

A multi-sectional analysis of building height, layout, and urban density on seasonal energy consumption: A case study

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Abstract

This study aims to investigate the influence of building height and layout on energy consumption. It also analyzes methods for reducing energy consumption in these buildings. The EnergyPlus software performs simulations under local climatic conditions for all seasons. The city is divided into several sections based on cardinal directions, and energy consumption is calculated for each section, considering the city's distinct seasonal variations. Buildings in suburban areas with more sunlight exhibited higher overall energy consumption due to the reliance on heating and cooling systems, compared to the city center where denser urban areas moderated temperature extremes. Additionally, building design and insulation played significant roles. The analysis also revealed a west-to-east trend; higher consumption at the edges compared to the center. This is attributed to factors such as building density and shade from taller structures. The study further examined the impact of varying building heights. While most buildings were 20 meters tall, specific rows ranged from 21 to 25 meters. Changing these heights resulted in decreased cooling and increased heating demands in the north-south analysis, and reduced demands for both heating and cooling in the west-east analysis. This highlights the complex interplay between building layout, height, and energy consumption.

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1. Introduction

Global energy consumption is indeed a significant issue investigated by many researchers [1], [2], [3], [4]. The energy consumption of residential buildings accounts for a significant portion of total energy use. While this energy brings creature comforts, it can harm the environment through greenhouse gas emissions and climate change, as shown in the references [5] and [6].

The researchers in [7] investigated the influence of reflective coatings on building energy use. Optimizing energy use in urban areas requires a comprehensive understanding of urban morphology and the potential effects

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of building materials on this morphology. Their study examined buildings with 1,820 square meters of floor space and a 47% window-to-wall ratio located in Phoenix, Arizona. They found that increasing the solar reflectance from 0.1 to 0.5 resulted in an 11% increase in annual cooling loads. The study also explored the impact on annual heating loads and surrounding air temperature. Additionally, a study in [8] examined reflecting and permeable pavements as a way to lessen urban heat islands. To evaluate the combined impacts of reflecting and permeable coatings on urban micro-dust, they used a thorough micro-urban and micro-model. The case study they conducted concentrated on a solitary downpour in a remote street canyon.

Several studies have revealed strategies to improve energy efficiency in buildings. For example [9], investigated the impact of lighting temperature color on indoor thermal perception. The research explored the impact of using light colors to minimize energy consumption from heating, ventilation, and air conditioning systems. The test room was divided into three sections with different lighting color temperatures. The authors in [10] estimated a new approach to mitigating the heat island effect of urban areas. Their study focused on energy savings achieved by combining high reflectivity with low heat radiation in glass-ceramic materials to improve solar reflectance properties, demonstrating over 20% energy savings compared to conventional tiles. Many studies have discovered the relationship between the design of buildings, materials, and their energy consumption. The investigation in [11] explored a model to quantify the impacts of pavement albedo and urban morphology on building energy. Their achievement, utilizing high-resolution data, obtained the impact of greenhouse gases by accounting for changes in air temperature and energy demand caused by albedo. Their study concentrated on a comprehensive analysis, including all nearby buildings and sidewalks in Boston.

A numerical study using EnergyPlus software was performed in [12] to study the effects of urban design on building energy consumption regarding the internal and external building energy simulator. While significant advancements have been made in modeling individual buildings and urban canopies, more complex and efficient models are required to understand the interactions between buildings and their surroundings. The authors' work contributes to this need by providing a tool to analyze the influence of urban reforms on building energy use. A separate study [13] investigated the use of advanced facades that focus on the glass and strategically placed fins in buildings. They found that strategically positioned protrusions or fins on the southwest and east-facing windows could remarkably reduce the annual amount of energy transferred into buildings, achieving energy savings comparable to using high-performance glazing. Authors in [14] tested the impact of infrared reflective (IR) paint on the balance of building energy. Their study depended on various factors like the angle of solar radiation, heat transfer by convection, and IR exchange. They utilized a model of an office building in Freiburg, Germany.

The current research studies the energy consumption patterns in urban residential buildings in cities where temperatures range between 0 to 38 degrees Celsius as a case study. It focuses on the following parameters: typology (type of building), orientation, height, and density. The primary goal is to identify factors influencing energy consumption for the investigated buildings. The study utilizes EnergyPlus software to model a city and calculate hourly energy consumption across different zones. The research aims to identify specific building characteristics that significantly affect energy consumption. These findings can inform design agencies in developing land-use policies and regulations that promote energy-efficient planning, ultimately contributing to a more sustainable society.

2. Methodology, building arrangement, design, and operating conditions

Residential buildings, with their high density, consume energy primarily driven by electricity utilized for lighting, cooling, and heating. The building design highlights plan form, orientation, height, and density as crucial physical aspects influencing energy use. By optimizing these design elements through urban planning, this research aims to reduce energy consumption in these residential buildings.

To achieve accurate energy consumption measurements for the examined buildings, several constraints are considered in this study. For winter, insulated walls are used to reduce heat loss and maximize solar heat gain.

Ventilation for fresh air and moisture control in kitchens and laundry areas is accounted for. The following parameters are featured according to references [15], [16], [17], [18]; windows are designed to meet balanced ventilation requirements, windbreaks and shades minimize heat loss from wind and direct sunlight, reducing energy consumption, and compact shapes with minimal surface area to volume ratio minimize heat loss.

In the current research, the buildings are arranged in a checkerboard pattern as shown in Figure 1. This plan positions buildings adjacent to each other, but not directly connected, as suggested in the literature [19]. This arrangement allows buildings to exchange energy with the surrounding environment in all directions. A one-hectare plot was simulated with 900 houses, each measuring 10m x 10m x 20m and spaced 5m apart. Each house (100 m²) has a central window and standard construction (4 walls, floor, roof). This data informs cooling and heating energy calculations across various design variations.

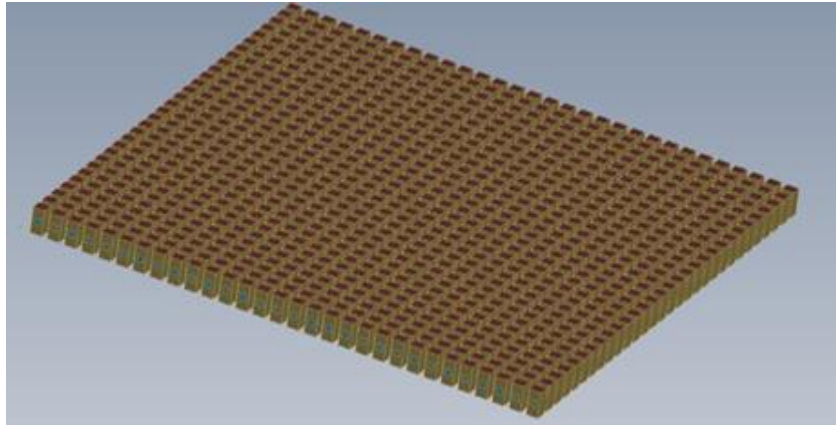


Figure 1. The cavity geometry as suggested in [19]

EnergyPlus software is used in the present study as a building energy simulation program, helping engineers, architects, and researchers model energy use in buildings, as illustrated in the references [20], [21], [22]. This console-based program reads input and writes output to text files. The physical and thermal properties of building components (walls, roofs, floors), including layer materials (e.g., steel door, glass door, mosaic, concrete block, thin brick, asphalt, glazed wool) along with their hardness, thickness, thermal conductivity, density, and specific heat capacity, are used in this program as stated in Table 1.

The heat transfer between the internal surfaces is considered negligible, and there is no exposure to wind or solar radiation. In top floor optimization, the roof and external wall of the last floor remain unchanged for the external surfaces exposed to the outside air. Only the optimized surface (wall, roof, or window) is modified for middle floors. Floors and roofs share the same structure, as each floor acts as the roof for the one below it. The wall construction details specify the material order within the wall, allowing for variable wall structures in different simulations. The study aims to create 900 layouts with a central window in each.

Table 1. The type of building material

Material	Brief description	Thickness (m)	Conductivity k (W/m.K)	Density (kg/m ³)
Mosaic Tile	A colored stone	0.025	2.9	2150
Pea Gravel	Rounded stones used in landscaping, driveways, and as a base for paving	0.02	0.27	1515
Metal Door	A door made from metal	0.05	54	7833
Glass Door	A door made primarily of glass	0.05	1.4	2500
Lightweight Concrete	A type of concrete	0.1	1.4	2300
Fiberglass Insulation	Made from fine fibers of glass used for insulation	0.025	0.038	24

Material	Brief description	Thickness (m)	Conductivity k (W/m.K)	Density (kg/m ³)
Lightweight Concrete	A type of concrete	0.05	1.4	2300
Lightweight Concrete	A type of concrete	0.25	1.4	2300
Fine Woodcraft	An object made from wood	0.025	0.72	1860
Asphalt	A sticky, black, and highly viscous liquid or semi-solid form of petroleum	0.02	0.062	2115
Fine Woodcraft	An object made from wood	0.01	0.72	1860
Fine Woodcraft	An object made from wood	0.06	0.72	1860
Fine Woodcraft	An object made from wood	0.02	0.72	1860
Fine Woodcraft	An object made from wood	0.03	0.72	1860
Lightweight Concrete	A type of concrete	0.2	1.4	2300
Lightweight Concrete	A type of concrete	0.02	1.4	2300
Brick Veneer	A layer of bricks	0.05	2.2	3000
Fiberglass Insulation	Made from fine fibers of glass	0.05	0.038	24
Mosaic Tile	A colored stone	0.02	2.9	2150

3. Results and discussion

The total building energy consumption is examined in the present study regarding the buildings' location and heights.

3.1. The buildings' location

As shown in Figure 2, the height of all buildings is fixed at 20 meters. Initially, the calculation of energy consumption for all plans was the aim of this investigation. However, an issue prevented comprehensive results, leading to the adoption of a simplified approach. This approach involves dividing the city and its suburbs into four sections: the yellow line (south-to-north) and the green line (west-to-east). Building energy consumption is then calculated for each section. It's crucial to mention that the tagged cities experience a Mediterranean climate with distinct seasons. Summer has an average temperature of 32°C, while the winter average temperature is 4°C. Additionally, the city experiences moderate to high humidity throughout the year, with the heaviest rainfall typically occurring in the fall.

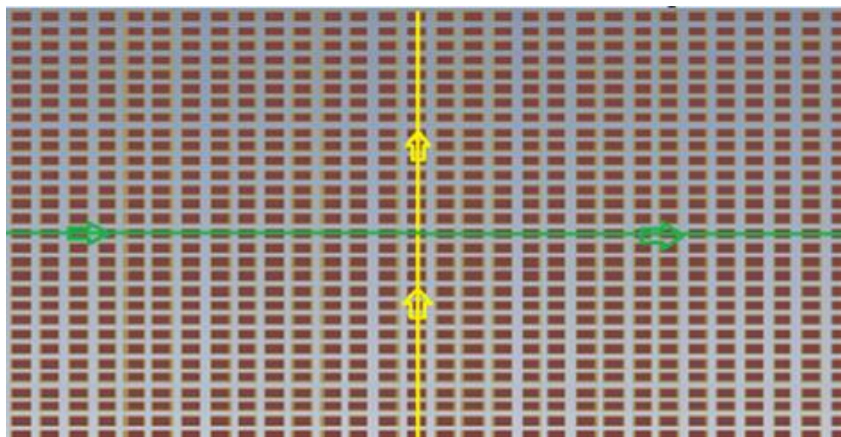


Figure 2. The view of the city's plan

The energy consumption analysis of the buildings across all districts reveals distinct patterns. While the suburban regions have greater access to sunlight, this advantage is offset by increased reliance on heating and cooling systems. This leads to higher overall energy consumption compared to buildings in the city center.

Zones 1-15, as shown in the yellow line in Figure 3 (the first number indicates the line arrangement on the x-axis, and the second number refers to the number of steps in the y-direction), experience the highest consumption with a total value for both heating and cooling of 1,385,730,000,000 J, as stated in Table 2. This consumption progressively decreases as the direction moves towards the center to zone 15-15, where the value of energy consumption reaches $3.97609\text{E}+11$ J. Beyond this central zone, consumption remains stable.

This trend is attributed to several factors. Denser urban areas located in the center tend to have a moderating effect on temperature extremes, minimizing the requirement for heating and cooling. Additionally, factors like building design and insulation play important roles in improving energy efficiency across the zones. Further research could explore the specific reasons behind these variations and identify potential areas for improvement in energy efficiency throughout the tagged cities.

Table 2. The amount of cooling and heating in the design months for each plan from south to north of the yellow line

Zone name	Cooling in J	Heating in J	Total in J
1-15	$5.16\text{E}+11$	$8.70\text{E}+11$	$1.38\text{E}+12$
3-15	$4.67\text{E}+11$	$7.74\text{E}+11$	$1.24\text{E}+12$
5-15	$1.73\text{E}+11$	$2.33\text{E}+11$	$4.06\text{E}+11$
7-15	$1.44\text{E}+11$	$1.99\text{E}+11$	$3.44\text{E}+11$
9-15	$1.81\text{E}+11$	$2.16\text{E}+11$	$3.97\text{E}+11$
11-15	$1.81\text{E}+11$	$2.16\text{E}+11$	$3.97\text{E}+11$
13-15	$1.82\text{E}+11$	$2.16\text{E}+11$	$3.97\text{E}+11$
15-15	$1.82\text{E}+11$	$2.16\text{E}+11$	$3.98\text{E}+11$
17-15	$1.82\text{E}+11$	$2.16\text{E}+11$	$3.98\text{E}+11$
19-15	$1.82\text{E}+11$	$2.16\text{E}+11$	$3.98\text{E}+11$
21-15	$1.82\text{E}+11$	$2.16\text{E}+11$	$3.98\text{E}+11$
23-15	$1.82\text{E}+11$	$2.16\text{E}+11$	$3.98\text{E}+11$
25-15	$1.82\text{E}+11$	$2.16\text{E}+11$	$3.98\text{E}+11$
27-15	$1.81\text{E}+11$	$2.16\text{E}+11$	$3.97\text{E}+11$
29-15	$1.81\text{E}+11$	$2.16\text{E}+11$	$3.97\text{E}+11$
30-15	$1.82\text{E}+11$	$2.16\text{E}+11$	$3.98\text{E}+11$
Total	$6.58\text{E}+12$	$8.85\text{E}+11$	$1.54\text{E}+13$

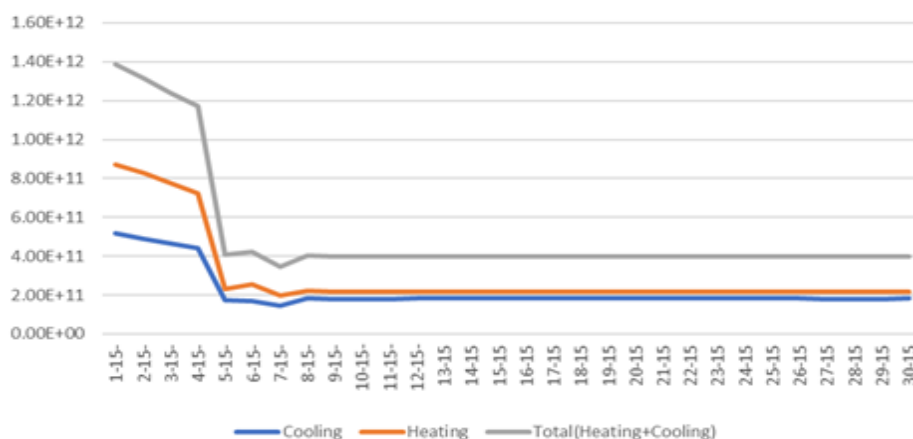


Figure 3. The energy consumption values in J per month of the plan from the south to north of the yellow line. The graph of the green line depicts building energy consumption from west to east suggesting higher energy consumption at the edges compared with the city center (as shown in Table 3 and Figure 4). In the suburban regions, cooling energy demands are higher as buildings receive more sunlight, reducing the need for heating.

compared to the city center where buildings experience more shade. This difference can be attributed to factors like building density and the presence of taller structures that cast shadows.

Table 3. The amount of cooling and heating in the design months for each plan from west to east of the green line

Zone name	Cooling in J	Heating in J	Total in J
15-1	2.00E+11	1.99E+11	3.99E+11
15-3	1.81E+11	2.16E+11	3.97E+11
15-5	1.81E+11	2.16E+11	3.97E+11
15-7	1.81E+11	2.16E+11	3.97E+11
15-9	1.82E+11	2.16E+11	3.98E+11
15-11	1.82E+11	2.16E+11	3.98E+11
15-13	1.82E+11	2.16E+11	3.98E+11
15-15	1.82E+11	2.16E+11	3.98E+11
15-17	1.82E+11	2.16E+11	3.98E+11
15-19	1.82E+11	2.16E+11	3.98E+11
15-21	1.82E+11	2.16E+11	3.98E+11
15-23	1.82E+11	2.16E+11	3.98E+11
15-25	1.82E+11	2.16E+11	3.98E+11
15-27	1.82E+11	2.16E+11	3.98E+11
15-29	1.83E+11	2.13E+11	3.96E+11
15-30	2.00E+11	1.98E+11	3.98E+11
Total	5.49E+12	6.44E+12	1.19E+13

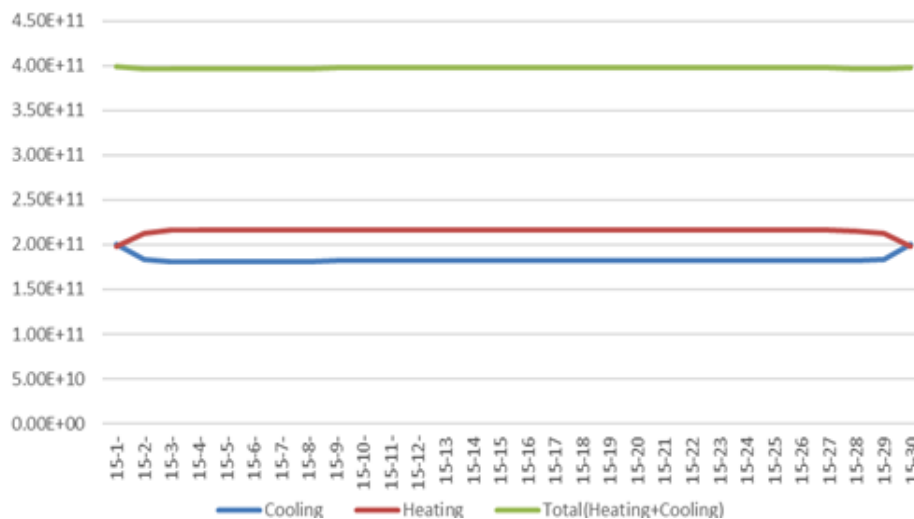


Figure 4. The energy consumption values in J per month of the plan from the west direction to the east of the green line

3.2. Regarding the buildings' heights

This section examines the impact of varying building heights on the city's overall energy consumption. In most cases, buildings will have a fixed height of 20 m. However, as shown in Figure 5, there are exceptions where specific rows of buildings will have heights ranging from 21 meters to 25 m.

As demonstrated in Figure 6, after changing the amount of building height, it is observed that the results for those buildings were decreased for cooling and increased for heating as stated in Table 4 under the previous changes in the design months for each plan unit from south direction to north.

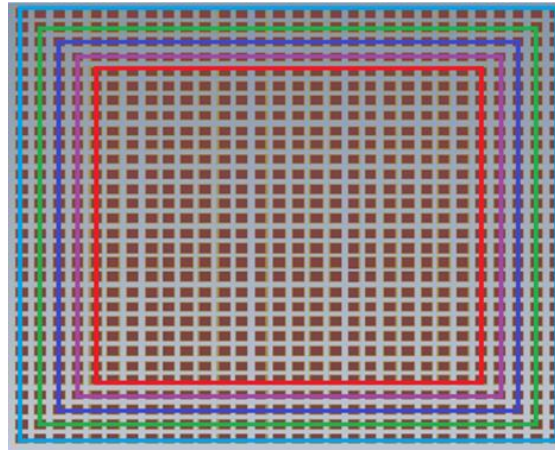


Figure 5. The view of the plan after changing the amount of height of some Buildings is as follows; red for 21 m, pink for 22 m, dark blue for 23 m, green for 24 m, and blue for 25 m

Table 4. The amount of cooling and heating in the design months for each plan from south to north of the yellow line after changing the building's height

Zone name	Cooling in J	Heating in J	Total in J
1-15	1.14011E+12	6.53103E+11	1.79322E+12
3-15	9.184E+11	5.39569E+11	1.45797E+12
5-15	2.47383E+11	1.78852E+11	4.26234E+11
7-15	1.99379E+11	1.44391E+11	3.4377E+11
9-15	2.15955E+11	1.81157E+11	3.97112E+11
11-15	2.15739E+11	1.81523E+11	3.97262E+11
13-15	2.1575E+11	1.81724E+11	3.97474E+11
15-15	2.15859E+11	1.81836E+11	3.97695E+11
17-15	2.15846E+11	1.81901E+11	3.97746E+11
19-15	2.15852E+11	1.81901E+11	3.97753E+11
21-15	2.15846E+11	1.81901E+11	3.97746E+11
23-15	2.15855E+11	1.81906E+11	3.97761E+11
25-15	2.15799E+11	1.8192E+11	3.97719E+11
27-15	2.44454E+11	1.90599E+11	4.35054E+11
29-15	2.65885E+11	2.07818E+11	4.73703E+11
30-15	2.83662E+11	2.11886E+11	4.95548E+11
Total	5.24E+12	3.76E+12	9.00E+12

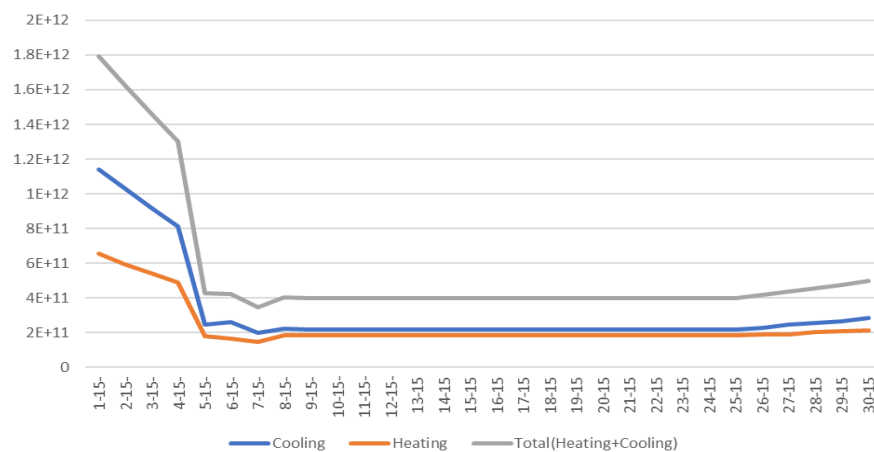


Figure 6. The energy consumption values in J per month of the plan from the south to north of the yellow line after changing the amount of height

As shown in Figure 7, after changing the amount of building height, it has been estimated that the results for those buildings were decreased for both cooling and heating as stated in Table 5 under the previous changes in the design months for each plan unit from west to east.

Table 5. The amount of cooling and heating in the design months for each plan from west to east of the Green line after changing the building height

Zone name	Cooling in J	Heating in J	Total in J
15-1	2.59601E+11	2.35945E+11	4.95545E+11
15-3	2.54436E+11	2.01187E+11	4.55623E+11
15-5	2.29074E+11	1.87721E+11	4.16795E+11
15-7	2.16254E+11	1.81198E+11	3.97452E+11
15-9	2.15947E+11	1.81504E+11	3.97451E+11
15-11	2.15882E+11	1.81753E+11	3.97636E+11
15-13	2.15845E+11	1.8182E+11	3.97665E+11
15-15	2.15859E+11	1.81836E+11	3.97695E+11
15-17	2.15703E+11	1.81833E+11	3.97535E+11
15-19	2.15708E+11	1.81897E+11	3.97605E+11
15-21	2.15704E+11	1.81783E+11	3.97486E+11
15-23	2.15759E+11	1.81511E+11	3.9727E+11
15-25	2.17397E+11	1.80224E+11	3.97622E+11
15-27	2.46661E+11	1.8992E+11	4.36581E+11
15-29	2.64076E+11	2.09526E+11	4.73602E+11
15-30	2.5813E+11	2.35868E+11	4.93998E+11
Total	3.67E+12	3.08E+12	6.75E+12

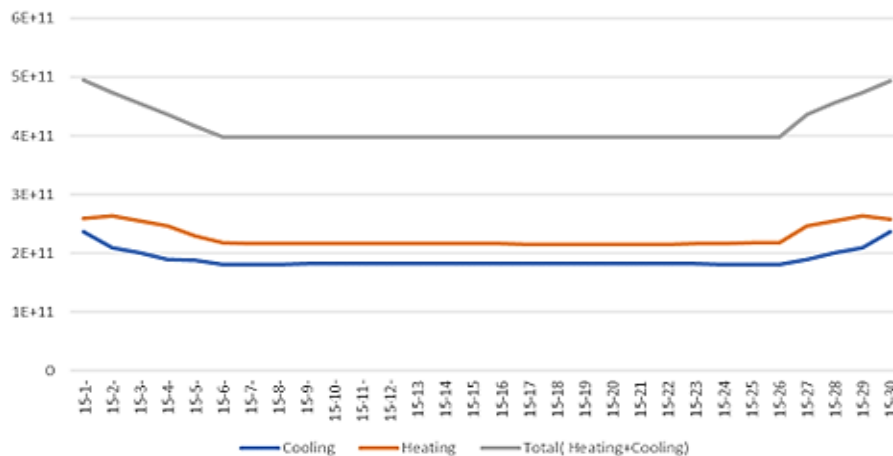


Figure 7. The energy consumption values in J per month of the plan from the west to east of the green line after changing the amount of height

4. Conclusions

The study examined the effect of varying building heights on energy consumption. Most buildings have a fixed height of 20 meters, but some rows have buildings ranging from 21 to 25 meters. For south-to-north design changes, increased building heights led to decreased cooling demands but increased heating demands. Conversely, for west-to-east design changes, increased building heights resulted in decreased demands for both

heating and cooling. This comprehensive analysis reveals the complex interplay between urban planning, building design, and energy consumption patterns in a Mediterranean climate. The findings underscore the importance of considering factors such as building height, urban density, and orientation when developing energy-efficient urban strategies. Future research should focus on optimizing these variables to create more sustainable and energy-efficient cities, potentially leading to significant reductions in overall energy consumption and improved urban livability. Future urban development strategies should prioritize these insights to create more sustainable and livable cities, potentially leading to substantial reductions in energy consumption and improved environmental performance across diverse urban landscapes.

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Declaration of competing interest

The authors declare that they have no financial interest in any of the topics covered in this article.

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Author contributions

The contribution to the paper is as follows: Ali I. Hameed and Heersh S. Kakoo: study conception and design; Abdulsalam Ebrahimpou: data collection; Shivan Ismael Abdulla and Abdulsalam Ebrahimpou: analysis and interpretation of results; Veyan A. Musa: draft preparation. All authors approved the final version of the manuscript.

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