	0.9914
		B_4S_2	8.37	
		B_4S_3	14.52	
		B_4S_4	20.67	
		B_4S_5	26.82	
		B_4S_6	32.97	
	Group 5	B_5S_1	2.53	0.9914
		B_5S_2	7.99	
		B_5S_3	13.45	
		B_5S_4	18.91	
		B_5S_5	24.37	
		B_5S_6	29.83	
	Group 6	B_6S_1	3.14	0.9851
		B_6S_2	7.88	
		B_6S_3	12.62	
		B_6S_4	17.36	
		B_6S_5	22.10	
		B_6S_6	26.84	

Table 7. Category B – Combined Power Consumption and Saving Regression in 6 Groups.

In Jordan, as the country consumed roughly 19,500 GWh of electricity[45], in 2021, households accounted for 8.77 billion kWh as 45% of total electricity used in Jordanian residential sector[11]. Based on 11 million population and an average 4.5 people per household[10,46], equate to 2.44 million households, each consuming about 3,587 kWh per year. Therefore, as 27% savings proposed applied, demand will be reduced by 968 kWh per household annually and adding up to 2.36 GWh national saving.

To demonstrate such savings, a plot of heating and cooling loads (kWh/m^2/year) against density, as in Figure 19, shows lowers household energy demand with higher residential density directly.

As a result, the study provides clear assessment across diverse building types and densities by expressing energy usge in kWh per square meter per year. That is, in most cases for cooling and heating, demands decrease as urban density increases. This fact highlights the value of merging residential densification schemes with building energy-efficient design to achieve significant decreases in electricity consumption per individual households.

The three zoning categories comparative analysis highlights both consistency and variability relationship between vertical density and annual energy savings. That is, all categories demonstrated a positive correlation, confirming that building height increases systematically advances energy efficiency by lowering envelope exposure per unit. However, the strength of this relationship was not consistent. Category A, which features extensive land plots and a minimal building coverage ratio of 39%, exhibited the strongest declines and the highest R^2 values, suggesting that increased vertical densification within these contexts produces the largest efficiency improvements. With intermediate plot sizes and a moderate coverage ratio of 45%, Category B showed a more evenly distributed trend, where height remained a core driving factor, albeit with increased

	Group	Case	Annual Heating Load (kW)	Saving % Heating Load	Annual Cooling Load (kW)	Saving % Cooling Load	Total Heating and Cooling Consumption (kWh)	Heating and Cooling Consumption per m^2 (kWh)	Total Saving% (within the group)
C	Group 1	B_1S_1	3260	0	4489.7	0	7749.7	30.4	0
		B_1S_2	3662.9	-12.4	3379.4	24.7	7042.3	27.6	9.1
		B_1S_3	3841.4	-17.8	2739.3	39	6580.7	25.8	15.1
		B_1S_4	3945.1	-21	2511.5	44	6456.6	25.3	16.7
		B_1S_5	4334	-32.9	1854.4	58.7	6188.4	24.3	20.1
		B_1S_6	4681.3	-43.6	1310.7	70.8	5992	23.5	22.8
	Group 2	B_2S_1	4140.8	0	8177.9	0	12,318.7	24.2	0
		B_2S_2	4673.8	-12.9	6595.5	19.3	11,269.3	22.1	8.5
		B_2S_3	5189	-25.3	4955.7	39.4	10,144.7	19.9	17.6
		B_2S_4	5343.1	-29	4342.5	46.9	9685.6	19	21.4
		B_2S_5	5700.6	-37.7	3531	56.8	9231.6	18.1	25.1
		B_2S_6	6333.7	-53	2013.7	75.4	8347.4	16.4	32.2
	Group 3	B_3S_1	5263.5	0	11,846.1	0	17,109.6	22.4	0
		B_3S_2	5666.8	-7.7	10,297.5	13.1	15,964.3	20.9	6.7
		B_3S_3	6239	-18.5	8157.7	31.1	14,396.7	18.8	15.9
		B_3S_4	6743.5	-28.1	6325.2	46.6	13,068.7	17.1	23.6
		B_3S_5	7073.5	-34.4	5485.8	53.7	12,559.3	16.4	26.6
		B_3S_6	7664.4	-45.6	4076.3	65.6	11,740.7	15.3	31.4
	Group 4	B_4S_1	6540.9	0	15,462.3	0	22,003.2	21.6	0
		B_4S_2	6894.9	-5.4	13,999.7	9.5	20,894.6	20.5	5
		B_4S_3	7321.7	-11.9	11,847.3	23.4	19,169	18.8	12.9
		B_4S_4	7902.4	-20.8	9507.4	38.5	17,409.8	17.1	20.9
		B_4S_5	8526.8	-30.4	7644.7	50.6	16,171.5	15.9	26.5
		B_4S_6	9082.4	-38.9	6119.2	60.4	15,201.6	14.9	30.9
	Group 5	B_5S_1	7919.8	0	19,066.9	0	26,986.7	21.2	0
		B_5S_2	8202.5	-3.6	17,640.7	7.5	25,843.2	20.3	4.2
		B_5S_3	8721.8	-10.1	15,533.1	18.5	24,254.9	19	10.1
		B_5S_4	9116.1	-15.1	13,168.9	30.9	22,285	17.5	17.4
		B_5S_5	9834.6	-24.2	10,805.3	43.3	20,639.9	16.2	23.5
		B_5S_6	10,622.5	-34.1	8781.5	53.9	19,404	15.2	28.1
	Group 6	B_6S_1	9269.6	0	22,628	0	31,897.6	20.8	0
		B_6S_2	9669.5	-4.31	21,221.1	6.2	30,890.6	20.2	3.2
		B_6S_3	10,053.5	-8.5	19,161.6	15.3	29,215.1	19.1	8.4
		B_6S_4	10,435.5	-12.6	16,829.2	25.6	27,264.7	17.8	14.5
		B_6S_5	11,041.6	-19.1	14,437.5	36.2	25,479.1	16.7	20.1
		B_6S_6	11,952.2	-28.9	12,101.9	46.5	24,054.1	15.7	24.6

Table 8. Category C—Annual Heating and Cooling Loads (kW).

reversibility across the scenarios. Category C, which is distinguished by its compact lots and 51% coverage ratio, represents the weakest statistical relation because the ground level of this category was already highly dense, thus limiting the potential value of additional vertical height. Overall, these observations suggest that while vertical densification remains a highly effective passive design refinement, the extent of its impact is most influenced by zoning regulations, with greater value derived in the more dispersed and less compact zones.

Conclusions

Understanding how densification affects the net electricity urban residential areas consume hinges on several intricately connected elements. These elements must be optimized, and the right balance achieved, such that well-designed density policies may reduce energy efficiency while minimizing climate change impact. This study analyzed the operational energy consumed within mid-rise residential apartment blocks and the relationship between gross housing density and the energy used vertically as building height is a significant factor. Focusing on the energy consumption rational, the proposed hypothesis analyzed how the density's shading effect diminishes cooling loads by reducing radiant heat transfer. Findings suggest that all residential building categories under study exhibited a positive association with savings on energy consumption, averaging 26% for category A, 28.6% for B, and 28.3% for C, indicating that the heating and cooling demand or loads substantially reduced as the floors increased. This was evaluated based on the solar access played through Radiance V4.0 with the Design

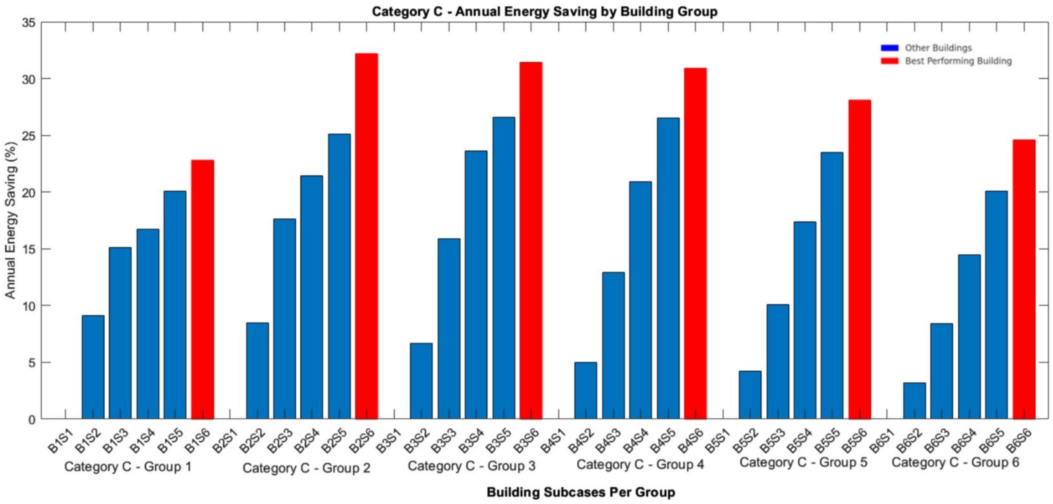

Fig. 14. Category (C) building annual electrical energy savings – six cases in six groups with red bar indicating building with highest saving case in each group.

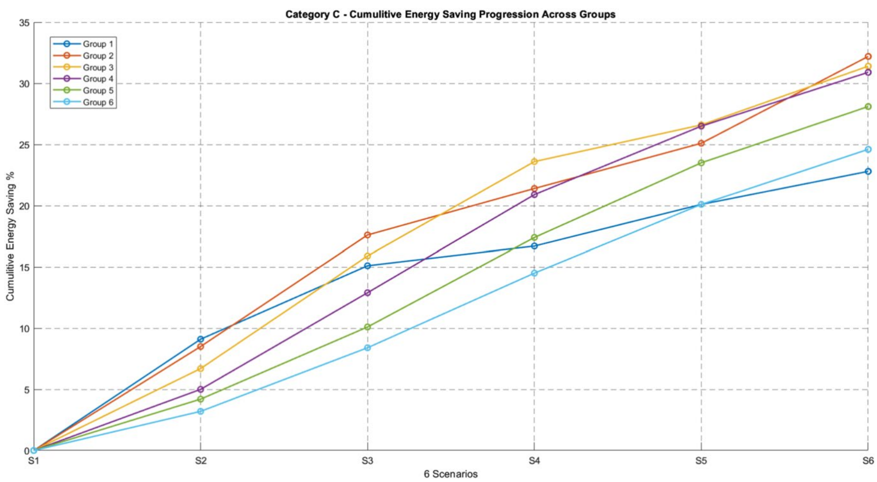

Fig. 15. Category C –cumulative electrical energy saving percentage over six cases with steady increase in energy saving.

Builder plugin for the whole year cycle. This was concluded by comparing the solar incidence (kWh/m^2/year) on the facade of the A, B, and C Categories, whereby as density increased, cooling loads decreased. It seems reasonable to conclude that higher residential urban density in Jordan resulted in lower cooling loads. This is mainly attributable to the enhancement of co-shading, which, in turn, lowers solar gains through glazing, solar incidence on the building envelope, and heat transfer into the building. Consequently, cooling energy demand is less. To summarize, this result can be acted upon in the following ways:

- Compact and comfortable building design is one way to achieve this ideal. For energy efficiency and natural light and ventilation access in the Mediterranean climate of Jordan, a height of four to six stories is ideal. Architectural elements like setbacks and treatment of facades to prevent excessive lower-floor shading will aid comfort.
- Efficient systems will aid the engineered side of the equation. For mid-rise compact blocks, tailored HVAC systems that include demand-controlled ventilation and heat recovery will lower loads. Assessing construction systems and insulation will give practical and cost-effective alternatives to construction upgrades.
- Fully considering energy performance in planning frameworks is a major task to be undertaken by policymakers. Regulations could include density limits that encourage 4–8 story residential buildings and prevent urban sprawl. Thoughtful requirements about street width and rules about solar access rights, ventilation corridors, and solar access rights will provide comfort in high-density areas.

Nonetheless, this study provides meaningful contributions on the effects building densification has on energy usage, several points need to be acknowledged. 1. Range of Control Variables-Only one building code parameter,

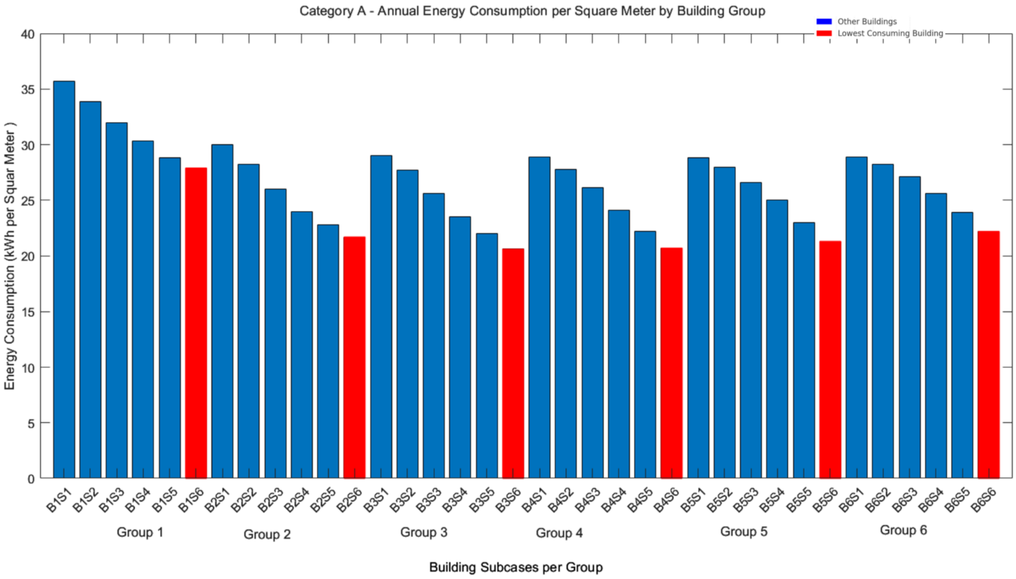

Fig. 16. Category C building annual energy consumption per square meter—six cases in six groups, with red bars indicating buildings with less consumption in each group.

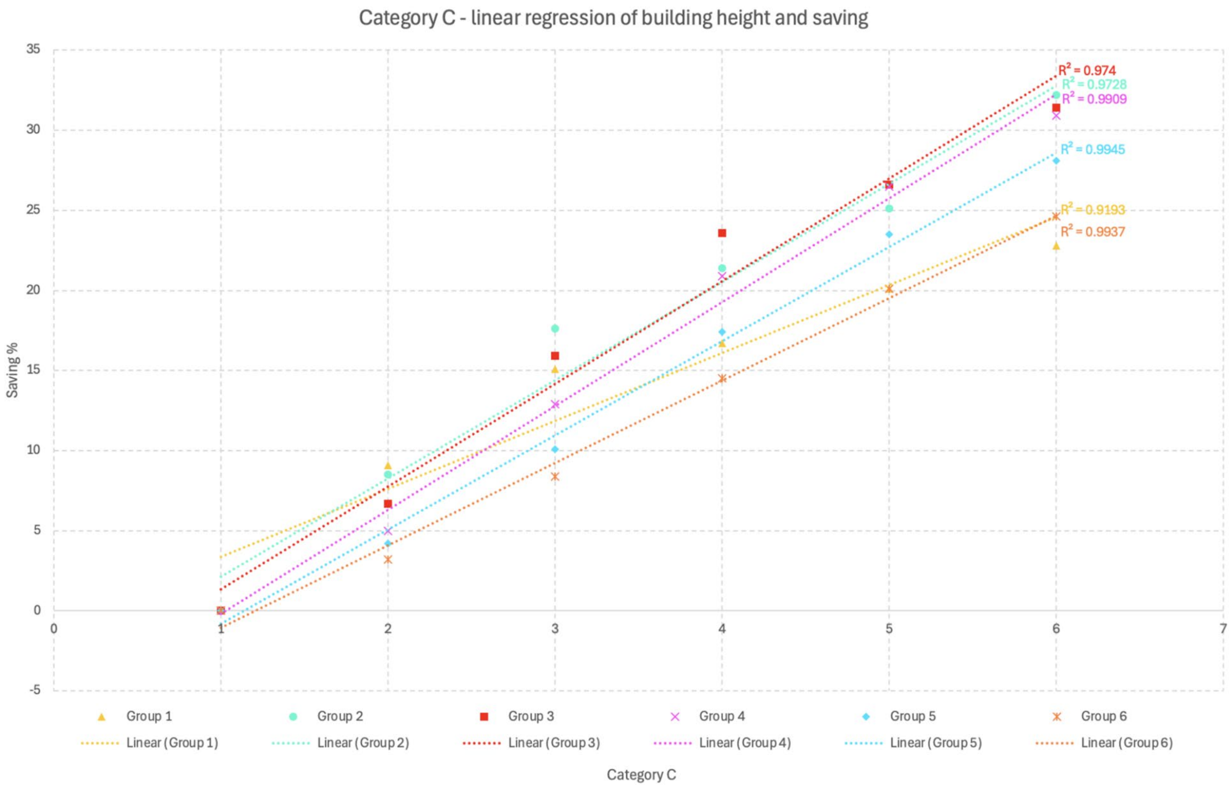

Fig. 17. Category C: Linear Regression of Building Height and Annual Saving Percentage.

building height, which has the most dominant influence on energy efficiency was considered. Other possible controls, such as setbacks, orientation, street width, and land-use mix, which can also influence the thermal environment, were left out. 2. Energy efficiency was determined only on the basis of air-temperature reduction without consideration of other factors that influence a person's comfort, such as humidity, wind speed, mean radiant temperature, and other layers of comfort. This may limit the analysis to some degree and needs to be prioritized in further work. 3. Geographical Context- In the study location of Irbid, northern Jordan, which has a Mediterranean climate, the conclusions are unlikely to be valid in other climatic situations. For example, more

	Group	Case	Power Saving Regression Predicted Y	Power Saving Regression Fit quality R^2
C	Group 1	B_1S_1	3.73	0.9193
		B_1S_2	8.29	
		B_1S_3	12.85	
		B_1S_4	17.41	
		B_1S_5	21.97	
		B_1S_6	26.53	
	Group 2	B_2S_1	2.77	0.9728
		B_2S_2	8.82	
		B_2S_3	14.87	
		B_2S_4	20.92	
		B_2S_5	26.97	
		B_2S_6	33.02	
	Group 3	B_3S_1	4.75	0.974
		B_3S_2	10.87	
		B_3S_3	16.99	
		B_3S_4	23.11	
		B_3S_5	29.23	
		B_3S_6	35.35	
	Group 4	B_4S_1	3.58	0.9909
		B_4S_2	9.30	
		B_4S_3	15.02	
		B_4S_4	20.74	
		B_4S_5	26.46	
		B_4S_6	32.18	
	Group 5	B_5S_1	2.72	0.9945
		B_5S_2	7.87	
		B_5S_3	13.02	
		B_5S_4	18.17	
		B_5S_5	23.32	
		B_5S_6	28.47	
	Group 6	B_6S_1	1.11	0.9937
		B_6S_2	5.83	
		B_6S_3	10.55	
		B_6S_4	15.27	
		B_6S_5	19.99	
		B_6S_6	24.71	

Table 9. Category C – Combined Power Consumption and Saving Regression in 6 Groups.

regular monitoring of the environment and longitudinal climate-sensitive research covering several seasons would justify the conclusions drawn and assist the development of climate-sensitive building regulations. 4. HVAC Systems: to assess building-form effects free of the bias of HVAC efficiency, an Ideal Load Air System was used. Although this may be common in simulation studies, future research should specify the type based on the building needs exactly.5. Although occupant real behaviour variations could affect results, a fixed parameter for residential occupancy was set on EnergyPlus templates to maintain consistency.6. As variations in building material and insulation may produce different outcomes, construction materials and envelope specifications were assumed fixed across all scenarios. As a result, sensitivity analysis for different material types and construction standards should be considered for future research. In addition, a broader analysis and applicability should be considered in other geographic climates as this work was performed on Irbid's Mediterranean climate. For instance, densification strategies testing under various Jordan climate conditions, such as Amman with its semi-arid highland climate versus Aqaba's arid climate, will intensify the understanding of applicability and recommendations.

As a result, while this study was aimed to support thoughtful design through efficient engineering and clear policy, vertical densification strategy can substantially lower household energy consumption to achieve a sustainable goal.

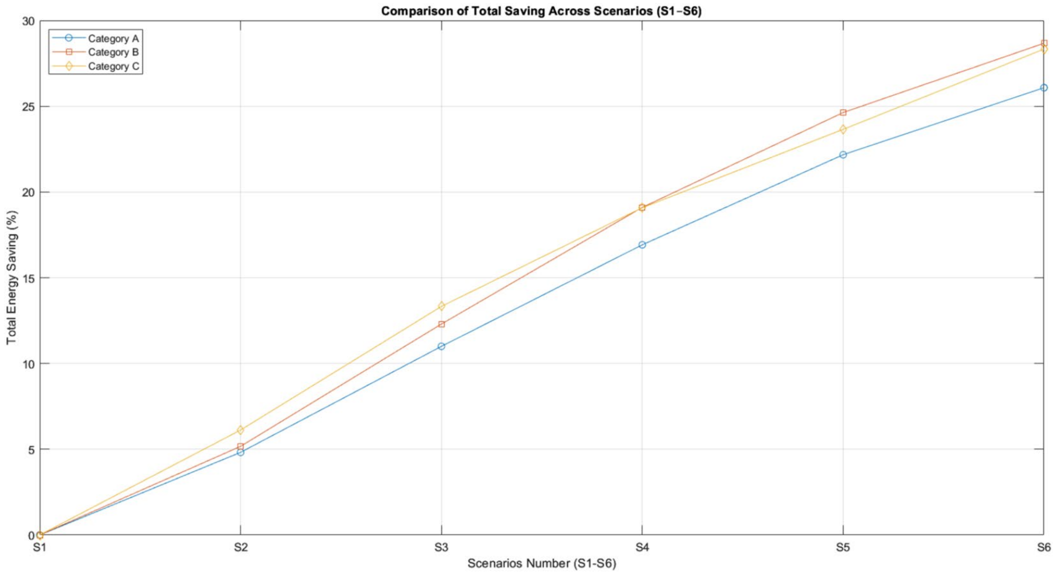

Fig. 18. Energy Saving Trends Across Scenarios (S1-S6) for Categories A, B, and C.

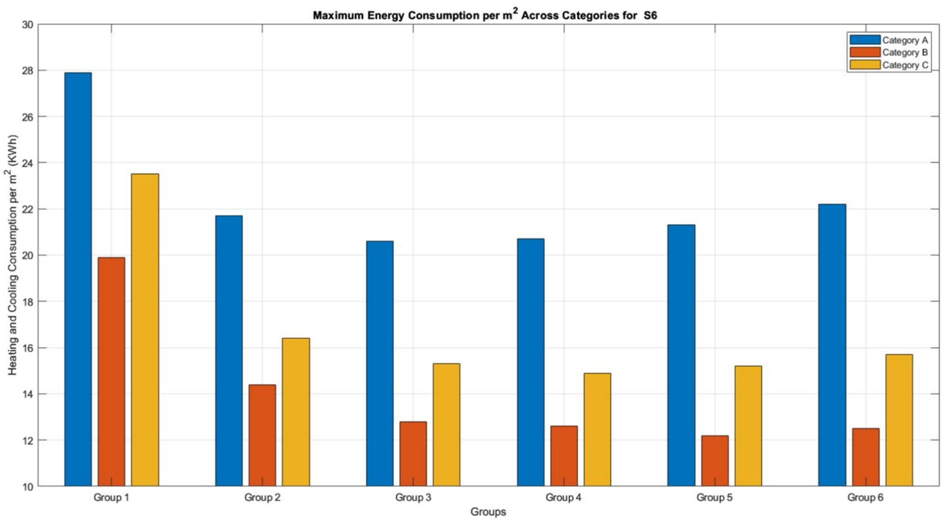

Fig. 19. Relationship of electrical (heating and cooling) annual consumption per square meter across categories A, B, and C.

Data availability

All data generated or analyzed during this study are included in this published article.

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Declarations

Competing interests
The authors declare no competing interests.

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