# ENERGY PERFORMANCE EVOLUTION OF UNDERGROUND HOUSING IN DIFFERENT CLIMATIC CONTEXT

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IN
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**Approval sheet of the Thesis**

This is to certify that we have read this thesis entitled **"Energy Performance Evolution of Underground Housing in Different Climatic Context"** and that in our opinion it is fully adequate, in scope and quality, as a thesis forthe degree of Master of Science.

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# ABSTRACT


ENERGY EFFICIENCY OF UNDERGROUND URBAN SPACES

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With the global challenge of urbanization, population growth, climate change, rising energy demands, and energy loss, this study explores the potential of underground structures, such as residential units, as a progressive sustainable solution. The objective is to study the energy efficiency of underground spaces representing different design typologies, in different urban contexts, considering factors such as different depth, transparency and balconies scenarios. The motivation behind this study comes as a direct need to address the immediate challenges of urbanization related to population growth, the impact on climate change as well as substantial energy consumption. Exploration of different housing alternatives conducts a positive approach towards these challenges. The aim of this research is to evaluate the potential benefits of underground spaces, focusing mostly in the energy efficiency. Originality of this study lies on its comprehensive attitude, considering diversity in climate conditions and urban setting. To archive these objectives, a comparative analysis is conducted, emphasizing simulations of underground courtyard houses. Three different cities, New York, Athens and Berlin are selected for their varieties in climate types, allowing a comprehensive understanding of the ground temperature on energy efficiency. The results show that, the oceanic climate of Berlin displays the lowest energy demand, followed by the hot-summer Mediterranean climate of Athens, with an average difference of 7.6 $kWh.m^{-2}y^{-1}$. The climate which presents a greater demand for energy is the subtropical climate of New York, with a difference from the climate of Athens, of an average of 11.71 $kWh.m^{-2}y^{-1}$, and with a difference of 25.41 $kWh.m^{-2}y^{-1}$ from the climate of Berlin. Morphologies perform poorer with the increase of depth and transparency, but with the increase in the depth of the balcony, we have better energy performance. This study offers a broad discussion of how underground space can contribute to future urban developments. Acknowledge of challenges are crucial to research’s transparency. Concerns related to human psychology, lack of natural light, humidity in underground spaces are identified. This research, through conscientious examination, offers valuable insights into the benefits of underground residential buildings.

***Keywords:*** *Energy efficiency, underground space, underground living, urban sustainability, courtyard housing, climate resilience, architectural typologies*

# ABSTRAKT

EFIÇENCA ENERGJITIKE E HAPIRAVE NENTOKESORE URBANE

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Kule, Zoica

Master Shkencor, Departamenti i Arkitekturës

Udhëheqësi: Prof. Dr. Sokol Dervishi

Me sfidën globale të urbanizimit, rritjes së popullsisë, ndryshimeve klimatike, rritjes së kërkesave për energji dhe humbjes së energjisë, ky studim eksploron potencialin e strukturave nëntokësore, siç janë njësitë e banimit, si një zgjidhje e qëndrueshme progresive. Objektivi është të studiohet efiçenca energjetike e hapësirave nëntokësore që përfaqësojnë tipologji të ndryshme projektimi, në kontekste të ndryshme urbane, duke marrë parasysh faktorë të tillë si dendësia e popullsisë, kushtet klimatike dhe tipologjitë arkitekturore. Motivimi pas këtij studimi vjen si një nevojë e drejtpërdrejtë për të adresuar sfidat imediate të urbanizimit që lidhen me rritjen e popullsisë, ndikimin në ndryshimet klimatike si dhe konsumin e konsiderueshëm të energjisë. Eksplorimi i alternativave të ndryshme të strehimit sjell një qasje pozitive ndaj këtyre sfidave. Qëllimi i këtij hulumtimi është të vlerësojë përfitimet e mundshme të hapësirave nëntokësore, duke u fokusuar më së shumti në efiçencën e energjisë. Origjinaliteti i këtij studimi qëndron në qëndrimin e tij gjithëpërfshirës, duke marrë parasysh diversitetin në kushtet klimatike dhe mjedisin urban. Për të arkivuar këto objektiva, bëhet një analizë krahasuese, duke theksuar simulimet e shtëpive me oborr nëntokësor. Tre qytete të ndryshme, Nju Jorku, Athina dhe Berlini janë përzgjedhur për varietetet e tyre në llojet e klimës, duke lejuar një kuptim gjithëpërfshirës të temperaturës së tokës mbi efikasitetin e energjisë. Gjetjet paraprake sugjerojnë se ndërtesat nëntokësore tregojnë kursim të konsiderueshëm të energjisë. Rezultatet tregojnë se klima oqeanike e Berlinit shfaq kërkesën më të ulët për energji, e ndjekur nga klima mesdhetare e verës së nxehtë të Athinës, me një ndryshim mesatar prej 7.6 $kWh.m^{-2}y^{-1}$. Klima e cila paraqet një kërkesë më të madhe për energji është klima

subtropikale e Nju Jorkut, me një ndryshim nga klima e Athinës, mesatarisht 11,71 $kWh.m^{-2}y^{-1}$, dhe me një ndryshim prej 25,41 $kWh.m^{-2}y.^{-1}$ nga klima e Berlinit. Ky studim ofron një diskutim të gjerë se si hapësira nëntokësore mund të kontribuojë në zhvillimet e ardhshme urbane. Njohja e sfidave është thelbësore për transparencën e kërkimit. Identifikohen shqetësime që lidhen me psikologjinë njerëzore, mungesën e dritës natyrore, lagështinë, fatkeqësitë dhe kufizimet në bimësi në hapësirat nëntokësore. Ky hulumtim, përmes ekzaminimit të ndërgjegjshëm, ofron njohuri të vlefshme për përfitimet e ndërtesave të banimit nëntokësore. Ndërsa qytetet po përballen me shumë sfida, ofrimi i zgjidhjeve alternative shihet si një hap i mëtejshëm drejt një të ardhmeje më të qëndrueshme.

***Fjalët kyçe:*** *Energy efficiency, underground space, underground living, urban sustainability, courtyard housing, climate resilience, architectural typologies*

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| **UUS** | Underground Urban Space |
| **UGB** | Underground Buildings |
| **WWR** | Window-to-wall ratio |
| **RC** | Relative Compactness |
| **SQ** | Square shape morphology |
| **RC_2:3** | Rectangle shape morphology, with 2:3 length-to-width ratio |
| **RC_1:2** | Rectangle shape morphology, with 1:2 length-to-width ratio |
| **CI_R40** | Circular shape morphology, with a radius of 40 m |
| **CI_R30** | Circular shape morphology, with a radius of 30 m |
| $\mathbf{Q_{h;i:j}}$ | Monthly thermal energy for heating in each thermal zone |
| $\mathbf{n_{h;i:j}}$ | Weighted average efficiency of the heating system |
| $\mathbf{f_{p;i}}$ | Conversion factor from secondary to primary energy for each thermal zone |
| $\mathbf{Q_{heat}}$ | The thermal energy for heating |
| $\mathbf{n_g}$ | The utilization gain factor |
| $\mathbf{Q_{ints}}$ | The internal gains, |
| $\mathbf{Q_{sol}}$ | The solar gains |
| $Qh$ | The heating performance of human |
| $Ql$ | The heating performance of the lighting |
| $Qe$ | The heating performance of the electrical equipment |
| $Qh,c$ | Heating performance of the mechanical cooling and heating |
| **ME** | Morphology effectiveness |

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# CHAPTER 1
# INTRODUCTIN

In the era of an excessively large urban development, with a relentless growth of the population, with an alarming urban densification, and with an escalation of climatic conditions, modern cities are facing a critical situation. Since 2007 more people live in urban areas than anywhere else in the rest of the planet. As explained by (Kaliampakos, 2016), according to statistics, by 2050, the world population is expected to reach about 9.3 billion, while the population living in urban areas may reach 6.3 billion people (Kaliampakos, 2016). This population growth has increased the demand for energy and energy production, turning its provision into a challenge to the authorities. In addition, population growth and immense densification has led to a great energy loss, directly influencing global warming and influencing climate change. On the other hand, the densification of cities by new buildings has influenced the disappearance of green spaces, as well as endangering historical sites. Most worryingly, consumption of land continues in the regions with falling populations, questioning success of developed countries in their sustainability efforts (Belyaev, 2016).

As cities continue to sprawl both horizontally and upwards (Jabareen & Sheinman, 2006), and face the consequences of their expansion, the need for a sustainable and long-term solution arises. The solution can be given by implementing the idea of underground housing, as a positive approach to all the above-mentioned challenges. Based on this context, this study tries to reveal the potential of underground courtyard houses, focusing especially on their energy efficiency, through simulation methods, which helps to mitigate the environmental impact. By confronting climatic conditions and different urban positions, this research aims to present an understanding of the sustainability of underground life at an urban scale.

## 1.1 Objective

The objective of this research is to study the energy efficiency of underground courtyard housing. This study will focus on how different morphologies of courtyard housing, located in a variety of urban contexts and different climates, serve as a solution to the challenges of urbanization in modern cities. The main objective is to reach a conclusion on how much energy is saved or wasted by using these types of morphologies of underground structures, and also to make a comparison between the results in different climates and urban contexts.

The use of different underground morphologies, have been referred to as a solution to urban densification in different areas of the globe, but on the other hand, these structures also present their own challenges. Among the main challenges we can list: the lack of lighting, ventilation, underground greenery, challenges related to human psychology and humidity. The purpose of this study is also to provide solutions to these problems related to these spaces, creating an environment as friendly as possible to its users and making the underground space always usable.

The goal of this study is to determine the most sustainable and energy-efficient courtyard underground house unit and the most optimal amplitude of the placement of underground tunnels. This research will employ a combination of case studies and simulation analysis to evaluate the energy performance, with the simulation analysis being carried out using the building energy simulation tools from DesignBuilder, Energy Plus, and Meteonorm. More particularly, this study seeks to:

1. Evaluate the energy efficiency potential in underground housing. This involves analysing thermal insulations of the earth, which is crucial in reducing the energy consumption related to cooling and heating.
2. Investigate the impact of climacteric variations on the performance of the underground units. By selecting three different urban contexts- New York, Athens, and Berlin- this study seeks to understand how different climates effect the energy efficiency of the underground living spaces.
3. Explore and compare 5 modules of underground courtyards houses. The purpose of using these architectural typologies is to address the challenges related to the use of underground spaces, such as the lack of light, ventilation, greenery, and concerns related to human psychology and humidity.

4. To explore and compare the energy performance those modules located at different heights below and above the earth's surface. The goal is to understand at what amplitude these modules reach the optimal results for the function they will perform.
5. It pays attention to human psychology and well-being, addressing the challenges of claustrophobia and mood swings, and the potential benefits of innovative design to provide solutions to overcome these concerns.
6. Investigates the potentials of implementing green spaces. This includes the solution of implementing courtyards and also the potential of artificial lighting.
7. The adoption of holistic equipment considering not only the benefits in energy efficiency but also approaching a sustainable environment. This means considering the entire footprint of the design.
8. Examine the resilience of the underground living spaces disasters, offering an alternative solution to existing traditional houses in regions threatened by earthquakes, floods and extreme weather conditions.

## 1.2 Motivation

The motive of this study focuses on the solution of global challenges and the development of solutions and opportunities within the realm of the urban development. As the world faces daily escalating concerns related to climate change, population growth and energy demand, a housing solution beyond traditional housing and an unusual usage of underground housing is offered.

The continuous growth of the population has led to the densification of urban spaces, resulting in an extremely high demand for the creation of sustainable and efficient spaces. The limit in the expansion of traditional buildings, due to the limit of the land or due to the threats that their expansion brings, offers another thought out of the box in architecture. The high demand for energy, as well as the high consumption of energy, leads to high pollution of the atmosphere and the environment, directly affecting global warming and thus also visible climate changes. These extremely dangerous challenges for humans require the provision of some sustainable solutions in the construction of human habitats. Underground spaces present an intriguing approach to the environmental impact of urban spaces, offering the earth as a natural insulator and thus reducing energy consumption. Many cities, including New York, Athens and Berlin, are characterized by rich cultural and architectural heritage. The preservation of these values is extremely important for humanity and its history. Therefore, the further development of housing in underground spaces provides a solution to this problem. By building underground, the expansion of traditional buildings above ground is not done with a threat to the historical, cultural and architectural values of the cities.

Due to climatic problems, many cities that are characterized by extreme weather conditions, face numerous challenges in maintaining the optimal temperature, leading to a large consumption of energy due to heating and cooling. By building underground, living spaces have fewer challenges in achieving optimal temperatures, benefiting from the characteristics of the earth as a natural thermal insulator. Underground living spaces can also be seen as a temporary or permanent solution to areas that are prone to floods, earthquakes, storms, and hurricanes - such as the cities of New York, Athens and Berlin. This study also takes into consideration the challenges associated with living in underground environments. Problems of human psychology, such as claustrophobia and mood changes, are directly related to living in these spaces, as a result of the lack of stimulation, greening and ventilation of these spaces. The purpose of this study is to overcome these challenges by creating an underground space that puts the person in the center.

The choice to study global metropolises such as New York, Athens and Berlin, reflects a strategic decision to explore different climatic conditions and urban contexts. Also, the purpose of choosing these cities is related to the fact that this type of approach can be applied anywhere in the world.

## 1.3 Organization of the thesis

This thesis is divided in 6 chapters. The organization is done as follows:

In Chapter 1, the problem statement, thesis objective and scope of works is presented. Chapter 2, includes the literature review and theoretical background. Chapter 3, consists of the methodology followed in this study. In Chapter 4, the experimental results and discussions of those results. Chapter 5, includes the results and discussions of balconies scenarios.

In Chapter 5, conclusions and recommendations for further research are stated.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

The immense increase of world population, coupled with the growth of cities, the lack of natural land, pollution increased indexes, lack of greenery and the need to preserve existing infrastructure and heritage in urban areas, has led to a paradigm shift in urban planning. This growth of the urbanization has highly impacted energy consumption. In response to these challenges, cities around the world are overlooking the underground assets (Admiraal & Cornaro, 2016). Underground buildings show great potentiality to encourage sustainable development by minimizing the building energy consumption (Alkaff, Sim, & Efzan , 2016). This study looks at different underground morphologies, courtyards and tunnels, as a solution to the energy demand of today's society and examine their impact on the energy performance. Considerable amounts of studies made in the recent years, demonstrate the link between urbanization and implementation of UUS and also the construction of UUS and the energy performance of those spaces. This chapter presents a summary of the literature reviewed, which will generate a more detailed concept of underground spaces, the driving factors, challenges and solutions and the link between UUS and energy performance. Section 2.1 examine the literature on the perspective of sustainable development of underground spaces. Section 2.2 review different studies on the implementation of underground urban spaces in urban planning. Section 2.3 focuses on the literature related to driving factors that can lead planners and government policies in implementation of UUS. Section 2.4 reflects different studies made on the challenges and solutions of UUS. Section 2.5 review different studies that analyses the relationship between energy performance and different underground morphologies.

## 2.2 Underground Sustainable Design Perspectives

The ultimate goal to be archived is the sustainable in the UUS development goal, therefore Alkaff et al. (2016) discusses that the underground building should be analysed carefully along three main sustainable aspects: environment, social and economic (Alkaff, Sim, & Efzan , 2016) illustrated in ***Figure 1***.

### 2.2.1. Environmental Aspect

The environment aspect of the underground urban space design has gained a great importance to planners and governance institutes, as a response to all ecological problems related to rapid urbanization. Alkaff, Sim, & Efzan (2016), discuses that because of the high thermal quality of soil, underground buildings are able to regulate indoor temperature (Alkaff, Sim, & Efzan , 2016). Being a natural insulation, by easily cooling and heating those spaces, soil features can help in saving energy and reducing pollutions related to energy consumption.

Broere (2015), goes further in the discussion, claiming that underground development has a crucial role in developing and reshaping urban area. He explains that by placing infrastructure underground, it will bring opportunities for long-term improvements in the environment impact on the cities (Broere, 2015). Demers (2016) further elaborates that improving the quality of the underground design of downtown Montreal, by reducing the automobiles' presence, and locating commercial centers underground and freeing up space for pedestrians, will contribute in a healthier and human-friendly environment, aiming towards a more sustainable city (Demers, 2016). Golzman (2016) and Korotaev (2016), both address the efficient use of underground potential and its implementation in urban planning, as a sustainable approach (Glozman, 2016; Korotaev, 2016). They claim that freer above-ground space can be saved for greenery, if underground space is well-considered in urban planning.

Lastly, Nezhnikova (2016), states that the lack of urban areas, population growth, traffic jams lead to the inability of the urban infrastructure to cope with the environmental deteriorations (Nezhnikova, 2016), thus the space for construction of underground residential buildings, allows the environment to meet the needs for today and tomorrow requests.

In summary, the environmental aspect of sustainably designed underground spaces presents an issue that should remain at the attention of all planners. Underground development can be seen as a strong and acceptable solution for the sustainable approach of today’s urban areas, by saving energy, reducing energy loss, and environmental pollution as well as by optimizing land use

### 2.2.2 Social Aspect

As cities are becoming denser every day, the need to build spaces that not only fulfil the energy efficiency but also increase human interactivity, is becoming important in urban planning. Social aspect can be seen as an important component of UUS sustainable development. The main challenge in developing UUS regarding social and human respective is to overcome all psychological aspects.

Alkaff, Sim, & Efzan (2016), discuss that the although UUS offer a better fire-resistant structure and a better protection against natural disasters, several social and psychological problems need to be considered and overcome. The authors explain that in order to overcome the psychological barrier the designer should take into consideration: optimization of natural light, natural and open view, good ventilation and reduce humidity, entrances and evacuation roads (Alkaff, Sim, & Efzan , 2016). It is also discussed by the authors, that the thermal comfort that UGS offer a great contribution in the society’s well-being. In addition, several authors suggest that while designing UUS designers should integrate human behaviour analysis and humanization into their work (Kallianiotis & Kaliampakos, 2016; Lai et al., 2023). Nezhnikova (2016), address all the psychological aspects that influence the relationship between humans and UUS, and clarify that design elements such as natural light, acoustics and visuality play a crucial role in the development of this relationship (Nezhnikova, 2016).

Lu, Hitoshi & Shu (2016), on the other hand, discuss the safety of the underground space, by taking as an example the underground subway of Shanghai. They identify the risks that can occur in the UUS such as: risk of floods and fire spread, risk of management in case of a natural disaster, disaster identification, the lack of practical and effective use of safety assessments, and the lack of long-term safety supervision (Lu , Hitoshi , & Shu , 2016).

In summary, the social aspect in overall can be seen as a multi-dimensional aspect. Social and human aspect should be seriously considered while planning the UUS design by defining ways of overcoming all the problems related with the abovementioned aspects.

### 2.2.3 Economic Aspect

Economic aspect in the development of UUS can be seen as a driving factor, since economical sector can benefit but also face some challenges regarding those implementations.

Alkaff, Sim, & Efzan (2016), discus that small heat load and less energy consumption, lead to less economical expenses, but on the other hand the cost of building underground is considerable, since underground construction could require heavier structure to withstand the land pressure (Alkaff, Sim, & Efzan , 2016). Sarchenko (2016) also argues that the engineering cost for underground buildings may be higher than above ground construction, but the underground space is economically advantageous (Sarchenko, 2016). Broere (2016) discus that the transition from above surface to above-surface construction can have much more cost (Broere, 2015). On the other hand, Lai et al. (2023), argues that any kind of accident or collapse in the underground can lead to huge economic consequences (Lai, Wang, Chen, & Liu, 2023). Zhao and Wo (2016) add another challenge to the economic aspect of the UUS, claiming that it is required more money to implement the UUS into urban policies of urban areas (Zhao & Wu, 2016).

Demers (2016) and Golzman (2016), both explain that UUS can be seen as a long-term economic benefit for the society. Demers argues that the development of above ground facilities can attract more business owners and consummator, hence playing a positive role in the improvement of cities economy (Demers, 2016; Golzman, 2016). Golzman also argues that the economic efficiency of the underground construction is strongly related to the certain place where this UGS is going to be placed (Glozman, 2016).

Nezhnikova (2016) and Niira et al. (2016) both highlight the good impact that UUS has on the development of real-estate. Authors examine the potential of modern economic process in residential housing development, which effect the sustainable improvement of industry (Nezhnikova, 2016; Niira et al., 2016).

To conclude, the economical aspect of UUS can be seen more as a challenge due to the struggles and more advanced technologies required for underground construction. However, thinking in the long-term perspective of UUS as an energy efficient environment, the economic benefits are higher than the above-ground constructions.

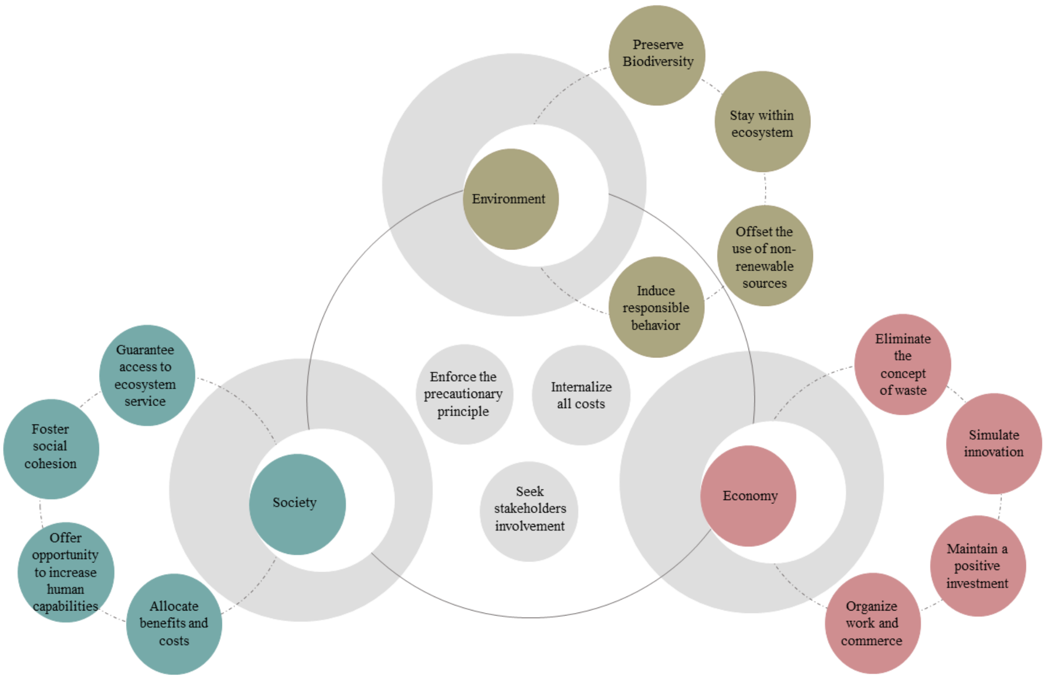



***Figure 1***. Underground Sustainable Design Perspectives

## 2.3 Urban Planning and Underground Urban Space (UUS)

With the great development of the concept of underground buildings, the implementation of these spaces has taken on a great importance in the urban planning policy and government notebooks. However, there are still many obstacles and the consideration of UUS should be taken more seriously by the authorities. The use of subsurface can contribute to make cities more liveable and sustainable (Admiraal & Cornaro, 2016).

Accoriding to Adriraal & Cornaro (2016), the UUS is a very strategic part of urban planning as it can provide valuable additional space for the above-ground urban space, therefore it should be considered as a permanent part of urban policy (Admiraal & Cornaro, 2016). Authors also count the governance and legal challenges of UUS use: land ownership, liability, and building costs. Belyaev & Pashkin (2016), Belyaev (2016) and Golzman (2016) study the possibilities of UUS development in city of Moscow as a response to the urbanization and sustainable development of the city (Belyaev & Pashkin, 2016; Belyaev, 2016; Golzman, 2016). Belyaev (2016) argues that the implementation of subsoil structures will eliminate the distortions of spatial development and would improve the sustainability of the development through the consideration of the US in the public administration, as well as in strategic planes for the future (Belyaev, 2016). Golzman (2016) argues that a city's master plan should simulate the reservation of US (Glozman, 2016).

Stones & Heng (2016) and Tann, Collins & Metje (2016) focuses on considering the UUS as an integral part of urban system (Stones & Heng, 2016; Tann et al., 2016). There may be many approaches and factors that impact the UUS planning, which include: planning factors: drivers and pressures; institutional support systems; principles; laws and regulations; policies; guidelines; planning approaches and data support (Stones & Heng, 2016). Planning approaches considerate: coordination of surface and underground use, intensity, access, prioritization by depth, value of reserving for future, changeability of systems, critical system thinking (Tann, Collins, & Metje, 2016) as illustrated in ***Figure 2***.

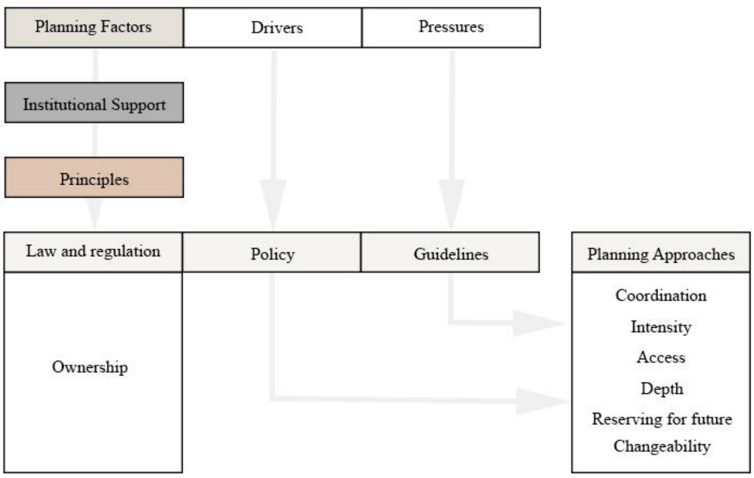



***Figure 2.*** Urban Planning of UUS Principles

Besner (2017) explains ACUUS (Associated research Centers for the Urban Underground Space) as an organization, which promote the partnership among all factors involved in planning, constucion, management and research in UUS construction, which has gained popularity in recent years as a promotor of the UUS. The author discusses the standards and regulations to guide the design, such as: universal accessibility and changes of levels, fire protection and emergency exits, the opening and closing hours of corridors and tunnels, and signal systems (Besner, 2017).

Golzman (2016) and Ho et al. (2016) focuses on the engineering complexity and design challenges that are associated with the construction of UUS. Golzman (2016) argues that there are a lot of challenges in the implementation of UUS in cities' master plan, such as: complexity of the engineering solutions, additional volume of engineering works; enforcement of bearing and supporting constructions; more complicated work on water isolation; more complicated sanitary installation; lack of space while conducting works on the construction site (Glozman, 2016). Ho et al. (2016) enforces this approach by stating that the relief is also a challenge in UUS development (Ho, Shum, & Wong, 2016).

On the other hand, Shiina et al. (2016) sees the underground space as a temporary urban solution for sheltering the people after an earthquake has happened, and authorities should include it in its policies. The authors explain that designers should improve the earthquake resistance of the ceiling, should provide functional enhancement of energy generators and increase the supply period and capacity (Sarchenko, 2016).

In conclusion, regardless of the fact that the idea of developing underground spaces has taken on increased importance recently, making these spaces included in urban planning and strategic planning of the future, more work should be done by urban planners and authorities to the implementation of these spaces in the master plan of urban areas.

## 2.4 Driving Factors of Underground Urban Space

Underground development is an important tool in developing and reshaping urban areas to meet the challenges of the future (Broere, 2015). The increased interest in the development of underground spaces during the last years has come as a result of several key factors. These factors include: land use pressure, population growth, energy efficiency, pollution, technological innovation, climate change, demand for new infrastructure, preservation of heritage and greenery. All these factors have been studied by different researchers, who have reached the conclusion of how they affect the development of UUS.

Underground space can play a very active role in the rational use of land, serving as an expansion to the above-ground urban space and offering an improvement on the space quality (Shang, 2016). Nezhnikova (2016) explains that the lack of urban land requires more and more urban extend in the US, claiming that those spaces can be used as residential buildings development (Nezhnikova, 2016). Korotaev (2016) goes father as he supports this idea by claiming that development of UUS will give an opportunity to form well-development of cities' systems. He also explains that the construction of utilities underground will offer more land for greenery, parks, and public gardens (Korotaev, 2016). Sarchenko (2016) also explains that the settlement of land resource shortage is one of the necessary factors for sustainable development of the cities (Sarchenko, 2016). Other authors: Ho, Shum & Wong (2016), Korotaev (2016), Lan (2016), Qiao & Peng (2016), Shang (2016) and Zhao & Wo (2016) go further in analysing the land shortage of big cities such as: Moscow, Hong Kong, Louyang, Beijing, and Xicheng; and also analyse how UUS can be implemented in those cities' master plans (Ho et al., 2016; Korotaev, 2016; Lan, 2016; Qiao & Peng, 2016; Shang, 2016; Zhao et al., 2016).

Land shortage is related directly to the population growth. Kaliampakos (2016) explains that urban areas are growing unproportionable and since 2007 more people live in urban areas than anywhere else in the rest of the planet. He also adds that by 2050, the world population is expected to reach 9.3 billion while the population living in urban areas is projected to reach 6.3 billion (Kaliampakos, 2016). Wang (2016) states that this population growth is the main reason of global change (Wang, 2016). Several authors Korotaev (2016); Lan (2016); Zhao & Wo (2016) have studied the population growth of big urban spaces in China and Russia reflecting the changes that those cities have gone through due to this phenomenon (Korotaev, 2016; Lan, 2016; Zhao & Wo, 2016). Korotaev (2016) on the other hand represent us with the concept of "compact city", which contributes in the preservation of environment as a whole, leading the cities to develop underground (Korotaev, 2016). This immense growth of population also influences the massive energy production and consumption. Building underground will reduce this huge energy production and consumption (Zhao & Wu, 2016).

Population growth has directly influenced the general pollution index. The higher a city population, the higher energy demand is, therefore more dioxide carbon is released in the atmosphere. In addition, a world-wide attention is grown towards energy conservation to reduce dioxide carbon emission. To avoid the energy consumption building underground is seen as a sustainable approach (Alkaff, Sim, & Efzan , 2016). Underground construction has also a great importance in energy inefficiency. Broere (2016) both discuss for noise pollution and claim that by placing different functions in the subsurface will reduce this phenomenon (Broere, 2015). On the other hand, Lu, Hitoshi & Shu (2016) consider the pollution of the UUS. The authors list chemical pollution as a risk of the subsurface and it should be well-considered by UUS designers (Lu , Hitoshi , & Shu , 2016). Population growth has also influenced the demand for new infrastructure. Authors such as: Golzman (2016), He et al. (2016), Kaliampakos (2016), all discuss that this population growth has led to an immediate demand for new infrastructure, and see UUS as a potential solution for fulfilling those demands (Golzman, 2016; He et al., 2016; Kaliampakos, 2016)

The continuous increase in pollution, as a result of the release of carbon dioxide into the atmosphere, has brought a great consequence to the climatic changes and global warming. According to Chen & Shi (2022) in recent years, global warming has accelerated sharply, with the global average temperature rising by approximately 0.87 ◦C between 2006 and 2015. Authors claim that energy-saving air-conditioning equipment is becoming increasingly important in order to mitigate the increasingly serious global climate change problem and this can be solved by constructing underground, aiming for a sustainable approach (Chen & Shi, 2022). Wang (2016) supports this idea by claiming that earth sheltering can be seen as a solution to the climate changes (Wang, 2016). In addition, Admiraal & Cornaro (2016) state that buildings and infrastructure housed beneath the earth's surface are better protected against climate threats caused by the greenhouse effect (Admiraal & Cornaro, 2016).

The immense development of urban areas, has led to the need of new infrastructures. Golzman (2016), while studying the city of Moscow, explains that the need for new infrastructure is taking up a certain amount of city surface, (Glozman, 2016), threating the heritage of those urban spaces. According to Qiao & Peng (2016), placement of infrastructure and other facilities underground presents an opportunity for realizing new functions in urban areas without destroying heritages (Qiao & Peng , 2016). Shang (2016), strengthens the argumentation by explaining that by moving a part of the infrastructure underground, the surfaces around the heritage areas are freed from the above-ground structures, making it easier to access these spaces (Shang, 2016). But on the other hand, Zhao & Wo (2016) present us with another aspect of the protection of heritage sites, arguing that underground constructions should be done within specific standards and distances, so as not to damage these areas (Zhao & Wu, 2016).

Korotaev (2016) claims that this need for new infrastructure is leading to a shortage of space for greenery, so by developing the city underground, more space will be available for greenery, parks and public gardens (Korotaev, 2016). Those green spaces, according to Safaee & Ghafoori (2016), are precisely those places that renew the quality of life of citizens, separating them from the noise and pollution of non-green areas (Safaee & Ghafoori, 2016). So, in order to fulfill the need for a better quality of life, we need to protect green spaces and to add as much as possible.

## 2.5 Challenges of Underground Urban Space

The development of UUS construction offers many solutions in terms of urbanization and related problems, but, on the other hand, it also has its own challenges. Some of the challenges that have been studied by different authors are:

construction prices, lack of natural light, lack of ventilation, humidity, challenges with human psychology, evacuation and natural disasters.

Construction of underground buildings is costly, as it can be considered 2-3 higher than above-ground construction as underground construction is more complex, require higher technology and lasts in time (Lai et al., 2023; Shan et al., 2017). Alkaff, Sim, & Efzan (2016) add that more geological complexity is also a great influencer in US construction cost (Alkaff, Sim, & Efzan , 2016). However, Lai et al. (2023) discuss that construction cost varies a lot on different project and that those constructions have also a bigger indirect income compared to their cost (Lai, Wang, Chen, & Liu, 2023).

The underground surrounded by soil and rock, offer a lack of natural light, ventilation and dehumidification, affecting users' comfort (Lai, Wang, Chen, & Liu, 2023). The authors discuss that the lack of natural light can be considered as the most disadvantage of UUS. Roberts et al. (2016) claims that the small amount of natural light influence directly humans' workability and concentration (Roberts, I. Christopoulos, Car, Soh, & Lu, 2016), therefore humans can hardly understand the surrounding environment and find the exit (Lai, Wang, Chen, & Liu, 2023). The lack on natural light can cause people to feel less safe and they are more likely to feel nervous (Sun & Leng, 2021). Insufficient ventilation is also a serious drawback, which can cause pollution, low air-quality, less amount of oxygen and a high amount of dioxide carbon, that will cause health problems (Lai, Wang, Chen, & Liu, 2023). Authors also argues that the machineries installed to regulate the amount of fresh air in the indoors of UUS will affect in the construction cost. Huang et al. (2021) explains that the amount of radon, which is a dangerous colorless poisonous gas, is higher in the UGS (Huang, Ninić, & Zhang, 2021), and the lack of ventilation makes the situation more complicated (Lai, Wang, Chen, & Liu, 2023). Kotol et al. (2014) argues that the lack of ventilation, cause more heat in the indoor underground space, affecting the occupants' health (Kotol, Rode, Clausen, & Nielsen, 2014).

High temperature and high humidity are UUS challenge that threat human health (Chen & Shi, 2022; Shan et al., 2017). Anyway Chen & Shi (2022) offers rotary dehumidification air conditioning (RDAC) system as an energy-efficient and environmentally friendly air conditioning system as a mean of dehumidification that will improve the health of occupants (Chen & Shi, 2022). The authors explain that the cooling unit controls the temperature of the supply air (sensible heat), and the rotary dehumidifier controls the humidity of the supply air (latent load).

The lack of natural light and ventilation of underground spaces cause people to have some physical and psychological obstacles while using those spaces (Shan, Hwang, & Wong, 2017). Underground spaces have strong closure, affecting therefore the human sense of direction, adaption and tranquility. The closed nature of underground spaces brings a sense of panic and disorientation to human nature (Lu , Hitoshi , & Shu , 2016). Furthermore, Romanova (2016) underground constructions have a negative impact in humans health and are the main factor in the development of phobias, mainly claustrophobia. The more time is spent on the underground spaces, the more a human is psychologically affected. The author goes further by explaining that according to statistics a short-term stay (10 minutes) causes a discomfort at 1.5% of people, a temporary stay (2 hours) can lead to chronic fatigue, a long stay (up to 4 hours) make people predisposed to mental health problems, and a constant stay (over 24 hours) can cause severe psychological distress and hallucination, due to the isolation. In addition, the author suggests that even though underground development solves a lot of urban challenges it can be a threat to human mental health, and therefore architects should find different architectural solution such as the usage of bright colors, natural lighting, greenery and open spaces (Romanova, 2016).

Based on the human psychology condition in the underground spaces, the challenge of evacuation from those areas arise. Lu et al. (2016) explains that the impaired mental state and the vertical circulation from the underground to the above ground that slows down the speed, makes evacuation very difficult for the users of those spaces (Lu , Hitoshi , & Shu , 2016). For this reason, it is important that the evacuation plans for these areas are well thought out and effective.

# THEORETICAL BACKGROUND

## *Energy efficiency and fundamental equations*

According to the IEA (2013), buildings produce 39% of primary energy (PE) consumption and 33% of the energy-related carbon dioxide (CO2) emissions worldwide, and there is an obvious tendency for these figures to increase, with the rapid growth of population, so we need to find a solution to this challenge (IEA, 2017). In order to design buildings that offer a good energy efficiency, the requirements for heating and cooling must be considered. Both sensible and latent loads, which are influenced by elements including thermal insulation, building design, soil thermal properties, internal sources, and infiltration, are taken into consideration in the calculation of the cooling and heating load. Different analytical methods are used to determine cooling and heating load estimation. The set of IRAM Standard 11900 refers to some guidelines that define building leading, based on monthly data. Calculation of thermal loads for cooling and heating, are restricted to sensible heating and cooling (E.Camporealea & Mercader-Moyano, 2019).

The energy demand analysis requires these **inputs**:

- Climate data
- Solar gain and internal gains
- Transmissions and ventilation properties
- Set-point temperatures and ventilation rate
- Heating, cooling, ventilation and lighting systems' data
- Components, systems and use of building
- Partition of building into different zones for calculation
- The ventilation supply, temperature, and air flow rate

The **outputs** for building energy analysis are:

- Yearly energy needs for the cooling and heating of the space (kWh/m$^2$)
- Yearly secondary use for the cooling and heating of the space (kWh/m$^2$)
- Monthly values for energy needs, energy consumption, energy balance
- Losses of the system for heating, cooling, ventilation and lightning

Although the conversion factors for En calculation are dependent on the local energy patterns and the location of the building, they are coordinated in such a way as to reduce the variables and focus totally on the analysis of the building's shape.

*Equation 1* shows the calculation for the energy consumption index (EnI) in kWh/m$^2$ annually (E.Camporealea & Mercader-Moyano, 2019):

$$En = \frac{En_{heat} + En_{Cool}}{A} \qquad \text{(Eq 1)}$$

where: $\mathbf{En_{heat}}$ is the primary energy consumption for heating [kWh] and $\mathbf{En_{cool}}$ is the primary energy consumption for cooling, [kWh]; $\boldsymbol{A}$ is the net area of the building which is the inner area without internal partitions, [m$^2$].

*Equation 2* calculates the PE consumption for heating:

$$En_{heat} = \sum_{j=i}^{M} \left[\sum_{i=1}^{N} \frac{Q_{h;i:j}}{n_{h;i:j}}\ x\ f_{p;1}\right] \qquad \text{(Eq 2)}$$

where: $\boldsymbol{Q_{h;i:j}}$ is the monthly thermal energy for heating in each thermal zone, [kWh] and $\boldsymbol{n_{h;i:j}}$ is the weighted average efficiency of the heating system: 0.7; $\boldsymbol{f_{p;i}}$ is the conversion factor from secondary to primary energy for each thermal zone whereas $\boldsymbol{M}$ is the number of months that requires heating and N is the number of thermal zones.

*Equation 3* calculates the thermal loads corresponding to heating for each zone:

$$Q_h = Q_{env;rad;vent} - n_g\ x\ (Q_{intg} + Q_{sol}) \qquad \text{(Eq 3)}$$

where: $\boldsymbol{Q_{heat}}$ is the thermal energy for heating, [kWh] and $Q_{heat;rad;vent}$ is the thermal energy transmitted through the envelope, [kWh]; $\boldsymbol{n_g}$ is the utilization gain factor which depends on the thermal capacity of elements whereas $\boldsymbol{Q_{ints}}$ are the internal gains, [kWh] and $Q_{sol}$ are the solar gains, [kWh].

*Equation 4* calculates the annual secondary energy needed for heating:

$$En_{Sheat} = \sum_{j=i}^{M} \left[\sum_{i=1}^{N} \frac{Q_{h;i:j}}{n_{h;i:j}}\ x\ f_{p;1}\right] \qquad \text{(Eq 4)}$$

where: $En_{Sheat}$ is the secondary energy for heating, [kWh].

*Equation 5* calculates the PE consumption for cooling:

$$En_{cool} = \sum_{j=i}^{M} \left[\sum_{i=1}^{N} \frac{Q_{c;i:j}}{n_{c;i:j}} \ x \ f_{p;1}\right] \qquad \text{(Eq 5)}$$

where: $\boldsymbol{Q_{c;i:j}}$ is the monthly thermal energy for cooling in each thermal zone, [kWh]; $\boldsymbol{n_{c;i:j}}$ is the weighted average efficiency of the cooling system: 3.2 and $\boldsymbol{f_{p;i}}$ is the conversion factor from secondary to primary energy for each thermal zone whereas $\boldsymbol{M}$ is the number of months that requires heating and N is the number of thermal zones.

*Equation 6* calculates the thermal loads corresponding to cooling for each zone:

$$Q_c = Q_{env;rad;vent} - n_g \ x \ (Q_{intg} + Q_{sol}) \qquad \text{(Eq 6)}$$

where: $\boldsymbol{Q_{heat}}$ is the thermal energy for cooling, [kWh] and $Q_{heat;rad;vent}$ is the thermal energy transmitted through the envelope, [kWh]; $\boldsymbol{n_g}$ is the utilization gain factor which depends on the thermal capacity of elements whereas $\boldsymbol{Q_{ints}}$ are the internal gains, [kWh] and $Q_{sol}$ are the solar gains, [kWh].

Equation 7 calculates the annual secondary energy needed for heating:

$$En_{Scool} = \sum_{j=i}^{M} \left[\sum_{i=1}^{N} \frac{Q_{h;i:j}}{n_{h;i:j}} \ x \ f_{p;1}\right] \qquad \text{(Eq 7)}$$

where: $\boldsymbol{En_{Scool}}$ is the secondary energy for cooling, [kWh].

For the underground, a mathematically dynamic representation describes the heat balance of a subterranean area considering the heat flux through the wall, internal thermal load, ventilation and heating-cooling demand. Partial differential equations can be used to describe the thermal events. Based on the subterranean space's heat balance, the Fourier's parabolic partial differential provides a time domain description of the heat conduction though soli mass (Kajtar, Nyers, & Szabo, 2015), illustrated also in ***Figure 3.***

The increase in the sum of the heat balance flux is the heat balance of the area and it can be calculated through *Equation 8*:

$$[Q - Q_w(\tau) - Q_s(\tau)]\ x\ d\tau = c_{p,a}\ x\ \rho_a\ x\ V\ x\ dt_a \qquad \text{(Eq 8)}$$

where: **Q** is the internal heat load, [kW]; $\boldsymbol{Q_w(\tau)}$ is the transmission heat through wall, [kW] and $Q_s(\tau)$ is the heat performance of ventilation [kW]; $\boldsymbol{c_{p,a}}$ is the heat capacity of the air in constant pressure, [kJ/kg K], $\tau$ is the time, [sec] and $\rho_a$ is the air density, [kg/m$^3$], whereas **V** is the volume of the underground space, [m$^3$].

*Equation 9* calculates the internal heat, which includes human, light, electrical equipment and mechanical cooling and heating loads:

$$Q = Q_h + Q_l + Q_e + Q_{h,c} \qquad \text{(Eq 9)}$$

where: $\mathbf{Q_h}$ is the heating performance of human, [kW]; $\boldsymbol{Q_l}$ is the heating performance of the lighting, [kW] and $Q_e$ is the heating performance of the electrical equipment, [kW], whereas $\boldsymbol{Q_{h,c}}$ is the heating performance of the mechanical cooling and heating, [kW].

*Equation 10* calculates the heat capacity of ventilation, which supplies the air enthalpy increment:

$$Q_w(\tau) = m_s\ x\ [h_a(\tau) - h_s] \qquad \text{(Eq 10)}$$

where: $\boldsymbol{m_s}$ is the mass flow of supply air, [kg/s]; $\boldsymbol{h_a}$ is the pressure of the air in underground space [kJ/kg K] and $h_s$ is the heating pressure of the supply air, [kJ/kg K].

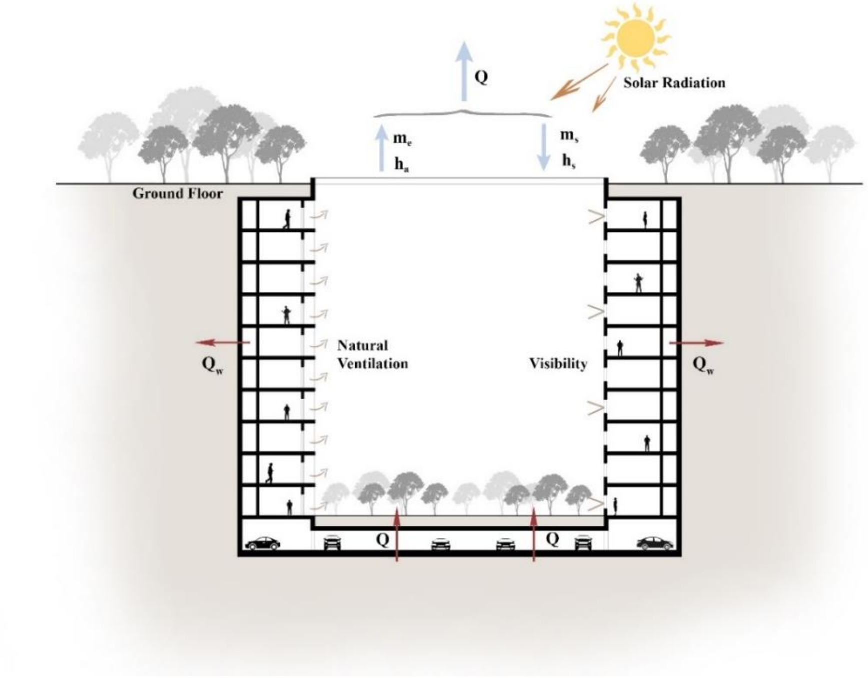



***Figure 3.*** Underground energy dynamic diagrams

## 2.6 Energy performance of underground buildings

Located in the ground, buildings benefit from the thermal performance of the ground mass, leading to energy conservation. It is proven that the temperature of the earth is higher during the winter and lower during the summer. The authors explain that the thermal properties of the soil can be considered as creating a thermal reservoir, directly influencing the internal temperature of the UUS spaces (Alkaff, Sim, & Efzan , 2016). However, regardless of the characteristics of the land mass, there are several factors that directly affect the energy efficiency of UGB, which are: thermal insulation, building design and typology, local climate, ventilation system, soil thermal properties, occupancy patterns, altitude above sea level, solar radiation, energy consumption reduction potential, and depth (Delzendeh, Wu, Lee, & Zhou, 2017).

### 2.6.1 Thermal Insulation

Thermal insulation of UGB is one of the most important design criteria as it affects the protection against humidity and a better energy performance. According to Breçani & Dervishi (2018) thermal insulation on the underground buildings serves not only as an indicator in temperature performance but also as a waterproofing mechanism (Breçani & Dervishi, 2018). Stetjukha (2023) also explain that the usage of thermal insulation in the UGB will replace the soil layer around the structure and ensure an immense temperature stabilization in certain depths, affecting the conservation of thermal energy (Stetjukha, 2023). Statenic and Nowak have conducted a research about the thickness of insulating materials and their impact on thermal performance and energy efficiency. They have concluded that the thinner the thermal insulation is, the better cooling effect is gained from soil (Staniec & Nowak, 2011). Kajtar et al., (2015) also support the findings by explaining that the use of thermal insulation in the outer walls of the UGB directly affects the energy transfer coefficient (Kajtar, Nyers, & Szabo, 2015) using *Equation 11*:

$$\alpha' = \frac{1}{\frac{1}{\alpha}+\frac{\delta}{\lambda}}, \qquad \text{(Eq 11)}$$

where: $\boldsymbol{\alpha'}$ is the modified heat transfer coefficient, [W/m$^2$K] and $\alpha$ is the heat transfer coefficient, [W/m$^2$K]; $\boldsymbol{\delta}$ is the thickness of the insulation, [m] and $\lambda$ is thermal conductivity [W/mK].

### 2.6.2 Building typologies

Some of the UGB typologies can be: underground hotel, basement, underground hospitals and exhibitions and also underground housing (Yu et al., 2020) and those buildings' design and typology has a great impact on the energy efficiency of UGB, as it determines the contact surface area of the building with the earth (Alkaff, Sim, & Efzan , 2016). Yu, Kang & Zhai (2020), also explains that UGB help in saving 23% of energy compared to similar above ground buildings (Yu, Kang, & Zhai, 2020). Design typology also effect the sun penetration and cold air infiltration into the building, influencing directly the energy efficiency of the building (Alkaff, Sim & Efzan, 2016; Anselm, 2012; Zhu & Tong, 2017).

In order to have a better approach to courtyard housing, many studies have been done regarding the impact that this type of typology and its proportions have on energy performance. According to Anselm (2012), 80% of courtyard housing typology surface is directly in contact with earth surface, becoming the most UGB type that offers better thermal and energy performance on the indoor spaces (Anselm, 2008), as illustrated in ***Figure 4***. In terms of courtyard proportions, Zamani et al. (2018), has studied how the length-width proportions have the greatest impact on their climatic functionality. From the obtained results, the authors claim that a length-to-width ratio of less than 5 enables a better air flow (Zamani, Shahin , & Pirouz , 2018).

Yaşa et al. (2014) continues further, making a closer study of energy performance and courtyards, focusing on certain climatic areas. The authors have studied 7 forms of courtyards in certain areas of Turkey, in terms of length-width proportions, shading, ventilation to determine their energy performance. According to the results of the conducted study, it is the square shape of the courtyard that is more influenced by shading, and affects the heating and cooling loads the most. With the increase in the length of the courtyard, the annual energy consumption also increases (Yaşa & Ok, 2014).

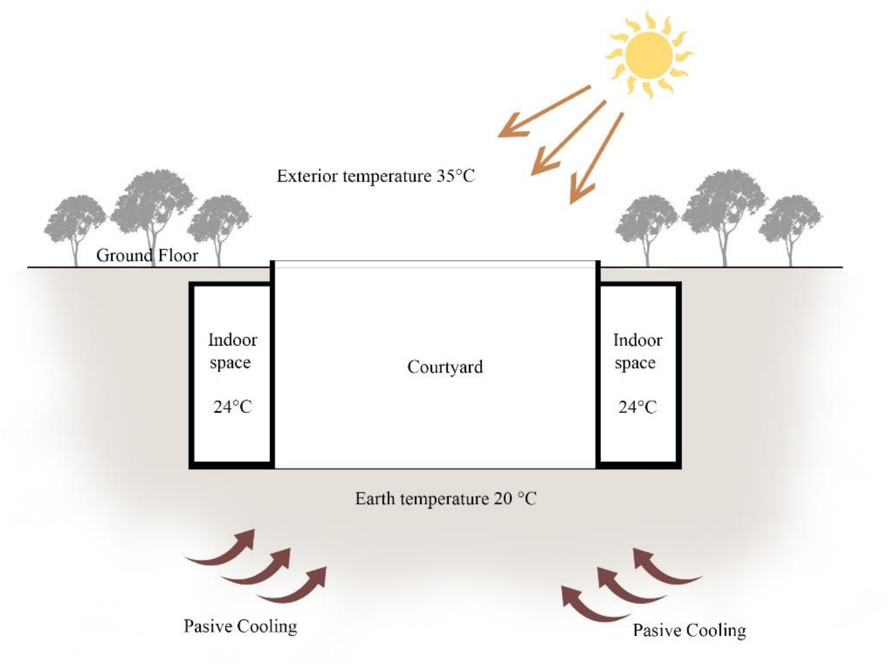



***Figure 4.*** Thermal and Energy Performance of Underground Courtyard Housing

### 2.6.3 Depth

In addition to the influence of the surface area in contact, the depth of the building also has a great affect in the energy performance of an UGB (Alkaff, Sim, & Efzan , 2016). Based on the temperatures of the ground, three different ground zones can be distinguished: surface zone (1m depth), shallow zone (1-8m depth), and deep zone (8-20m depth) (Popiel, Wojtkowaik , & Biernacka, 2001). According to Kajtar et al. (2016), soil temperature has a change with 0.8 $^{o}$C in 8m depth and 0.2 $^{o}$C in 10m depth, illustrated in **Figure 5**, providing a better energy performance for the UGB (Kajtar, Nyers, & Szabo, 2015). The dependence of the soil temperature from the depth is explained by *Equation 12* (Alkaff, Sim, & Efzan , 2016):

$$T_{(z,t)} = Ta + A_0 e^{-z/d} \, sin\left[\frac{2\pi(t-to)}{365} - \frac{z}{d} - \frac{\pi}{2}\right] \qquad \text{(Eq 12)}$$

where: $\mathbf{T_{(z,t)}}$ is the soil temperature at time t [d] and $T_a$ is the average soil temperature [$^{o}$C]; $\mathbf{A_0}$ is the annual amplitude of the surface soil temperature [$^{o}$C], whereas **d** is the damping depth [m] and $t_0$ is the time lag [d].

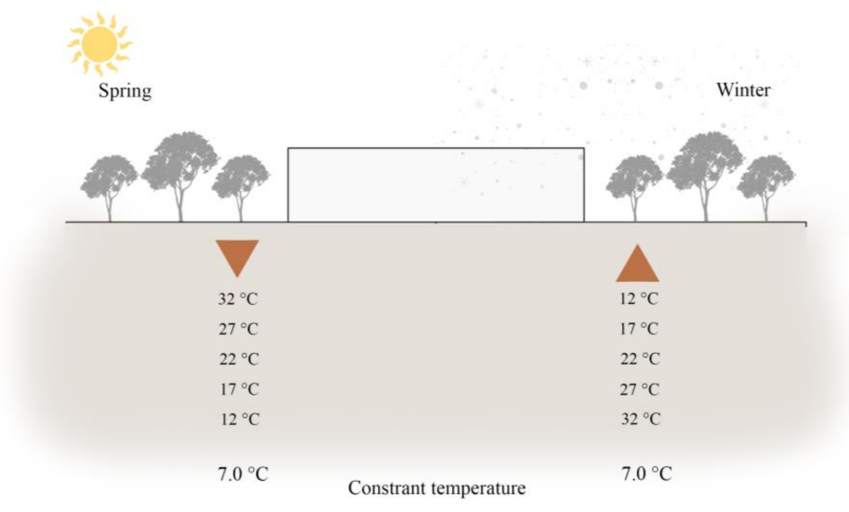



***Figure 5*** Soil temperature affected by depth

### 2.6.4 Local climate

Local climate, especially soil temperature, plays a crucial role in the energy performance of the UGB, as it directly controls the temperature of the indoors and energy saving. It is indicated that outside climate influences the relationships between heat gain and loses (Tan, et al., 2018).. Yu, Kang & Zhai (2020) explains that even though the UGB is not directly exposed to outside climate, the energy performance is directly affected by the temperature of the soli that is connected to climate conditions (Yu, Kang, & Zhai, 2020).

Soil's temperature varies throughout the year (Kajtar, Nyers, & Szabo, 2015). Factors which indicate the soil's temperature are: structure and physical properties, ground surface cover and climate interaction (Popiel et al., 2001; Yu et al., 2020). Stetjukha (2023) explains that ground temperature at a certain depth is more stable and it remain closer to the indoor temperatures. Heat loss through a selected area with a given area can be calculated by *Equation 13* (Stetjukha, 2023):

$$Q = z * F * K * (t_v - t_s) \qquad \text{(Eq 13)}$$

where: **Q** is the heat loss at a selected area [W/m$^2$]; z is the heat transfer time [h]; **F** is area [m$^2$] and K is the calculated heat transfer coefficient, whereas $\mathbf{t_v}$ is the indoor ai temperature [$^o$C] and $\mathbf{t_s}$ is the temperature of the adjacent ground [$^o$C].

Anyway, ground properties are not always precisely determined, therefore *Equation 14* is used to solve the heat conduction, where the temperature of the surface varies with time (Popiel, Wojtkowaik , & Biernacka, 2001):

$$T_{x=0,t} = A_s \cos[2p(t-t_0)/365] \qquad \text{(Eq 14)}$$

where: **T** is the temperature [$^o$C]; $\boldsymbol{A_s}$ is the amplitude of annual average air temperature wave [$^o$C]; **t** is time [days] and $t_0$ is the phase of air temperature wave [days].

For the northern hemisphere *Equation 15* has the form:

$$T_{(x,t)} = (T_m \pm \Delta T_m) - 1.07 k_v A_s \, exp(-0.00031552 \chi \alpha^{-0.5}) * cos[\frac{2\pi}{365}(t - t_0 +$$

$$0.018335\chi\alpha^{-0.5})] \quad \text{(Eq 15)}$$

where: **T** is the temperature [°C] and $\mathbf{T_m}$ is the average annual air temperature [°C]; $\mathbf{k_v}$ is the vegetation coefficient; $\boldsymbol{A_s}$ is the amplitude of annual average air temperature wave [°C]; **x** is the depth below ground surface [m] and **a** is the average annual thermal diffusivity of undisturbed ground [$m^2/s$]

Ground temperature also influence directly the heat flux, following the *Equation 16* (Popiel et al., 2001):

$$q= -k\frac{\partial T}{\partial x}, \quad \text{(Eq 16)}$$

where: **q** is heat flux density [$W/m^2$]; **T** is the temperature [°C] and **x** is the depth below ground surface [m].

Average heat flux density can be calculated by *Equation 17* (Zdankus et al., 2022):

$$q_{av} = \frac{\sum_{i=1}^{n} P_i t_i}{At_{set}} \quad \text{(Eq 17)}$$

where: $\mathbf{q_{av}}$ is the average heat flux density [$W/m^2$] and $\mathbf{t_{set}}$ is the time interval [s]; **i** is te number indicating the specific charge and n is the number of changes set per time interval; $\mathbf{P_i}$ is the power of specific charge [W]; $\mathbf{t_i}$ is the duration of e specific charge [s] and **A** is the area of hating surface [$m^2$].

### 2.6.5 Soil thermal properties

In addition, soil's thermal properties are factors that have a direct effect on heat transfer and heat flux in UGB (Alkaff, Sim, & Efzan , 2016). Those properties, the thermal conductivity and heat capacity of the soil, play a crucial role in determine the temperature distribution in the underground. The thermal conductivity of the soil is referred as the ability of the soil to conduct the heat and it is highly depended on the soil moisture content (Delmastro, Lavango, & Schranz, 2016). In order to verify the impact of those properties, a study was conducted, where 5 types of soil were considered, from sand and clay with different moisture content, and it was concluded that the lower the thermal conductivity, the better the energy performance of the underground will be On the other hand, moisture does not only affect the thermal conductivity of the soli, but it also have a great impact on the soil heat transfer capability (Alkaff, Sim, & Efzan , 2016).

Another property of the soil is the thermal mass provided by the earth. This thermal mass serves as a thermal reservoir, which emits or collects heat, affected by the heat difference between soil and indoor space temperature (Ip & Miller, 2009). Papada et al. (2016), add also that soil layer serves as a membrane for the underground constructions and plays a crucial role in reducing the thermal loses and maintaining a constant indoor air temperature (Papada, Katsoulakos , & Kaliampakos , 2016).

### 2.6.6 Ventilation

Ventilation is another factor that has its direct impact on the energy performance of underground buildings, and is closely related to the occupants of these buildings, since the amount needed for clean air is directly related to the number of individuals who use the building (Alkaff, Sim, & Efzan , 2016). As mentioned above, one of the biggest challenges of UGB is ventilation, and the low quality of air together with the high amount of humidity is closely related to insufficient ventilation (Yu, Song, Song, Lau, & Han, 2022). Although the addition of underground ventilation equipment adds costs and energy consumption, which should be avoided for UGB, it is interesting to understand that some studies have used passive methods of underground ventilation (Alkaff, Sim, & Efzan , 2016). A solution is given by the study carried out by Yu et al., (2020), is the construction of a ventilation system using the solar chimney effect and photovoltaic-thermal technology, thus reducing the constant temperature of the underground spaces, but also benefiting from the heat which comes from natural ventilation (Yu, Kang, & Zhai, 2020). In this way, we not only maintain the energy performance but also create a friendlier environment and reduce the level of humidity for the occupants of these spaces (Alkaff, Sim, & Efzan , 2016).

### 2.6.7 Occupants Behavior

The behavior of the occupants of a building plays a key role in how a building will perform in terms of energy. The users of a building, in order to have an environment as suitable as possible for their well-being and to achieve thermal comfort, use windows, HVAC systems, lighting, hot water, which have an impact on the energy of the building as illustrated in ***Figure 6***. The main challenge in the studies developed reviewed in the work of Delzendeh et al. (2017), is the behavior of the occupant of the space, as different users show different demands for the use of HVAC, lighting, hot water, and ventilation. These requirements vary based on several parameters such as the climate, the type of building, the condition of the user, architecture, economy and policies and rules. It is also the activities of these occupations that determine and influence the energy performance (Delzendeh, Wu, Lee, & Zhou, 2017). *Figure 7*. shows a scheme of how the behavior of the occupants affects the energy.

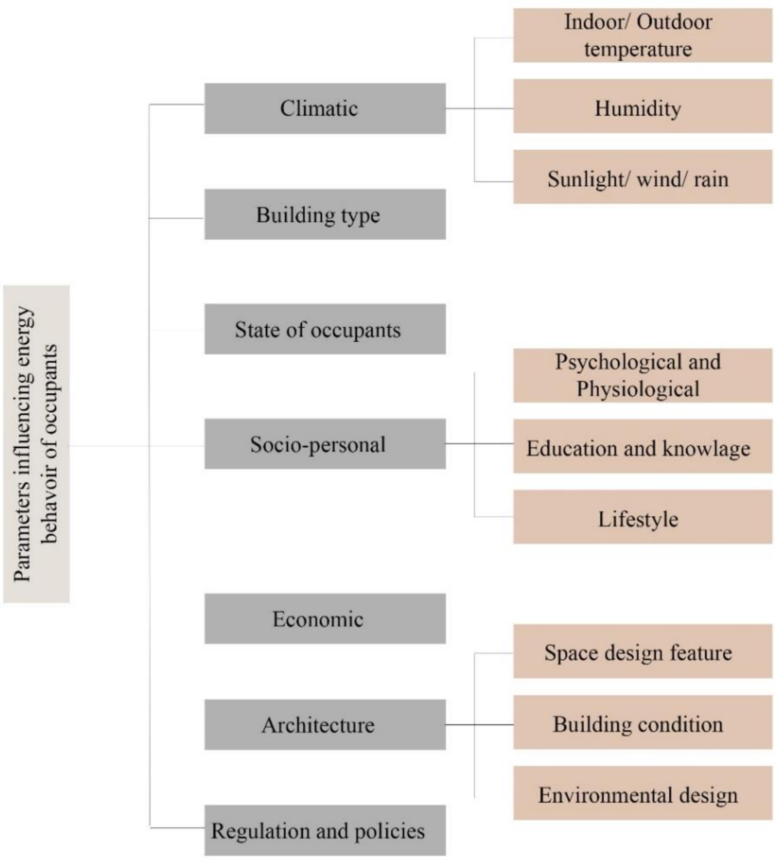


***Figure 6.*** Factors affecting energy performance of occupants

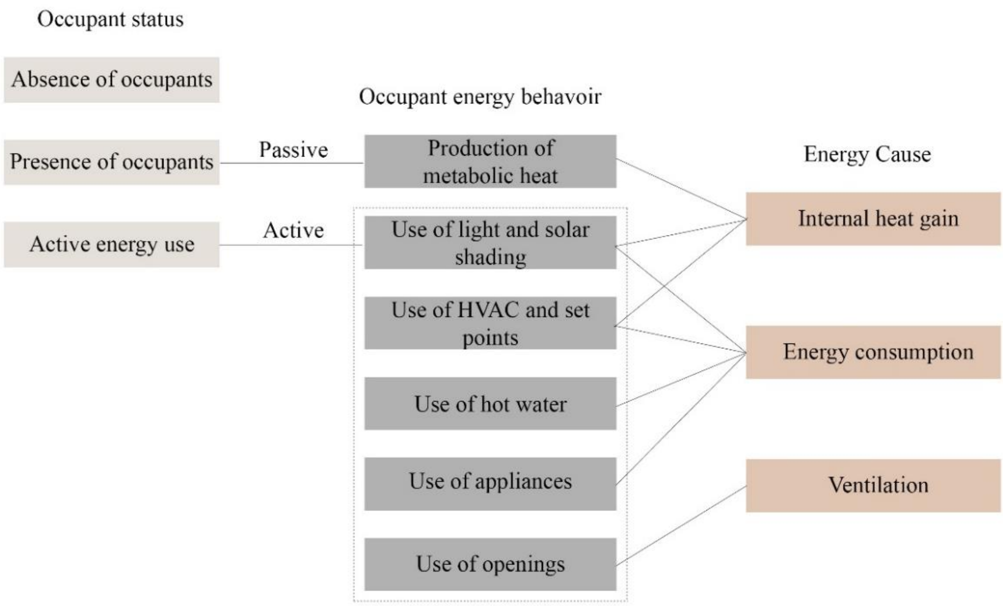



***Figure 7.*** Building consumption energy influenced by occupants' activities

## 2.7 Advantages of UGB

Regardless of all the challenges, underground construction has its own advantages, which are mainly related to the solutions that the use of this space gives to the problems that the globe is facing today.

The first and most important advantage is the possibility of more free spaces on the ground. In many studies conducted by different authors, they explain how by moving some of the daily activities underground, then we will have more space above ground. Ho et al., (2016), presupposes that caves and underground spaces are an asset of urbanization, which is not used very much, but if it is put to use, a lot of activities will be moved there, urban planning will benefit from the spaces that will be freed and these spaces can be developed other activities (Ho, Shum, & Wong, 2016). In addition, a study conducted by Broere (2015), proposed that a large part of the car traffic can be transferred underground, since it takes up 30-90 times more space than public transport, thus enabling more free land on the surface, where other activities can take place (Broere, 2015). Korotaev (2016), goes further by emphasizing that moving traffic, but also parking, in underground spaces opens up more space for pedestrian circulation, but also enables land for the development of greenery and recreational activities, turning the urban environment into a friendly space for people. He also presents the concept of "Compact city", which means that the more the city develops in underground spaces, the more the environmental qualities of urban spaces will improve (Korotaev, 2016).

Another advantage of using UGB is the optimized use of resources. Bulakh and Marylara (2020), discuss that the use of underground spaces will bring benefits such as reducing the perimeter of the building above ground, which brings benefits for buildings with climate change, which also means enabling an optimal room temperature. Another benefit is the fact that these buildings can use the benefits of the soil, the air environment as well as the use of ground water. The authors go further by adding that underground buildings have a greater possibility of expanding the perimeter (Bulakh & Merylova, 2020). Shan et al. (2017), also add that underground buildings benefit form soil, as it serves as a natural insulation (Shan, Hwang, & Wong, 2017).

Building underground also has a positive effect on avoiding many natural disasters. Shan et al. (2017), explains that the fact that these buildings are surrounded by a fire-insulating material, such as soil, positively affects the reduction of fire cases. The authors go further by explaining how the underground placement of buildings avoids many other disasters, such as: hail storms, strong winds, tornadoes, etc, making these environments friendlier to people (Shan, Hwang, & Wong, 2017). Shiina et al. (2016) explains how different cities in Japan are seeing the underground as an accommodation in case of earthquakes, suggesting a plan and manual for access and living in these spaces (Shiina, Sasaki, Harada, & Kasuya, 2016).

Another advantage of UGB is the reduction of pollution. First off, by building residential buildings underground, traffic is at low levels, we have a significant reduction in noise pollution. The authors also explain that underground construction will open up more green spaces above ground, increasing the quality of oxygen in the soil. Another aspect that is discussed is the fact that, according to studies, underground has a better energy efficiency performance than above ground, we will have a lower release of carbon dioxide into the atmosphere (Bulakh & Merylova, 2020).

## 2.8 Previous studies

To develop a better predictive framework for the energy efficiency performance of underground buildings, scientific literature is reviewed.

Alkaff, Sim & Efzan (2016) presents a review for underground buildings, as a solution for energy efficiency under the threat of urban challenges and global warming. This study presents examples from different areas of the world, from Asia to America, studying their thermal energy performance criteria. The study also focuses on the earth sheltered home and highlights the different typologies, their applications, the impact of climate on performance. In general, the paper studies the potential of underground buildings, as a passive cooling and heating technique and reducing the use of HVAC, presenting a sustainable development (Alkaff, Sim, & Efzan , 2016).

Camporeale & Mercarder-Moyano (2019) is focused on the optimization of floor shapes and housing typologies in Ibero-American temperature climate cities to make possible the reduction of energy consumption. In this study, passive strategies were used to minimize energy consumption per square meter, maximize the passive ratios of the buildings, and optimize the orientation of the buildings. To develop this study, algorithmic generations were used. Studies have been developed in Resistencia, Buenos Aires, Seville, and Madrid, with the aim of reducing energy consumption and the release of carbon dioxide in the climatic context (E.Camporealea & Mercader-Moyano, 2019).

Kajtar et al. (2015) gives explanations on the mathematical description of heat transfer in underground spaces. The authors explain heat conduction through the soil through Fourier's parabolic partial differential equation (Kajtar, Nyers, & Szabo, 2015).

Stetjukha (2023), is focused on improving energy efficiency in harsh climates, in the area of Russia, focusing on the features of thermal insulation. The authors explain that the conducted study shows that the deeper you go, the thicker the thermal insulation should be. They also assume that the technical insulation properties also make it possible to protect against moisture. (Stetjukha, 2023).

To give a clear reflection of the influence of building typologies in the underground for energy performance, Anselm (2008), has developed a detailed study of earth-shelter houses in the north-western area of China. The author explains how these typologies are very efficient for energy-saving benefits, and serve as a passive heat source in winter. The study of these types of typologies is done by looking at these buildings on a larger scale. Passive annual heat storage (PAHS) has been explored by the authors as a way for passive cooling and thermal comfort, highlighting the importance of orientation and depth in energy performance (Anselm, 2008).

Zamani, Shahin & Pirouz (2018) focus their study on the thermal and microclimatic function of courtyards, giving a review of the studies carried out. The whole study focuses on three main points: those that focus on the microclimatic functions of the courtyards, those that focus on the thermal function, and those that take an interactive approach (Zamani, Shahin , & Pirouz , 2018).

The study conducted by Tan et al. (2018), is focused on the energy performance of underground openings in the Beijing area. It is explained how climatic conditions affect energy consumption, as well as the measures taken to have spaces with optimal thermal comfort (Tan, et al., 2018).

The study conducted by Yu et al. (2022) focuses on the Shanghai area, to create a model UGB landscape, focusing on natural ventilation and the use of HVAC. From the 1512 dates generated by the analysis, it results that the model built underground saves 35.5% of energy in December (Yu, Song, Song, Lau, & Han, 2022).

Papada et al. (2016) have focused their study in Greece, proposing the use of the underground as a solution to today's social challenges, related to urban growth and global warming. The authors have done studies above and below ground, claiming that UGBs benefit from soil thermal properties and benefit better from the energy side, compared to buildings above ground (Papada, Katsoulakos , & Kaliampakos , 2016).

In this study Yu et al. (2022) show how the behavior of the occupants in a building affects the energy analysis, reinforcing the important gap between the predicted and actual consumed energy. He discusses the factors that affect a performance gap, including workmanship, construction details, HVAC systems, and occupant behavior. In general, the study discusses how the behavior of the occupants has a great impact on the energy performance of the building (Yu, Song, Song, Lau, & Han, 2022).

Ho, Shum & Wong (2016) discusses the challenges that Hong Kong is going through as a result of urban growth, and explains how by placing some of the functions underground with the city they benefit from more free land. Freeing the land from the buildings gives the opportunity for these spaces to be used for greening, increasing the quality of life for people (Ho, Shum, & Wong, 2016).

Shiina et al. (2016) discuss how the use of underground accommodation serves as a solution in case of natural disasters, specifically during earthquakes. Their study was conducted in the Umeda area of Osaka, Japan. It turned out that the area of Umeda can accommodate 10,600 people, which are approximately 9-14% of the population of the area. However, the authors also raise their concern for the functionality of this type of scenario, proposing a guideline for the use of spaces (Shiina, Sasaki, Harada, & Kasuya, 2016).

***Table 1.*** Data available in scientific literature for energy performance of UGB (please, note that UGB is Underground Buildings)

| Contribution area | Authors | Description |
|---|---|---|
| Energy consumption of UGB | Alkaff, Sim & Efzan (2016) | A comprehensive review is made for the energy performance of underground buildings' design, thermal performance, and potential for sustainable development, proposing also some conceptual design features and optimization of the energy efficiency. |
| | Camporeale & Mercarder-Moyano (2019) | A methodology is proposed to optimize building shapes by using a multi-objective algorithm to minimize primary energy consumption and maximize the volume ratio, maximize roof and best-oriented area in Argentina and Spain. |
| | Kajtar et al. (2015) | A mathematical model and dimensioning is represented to determine the dynamic heat transfer and thermal comfort characteristics in UGB, including factors like internal heat loss, thermal insulation and air exchange rates. |
| Thermal inulation | Stetjukha (2023) | The harsh climatic condition of Russia is studied in terms of energy performance and thermal comfort, putting emphasis in thermal insulation properties and its influence in energy consumption. |
| | Anselm (2008) | A study conducted in north-west China emphasis how earth-sheltered buildings have a better energy performance compared to above-ground buildings. |
| Building typologies | Zamani, Shahin & Pirouz (2018) | The courtyard length-to-height ratio is one of the most influential factors on courtyard climatic function. Airflows can be managed through keeping the right ratio of courtyard`s length to height (less than 5). Vegetation cooling effect is greater than water basins. |
| | Yaşa et al. (2014) | A courtyard should be applied in a form compatible with the features of the climatic region it is used. |
| Local climate | Tan et al. (2018) | Thermal comfort and energy performance is studied in Beijing area, putting a great empathizes on local climate influence on energy efficiency. |
| | Yu, Kang & Zhai (2020) | A wide study developed in different areas of China, Japan, Malaysia and Slovakia, shows that the energy performance of the studied underground buildings is greatly influenced by the local climate. |
| Soil thermal properties | Papada (2016) | A study focused in Greece claims that the underground buildings not only serve as a solution to urban challenges, but also have a better energy performance compared to above-ground |

| | | |
|---|---|---|
| | | buildings, since those spaces benefit from soil thermal properties. |
| Ventilation | Yu et al. (2022) | The study focuses on the Shanghai area, to create a model UGB landscape, focusing on natural ventilation and the use of HVAC. Results show that the model built underground saves 35.5% of energy in December |
| Occupant behavior | Yu et al. (2022) | Occupants' behavior and activities directly affect the energy performance of a building. |
| Advantages of UGB | Ho, Shum & Wong (2016) | The challenges that Hong Kong is going through as a result of urban growth, and placing some of the functions underground as a solution, offer the city to benefit from more free land. Freeing the land from the buildings gives the opportunity for these spaces to be used for greening, increasing the quality of life for people |
| | Shiina et al. (2016) | Underground accommodation serves as a solution in case of natural disasters, specifically during earthquakes. The studied area of Umeda can accommodate 10,600 people, which are approximately 9-14% of the population of the area. However, the authors also raise their concern for the functionality of this type of scenario, proposing a guideline for the use of spaces |

## 2.9 Aim and Originality

Nowadays, increasing energy efficiency in urban areas is considered one of the most important aspects of the development of these contexts. The purpose of the study is to highlight the potential of underground spaces in the development of a sustainable energy efficiency scheme. This topic represents a great challenge for the authorities, architects and stakeholders considering it as impossible or very difficult to develop both from the urban and architectural aspect. As a result, very little research has been done on this topic. The originality of this study lies in the following points: Unlike other studies that focus very little on the energy efficiency of UUS, this study considers different factors such as the identification of challenges and the use of energy in underground spaces as a more holistic approach that considers multiple factors.

This study employs simulation methods to examine a large number of design aspects, focusing on different heights, shapes, proportions, amplitudes and material uses. This approach has been studied very little before in the context of underground spaces. It is the first to highlight the advantages of using underground spaces and the integration of these spaces in urban planning. There have been no studies done about energy performance simulations in different climates and urban contexts.

Morphological studies of energy performance in underground spaces have been limited in form and surface. This study aims to enable deep analysis related to different forms of buildings, different latitudes, use of balconies, consideration of different orientations, window to wall ratio, locations at different heights above and below sea level and use to the materials. Another contribute is related to the fact that this study tries to provide solutions and proposals related to different challenges of using UUS, which are related to the lack of the natural factors that affect daily of life, concerns about human psychology, the implementation of these spaces in urban planning, and also considers the economic costs, as an extremely difficult investment and with considerable risk

Previous studies have been done about the use and consideration of underground space and how this space has a positive impact on energy efficiency. However, this study takes a unique approach by considering the underground as a residential space, as well as a space that can be used for hospital or laboratory services, museums and food preservation space. In addition, this study also examines different factors that influence the development of this idea. Considering the benefits that underground brings, this study aims to offer a comprehensive approach to improve sustainability and self-sufficiency in residential, hospital, museum and storage spaces in UUS.

# CHAPTER 3

# METHODOLOGY

## 3.1 Overview

A mixed-method research is going to be used for this research. The study will have components: selection of different climates, selection of different morphologies and modeling of the selected underground buildings. *(Figure 8)* depicts the methodology used in the study. Five multi-storey residential buildings with different window to wall ratios are proposed. Variations in height are introduced, as well as different balcony width. Simulations that include climatic characteristics have been run on the proposals.

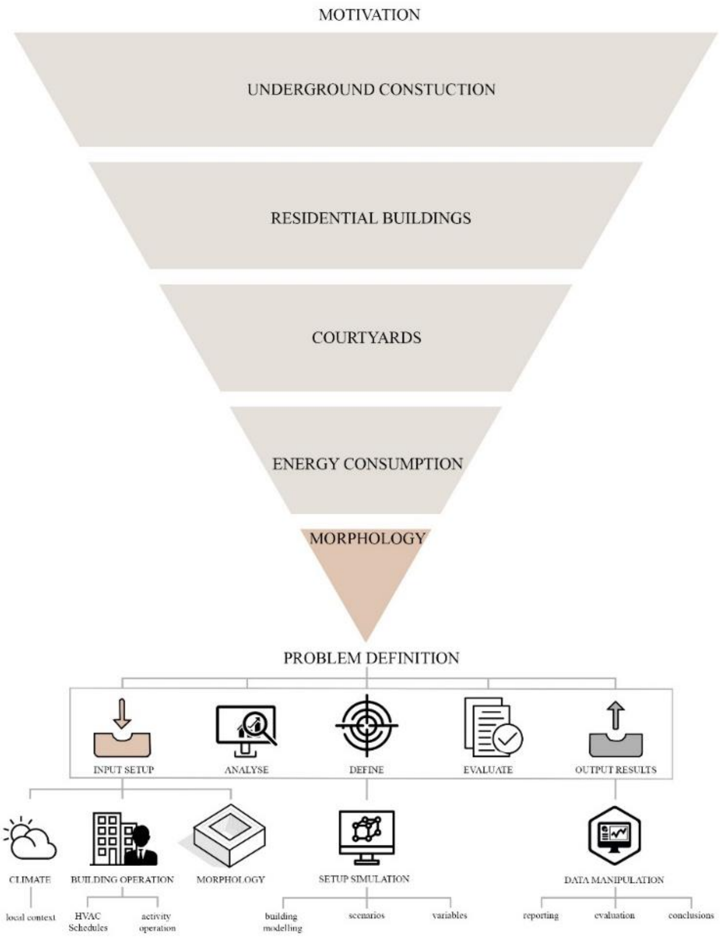



***Figure 8***. Methodological framework of the study.

- ***Data Analysis:***

The data analysis process will involve a comprehensive study of the data that are collected from case studies examples and simulation analysis. A blend of qualitative and quantitative approaches will be used, to receive notable insight from data. Illustrative statistics will be employed to demonstrate a comprehensive view of the energy performances across varieties of underground buildings morphologies. Additionally, qualitative data analysis will be conducted to discern the central factors influencing the effectiveness of UUS systems.

- ***Ethics***

In the simulation analysis and of the case study method, the ethical aspects are considered with special importance. Lack of human interactions using non-invasive and safe life simulation tools. Selected cases will be treated with special care and will be acted upon with ethical norms. Personal or private information may not be collected; all data does not remain anonymous and confidential. The research will comply with applicable rules and laws, including those related to the use of simulation software and the collection of data from structures.

The results of the study will be shared widely and an accurate, unbiased and ethical view of them will be compiled. As a whole, mine of this analysis will be deepening the preserved and respect of privacy and companies for all those who participate in their involvement. This will be done following the highest professional standards and adhering to all applicable guidelines and regulations.

## 3.2 Site Selection Criteria

For the development of this study, three cities in the northern hemisphere were chosen: New York, USA; Athens, Greece and Berlin, Germany *(Figure 9)*. The choice of these cities for the investigation of the energy performance of the UGB steams from their common characteristics and the urban challenges they are facing.

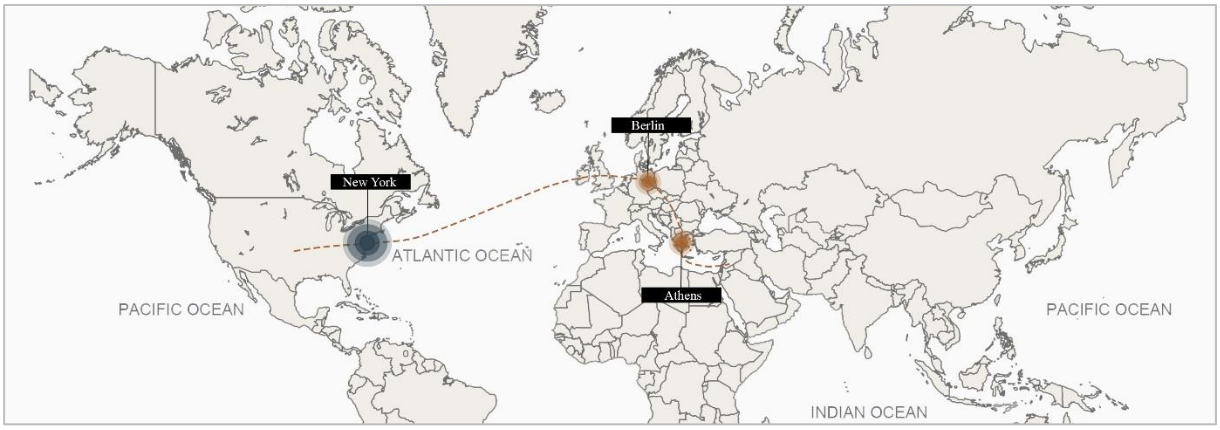



***Figure 9.*** *The selected locations*

The city of New York, located on the east coast of USA, known for its density, high population and vertical architecture, is a good example where innovative architectural forms can be developed with the aim of further urban development and solving the challenges of urbanization to a certain extent (*Figure 11*). According to Worldometer (2024) statistics, 88% of the American population lives in urban areas (Worldometer, 2024). The trends in the population graph show that the population in New York will continue to grow (*Figure 10*).

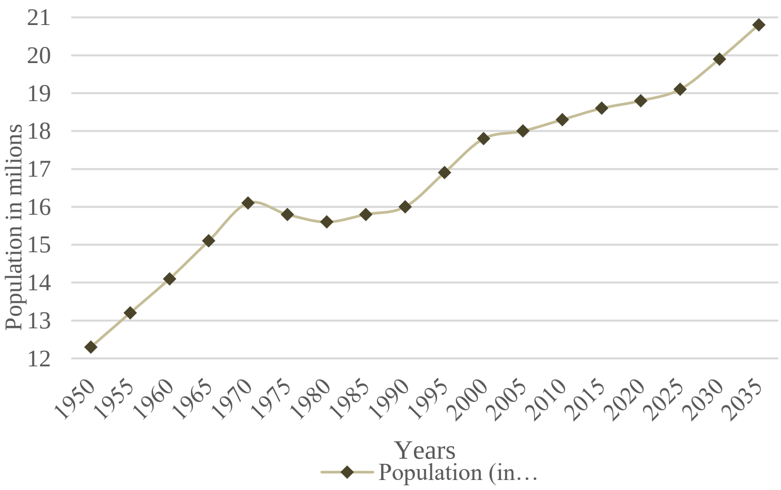



***Figure 10.*** New York city population data

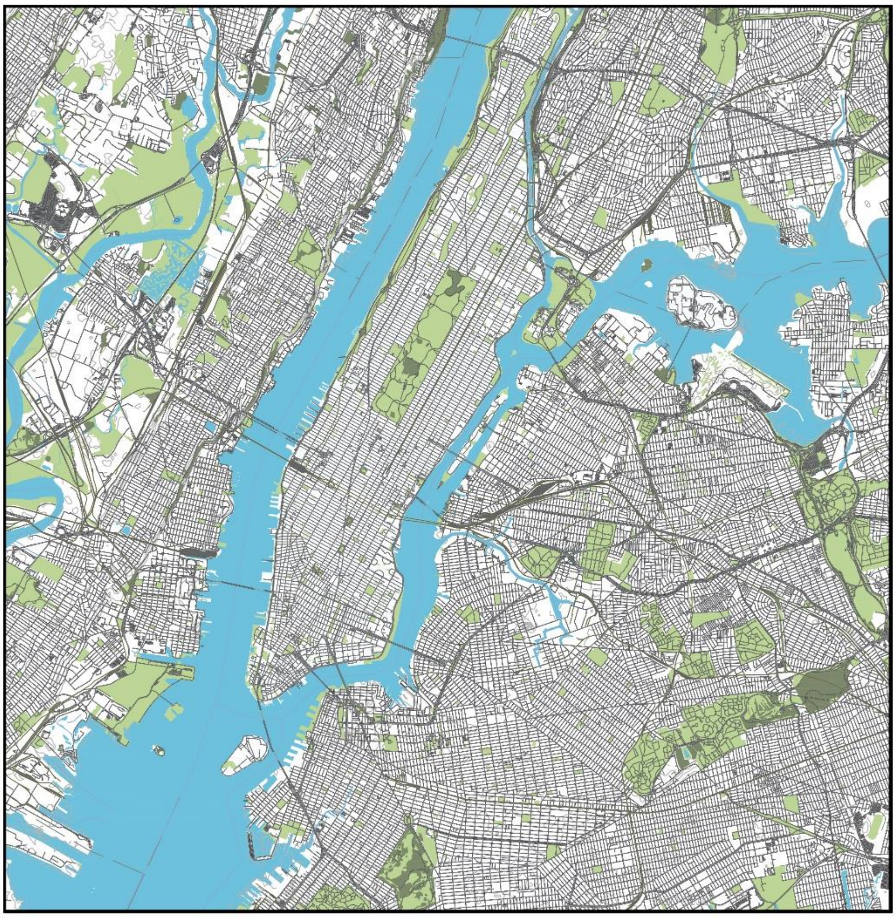


***Figure 11.*** New York city's Map

Athens, the ancient city located in Southeast Europe, characterized by unique and modern architecture, is also facing the challenges of rapid urbanization. With a dense population and limited infrastructure, Athens faces every day polluted air and climate changes with a significant rise in temperatures. The thousand-years-old historical areas of Athens are being threatened by the rapid growth of the population and its demand for new buildings. (*Figure 13)* show Athens city’s map, making it clear how dense it is and how little greenery there is in relation to the buildings that cover the city. Located in an imbalance between the historical and the modern area, Athens needs an innovative solution. According to Worldometer (2024) statistics, 86% of the Greek population lives in urban areas (Worldometer, 2024). The trends in the population graph show that the population in Athens will continue to grow (*Figure 12*).

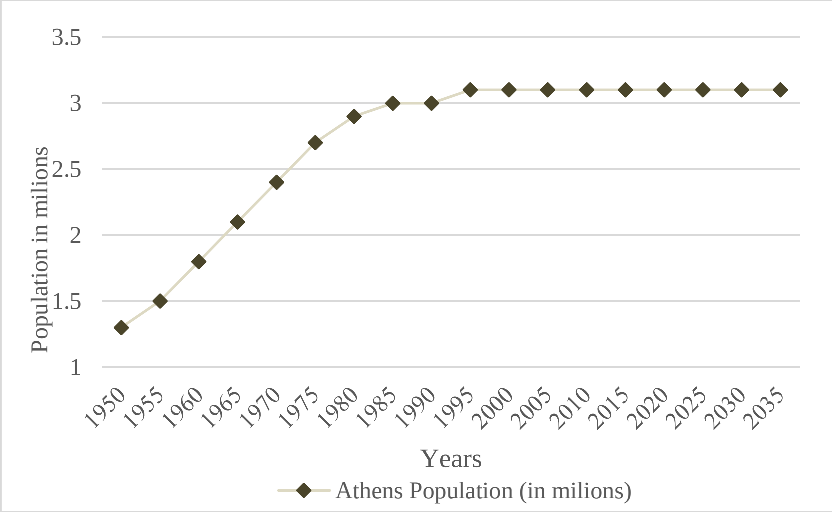



***Figure 12.*** Athens city population data

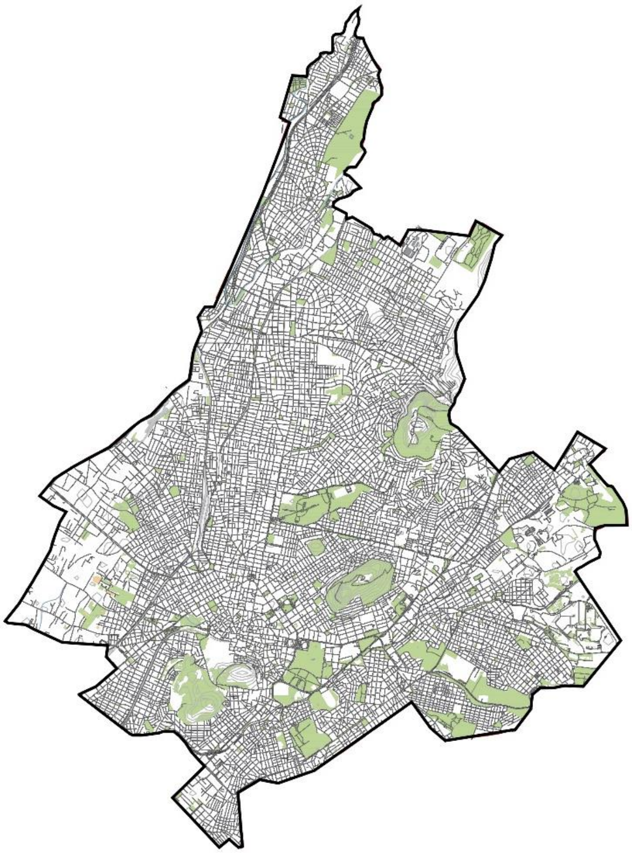


***Figure 13.*** Athens city's map

Berlin, located in the central Europe, a city with its rich history and culture, is also facing the increasing challenges of urbanization and climate change. According to Worldometer (2024) statistics 77% of the German population lives in urban areas. This population growth, shown in urban intensification, is threatening the historical areas of the city and their identity. Berlin is also facing numerous climate changes and extreme weather conditions, creating an imbalance between historic and modern buildings.

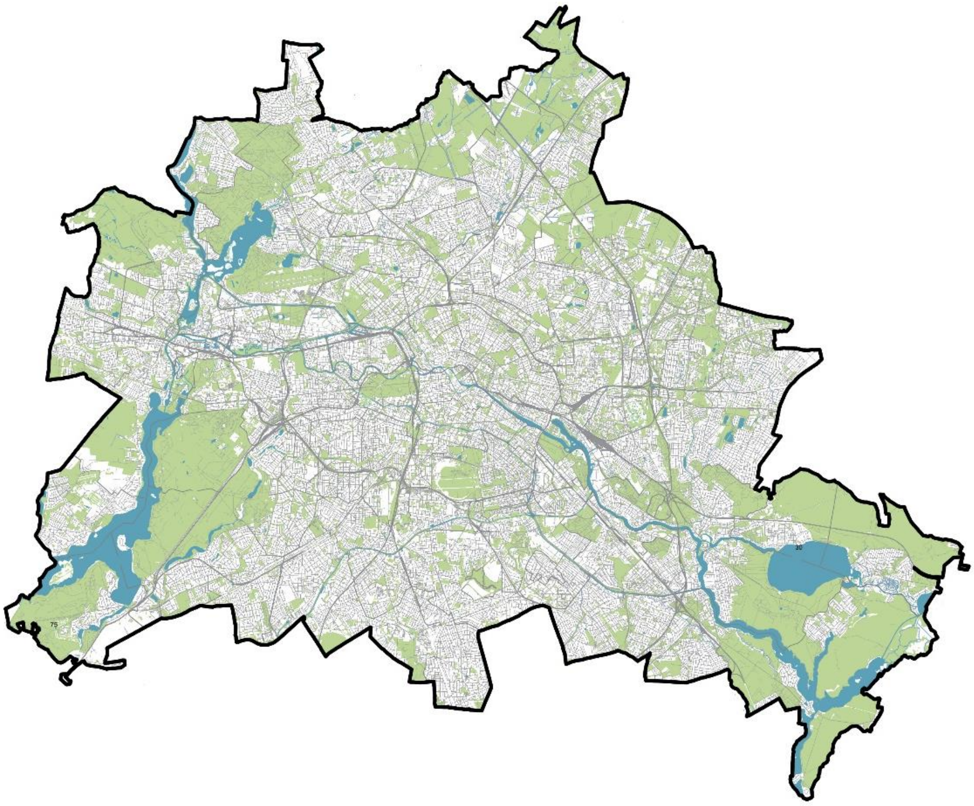


***Figure 14.*** Berlin city's map

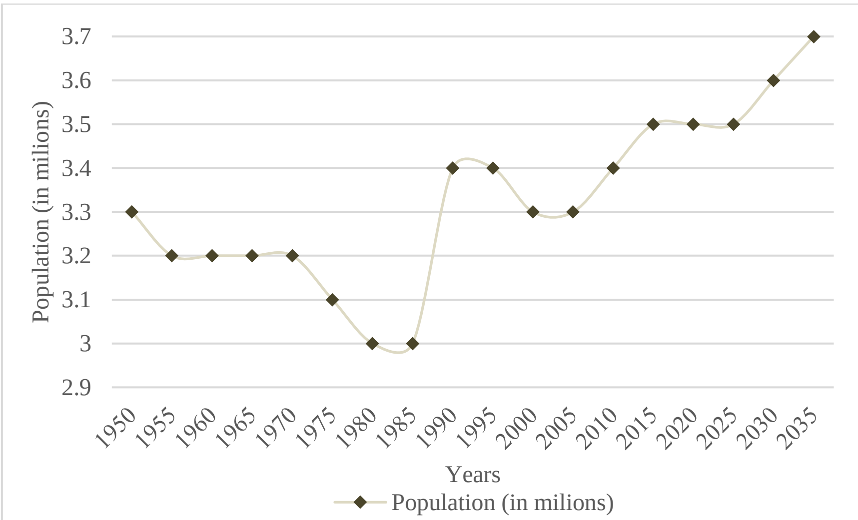



***Figure 15.*** Berlin population data

To conclude, the three selected cities are facing the challenges of urbanization, climate change, population growth, energy consumption, the threat of historical sites and the lack of green areas. The expansion of underground cities can be seen as the most sustainable solution to face all challenges.

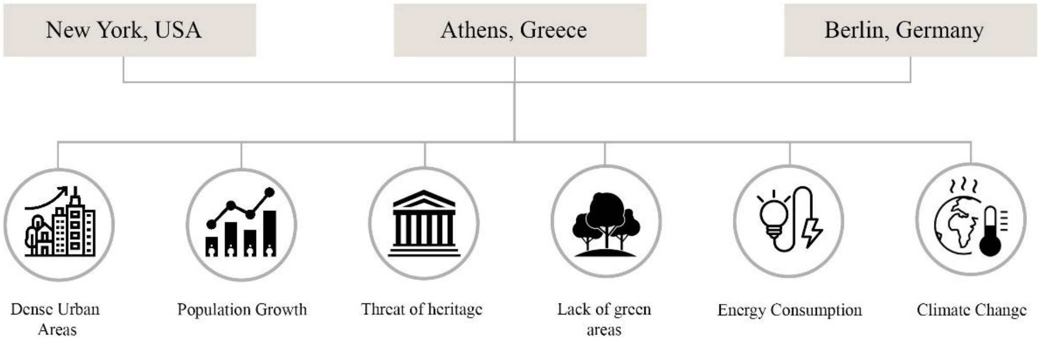



***Figure 16.*** Urban challenges of the selected cities

## 3.3 Climate characterization

In order to facilitate the accurate generation of energy performance assets of underground spaces, this study aims to get a more complete understanding by considering different climates in different areas of the globe. In order to have the most accurate results, it is important to provide a detailed description and assessment of the climatic conditions of the selected areas. In this way, these data create a strong basis for all the analyzes that will be carried out. For this purpose, Meteonrom 7.2 is used as the main software to generate accurate data on regional weather and climate patterns. By using this method, it is certain that the climate descriptions are based on current data, having the most accurate meteorological aspects to develop the analyses.

The cities chosen to perform the meteorological analysis and study are New York in the United States, Athens in Greece, and Berlin in Germany. It was crucial to consider a wide range of climatic aspects unique to each site that affected the selection of these regions. Also, these areas are included in this study, as they are areas that have a significant impact on global problems, the demand for energy, energy consumption and the release of carbon dioxide into the atmosphere. The findings of this study can offer perspectives that can help shape sustainable building practices and regulations in these areas and beyond.

### 3.3.1 New York, USA

New York climate is considered by Köppen-Geiger climate classification system as Cfa, which stands for humid subtropical climate, with some parts of the city standing as Dfa, humid continental climate. Humid subtropical climate is characterized by high humidity, mild temperatures throughout the year, with hot summers and cold winters. The rainfall is spread throughout the year, with summers having heavier rainfalls due to convective thunderstorms. The city has an average temperature of 26.1$^{o}$C in July, which is the warmest month of the year, and an average temperature of -0.1$^{o}$C in January, as the coldest month of the year. New York city's annual temperature varies from 12$^{o}$C to 13 $^{o}$C.

The city's average annual global radiation is 166 kWh/m$^2$, with 166 kWh/m$^2$ of beam radiation and 75 kWh/m$^2$ of diffuse radiation horizontal. The average temperature throughout the year is 13.5 $^{o}$C, and the average relative humidity of 61%. The average annual air pressure of New York is 1012 hPa, and the wind speed ranges from 3.1 m/s in July and August to 4.3 m/s in January, February, March and December. The direction of the wind throughout the year is from west to east.

Due to its location and climate characteristics, New York, experiences several climate events throughout the year, such as: storms, snow, thunderstorms, rain showers, etc. During the whole year, the precipitation is spread in all months, with an average of 101.6 cm of rain and 177.8 cm of snow annually. (*Figure 17)* presents a monthly chart of the air temperature and global radiation data.

In overall, New York can be characterized as having a moderate to high solar radiation, with the highest value in July and the lowest in January. But, despite some varieties in the temperature's and radiation's values, city's climate is characterized by sunny days and warm temperatures.

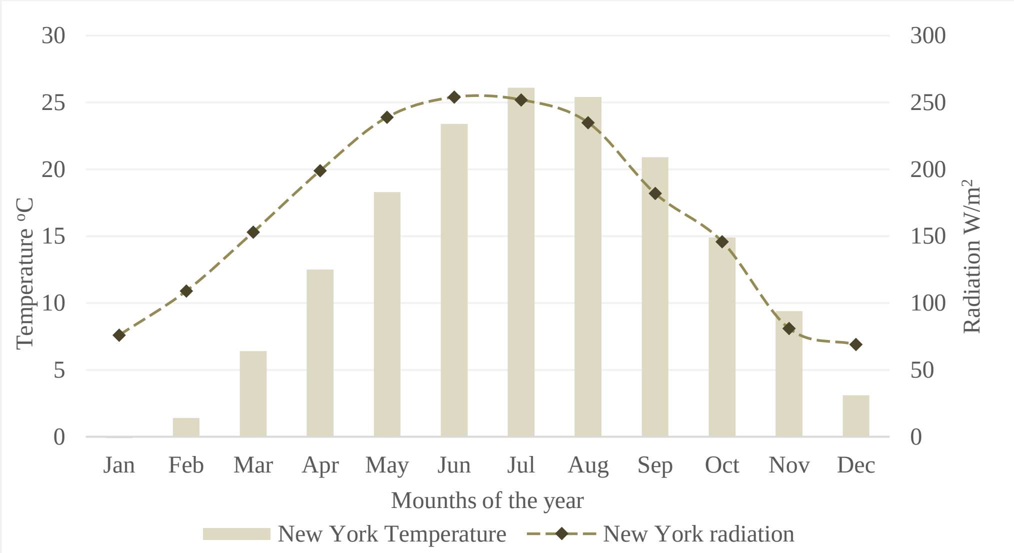



***Figure 17***. New York City's monthly weather data

### 3.3.2 Athens, Greece

Athens's climate is considered by Köppen-Geiger climate classification system as Csa, which stands for hot-summer Mediterranean climate. Mediterranean climate is characterized by hot and dry summers, mild and wet winters, and moderate temperatures throughout the year. The rainfall is spread mostly throughout the winter, practically from November to March. Summers on the other hand in Athens are mostly dry, causing droughts throughout the summer months. The city has an average temperature of 28.4°C in July, which is the warmest month of the year, and an average temperature of 10.2°C in January, as the coldest month of the year. Athens city's annual temperature is 18.7 °C.

The city's average annual global radiation is 203 W/m$^2$, with 222 W/m$^2$ of beam radiation and 72 W/m$^2$ of diffuse radiation horizontal. The average relative humidity of the city is 60%. The average annual air pressure of Athens is 1004 hPa, and the wind speed ranges from 4.0 m/s in May to 6.5 m/s in February. The direction of the wind throughout the year is from northeast to east-northeast.

Due to its location and climate characteristics, Athens, experiences several climate events throughout the year, such as: summer heatwaves, rainstorms, drought, strong winds, etc. During the whole year, city's precipitation is well-distributed, with an average of 450 mm of rain.  presents a monthly chart of the air temperature and global radiation data.

In overall, Athens can be characterized as having a medium to high solar radiation, with the highest value in June and the lowest in December. But, despite some varieties in the temperature's and radiation's values, city's climate is characterized by sunny days and hot temperatures.

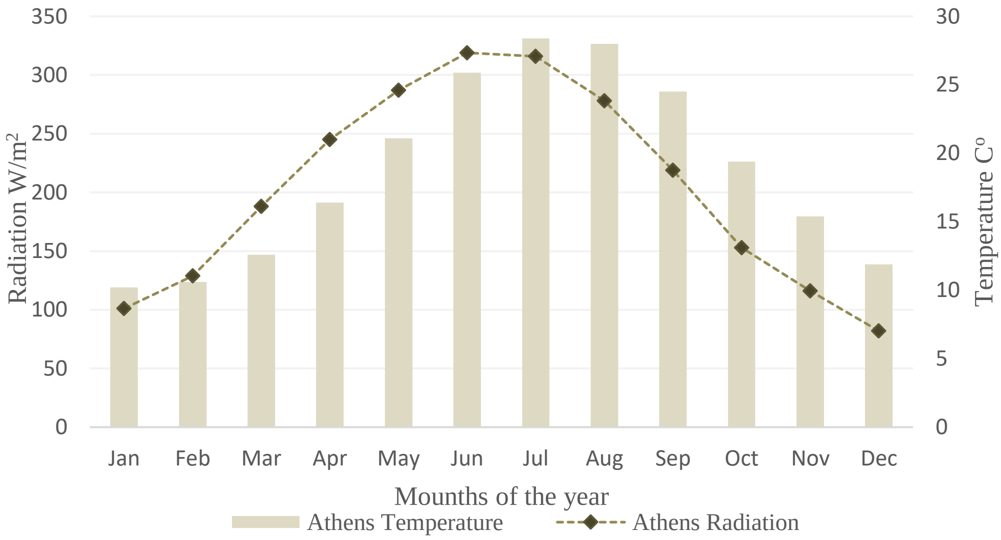



***Figure 18.*** Athens monthly weather data

### 3.2.3 Berlin, Germany

Berlin's climate is considered by Köppen-Geiger climate classification system as Cfb, which stands for oceanic climate. Oceanic climate feature cool summers and mild winters, with a narrow temperature range. The city has an average temperature of 18.7 $^{o}$C in July, which is the warmest month of the year, and an average temperature of 0.2 $^{o}$C in January, as the coldest month of the year. Berlin city's annual temperature is 9.4 $^{o}$C.

The city's average annual global radiation is 120 kWh/m$^2$, with 109 kWh/m$^2$ of beam radiation and 65 kWh/m$^2$ of diffuse radiation horizontal. The average relative humidity of the city is 65%. The average annual air pressure of Berlin is 1007 hPa, and the wind speed ranges from 3.6 m/s in February, May, and October to 6.2 m/s in March.

The direction of the wind throughout the year is headed towards east-southeast.

Due to its location and climate characteristics, Berlin, experiences several climate events throughout the year, such as: high rainfall, frequent cloud-cover, cyclonic storms, etc. During the whole year, city's precipitation is well-distributed having no dry season, with an average of 750 cm of rain and 44 cm of snow annually. (*Figure 19)* presents a monthly chart of the air temperature and global radiation data.

In overall, Berlin can be characterized as having a moderate to high solar radiation, with the highest value in July and the lowest in January. But, despite some varieties in the temperature's and radiation's values, city's climate is characterized by sunny days and warm temperatures.

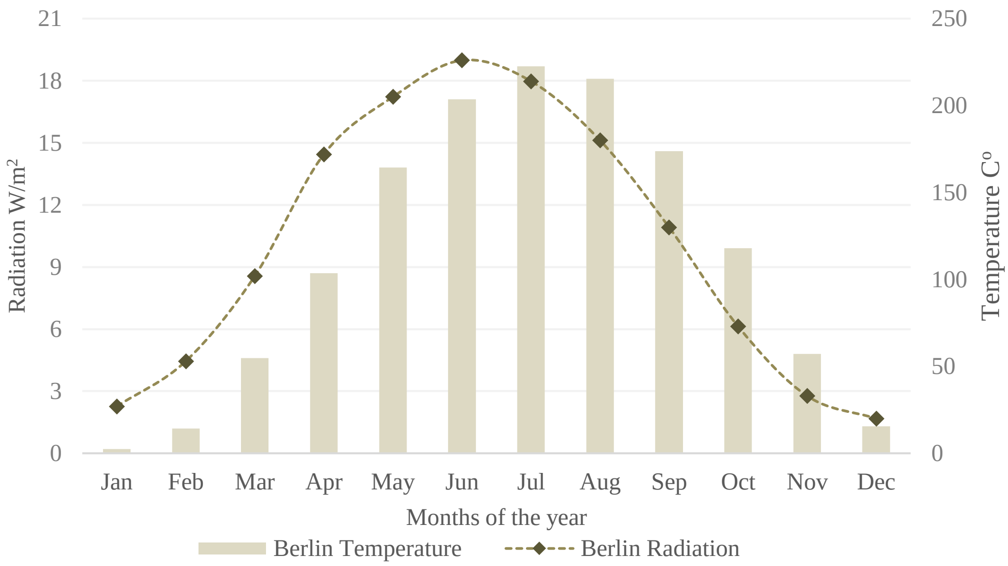



***Figure 19.*** Berlin monthly weather data

### 3.2.3 Comparison of Selected Climates

The cities studied, New York, Berlin and Athens, have distinct climates. New York has humid subtropical climate (Cfa), characterized by hot summers, mild to cold winters, with a precipitation distributed throughout the year. Athens is categorized as Csa, characterized by hot-summer Mediterranean climate. On the other hand, Berlin has oceanic climate, characterized by cold summer, mild winter, and a narrow temperature range. New York has a relatively even distribution of precipitation throughout the year, while Athens experiences more rainfall during the winter seasons, but summer experiences a dry season. Berlin, on the other hand, experiences moderate precipitation levels. The warmest month for New York City is July, with an average temperature of 26.1 $^{o}$C. Athens reaches the highest temperature of the year during the month of July, with an average temperature of 28.4 $^{o}$C. The coldest month for both cities is January, although there is a difference of 11.2 $^{o}$C, since the lowest average temperature for New York is -1 $^{o}$C, while for Tokyo it is 10.2 $^{o}$C. Berlin, compared to the other two cities, has lower temperatures throughout the year, with July being the warmest month of the year, reaching an average temperature of 18.7 $^{o}$C, and January being the coldest month of the year reaching an average temperature of 0.2 $^{o}$C. *(Figure 20)* presents a comparison of the monthly air temperature. In terms of radiation, New York and Athens have higher levels of solar radiation throughout the year compared to Berlin. Athens has the highest annual global radiation average, followed by New York and Berlin.

Despite the differences between each other, all three cities have their own unique climatic characteristics. New York, experiences several climate events throughout the year, such as: storms, snow, thunderstorms, rain showers; while Athens experiences summer heatwaves, rainstorms, drought, strong winds. Berlin, on the other hand, experiences high rainfall, frequent cloud-cover, cyclonic storms.

Overall, the different climatic characteristics of those cities have significant importance for energy performance, soil features and temperatures, as well as local lifestyle.

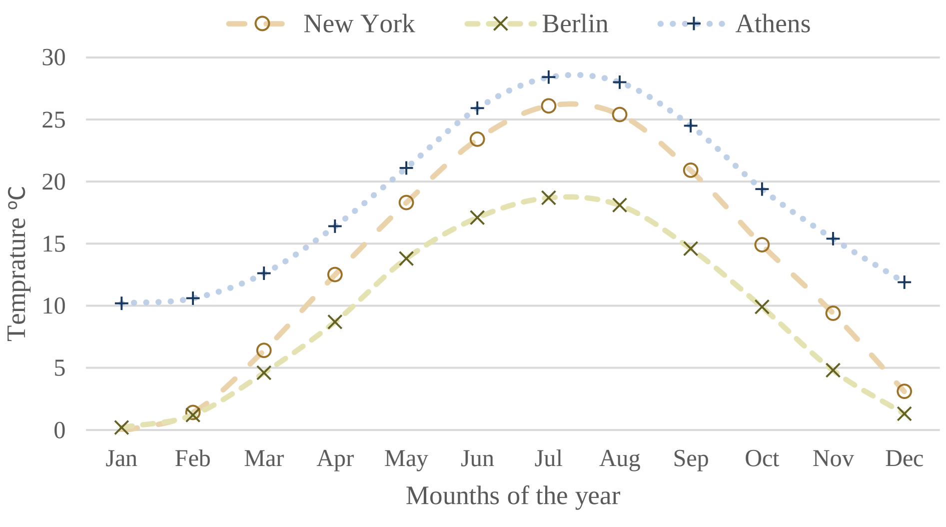



***Figure 20.*** Weather data comparison.

## 3.4 Morphologies

The level of life, the number of inhabitants, the challenges of living underground, the climatic zone and the context are the factors that determine the choice of morphology for the development of this study. The selection criterion for the development of morphologies is the presence of innovative spaces that meet all the living conditions for the underground. Since the underground has many challenges related to the lack of lighting, ventilation and causing psychological consequences for the users of these spaces (Shan, Hwang, & Wong, 2017), 5 morphologies with courtyards have been proposed. These morphologies are: square morphology, rectangular morphology with 1:2 ratio; the rectangular morphology with 2:3 ratio, the circular morphology with a courtyard radius of 30m, and the circular morphology with a courtyard radius of 40m, as shown in (*Figure 21).* Courtyards serve to bring light to the interior spaces, to enable natural ventilation, to simplify mechanical ventilation and to avoid the psychological consequences that may come as a result of using the spaces, without the aforementioned conditions. The interior and exterior layouts are not intended to be ground-breaking, but rather to present a hypothetical scenario of commonly used designs in the region. All morphologies are designed in 4 different heights: 4 floors, 6 floors, 8 floors and 10 floors; three different WWR and different balcony widths. The plans of each have differences in the surface, but all the apartments have the same typology of apartments.

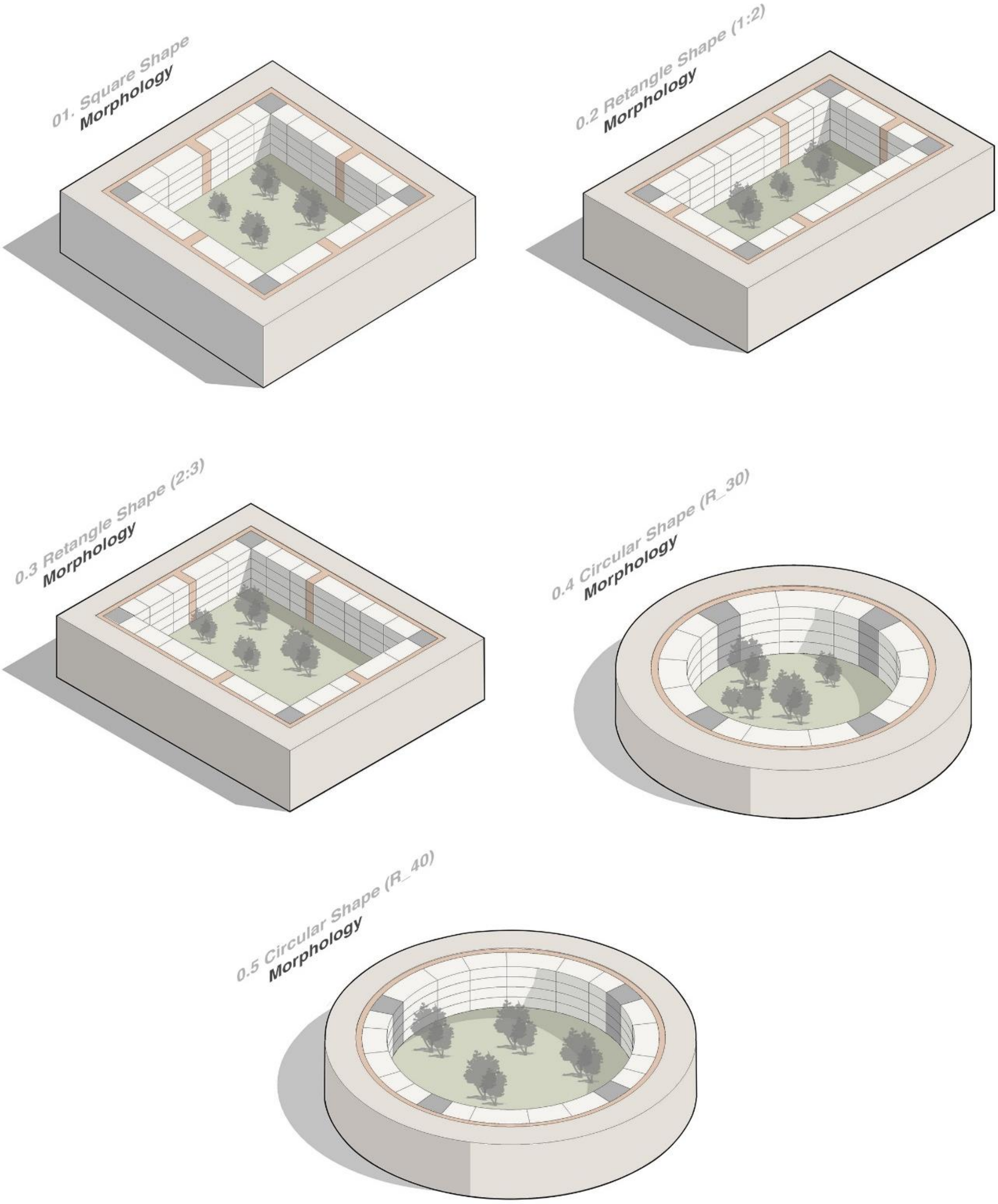



***Figure 21.*** Underground Building Morphologies

### 3.4.1 Circular Morphology (30m radius)

The fourth morphology is circular shape plan, with a courtyard. The ground floor is dedicated to parking, while the other floors are residential. The courtyard geometry is kept clean, and its radius is 30m.

The total floor area is 2200 m$^2$. In total there are 14 apartments per floor (***Error! Reference source not found.***). 28% or 4 apartments are of the 1+1 typology. 50% or 7 apartments are of the 2+1 typology. 22% or 3 apartments are of the 3+1 typology (***Error! Reference source not found.***).


***Figure 22.*** CI_R30 morphology layout.

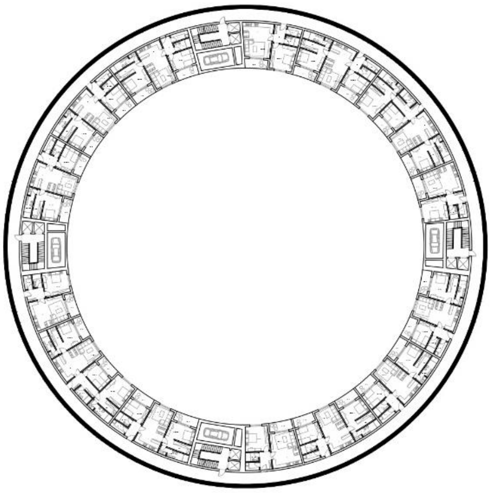


***Figure 23***. CI_R30 morphology typical floor plan.

The morphology is developed in 4 different heights, 4 floors, 6 floors, 8 floors and 10 floors. The height of the floor is 4 m. The design of the interior spaces is simple, and the arrangement is similar to the commonly used domestic concepts within the context.

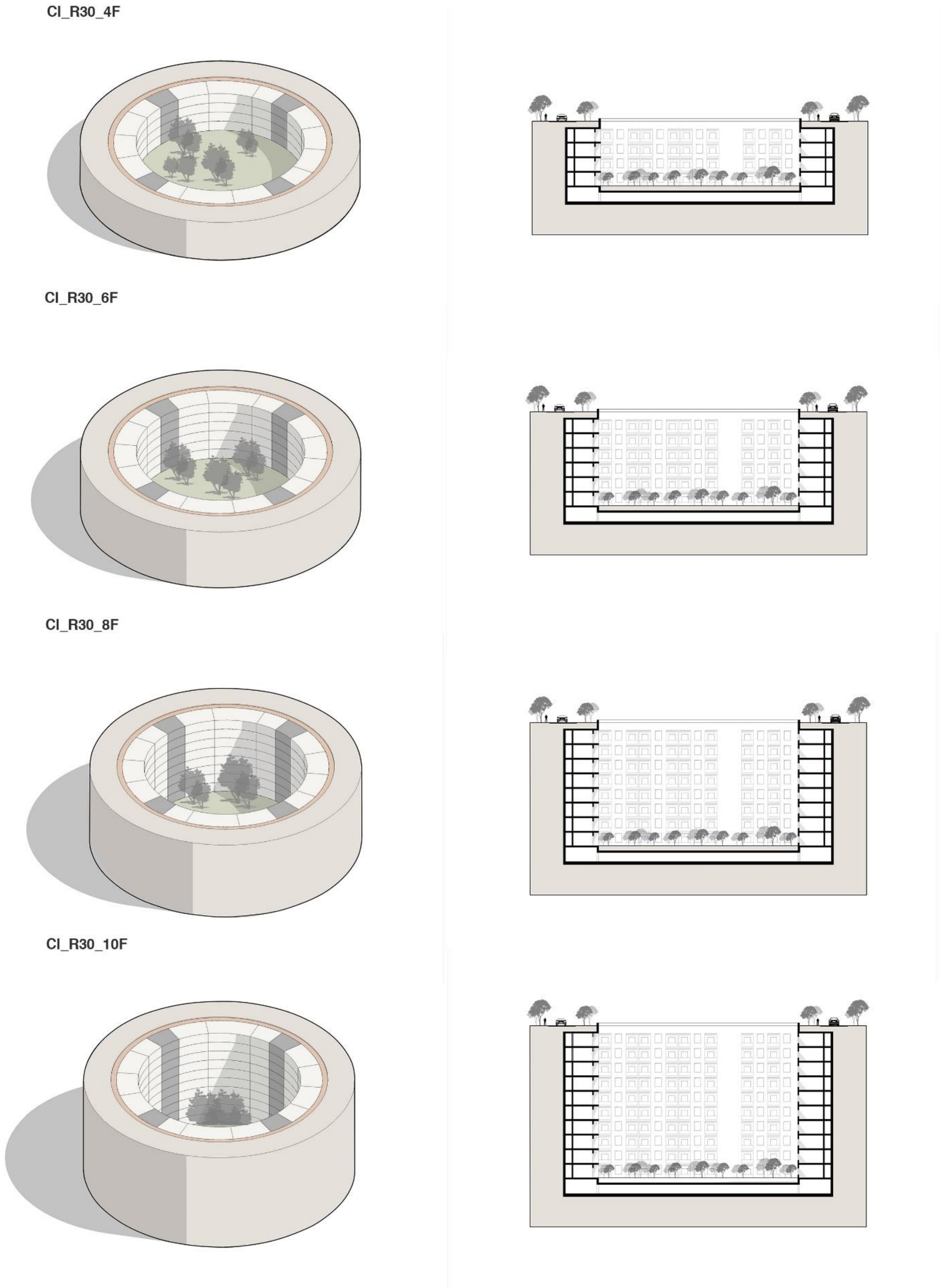



***Figure 24***. Circular (30m radius) morphology

### 3.4.2 Square Morphology

The first morphology is square shape plan, with a courtyard. The ground floor is dedicated to parking, while the other floors are residential. The courtyard geometry is kept clean, and its dimensions are 60 x 60 m.

The total floor area is 2800 m$^2$. In total there are 20 apartments per floor (*Figure 25*). 40% or 8 apartments are of the 1+1 typology. 40% or 8 apartments are of the 2+1 typology. 20% or 4 apartments are of the 3+1 typology (*Figure 27).*


***Figure 25.*** SQ Morphology layout

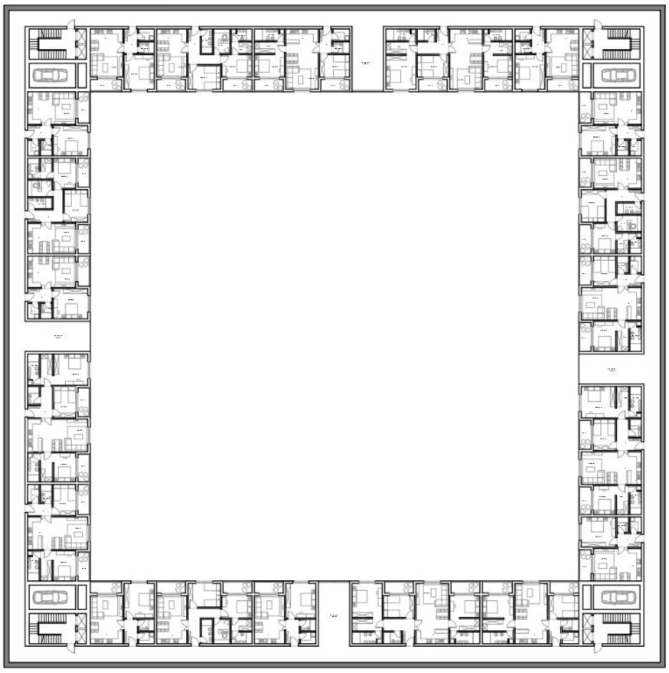


***Figure 26.*** SQ morphology typical floor plan

The morphology is developed in 4 different heights, 4 floors, 6 floors, 8 floors and 10 floors (*Figure 27*). The height of the floor is 4 m, so that the interior spaces are spacious. The design of the interior spaces is simple, and the arrangement is similar to the commonly used domestic concepts within the context.

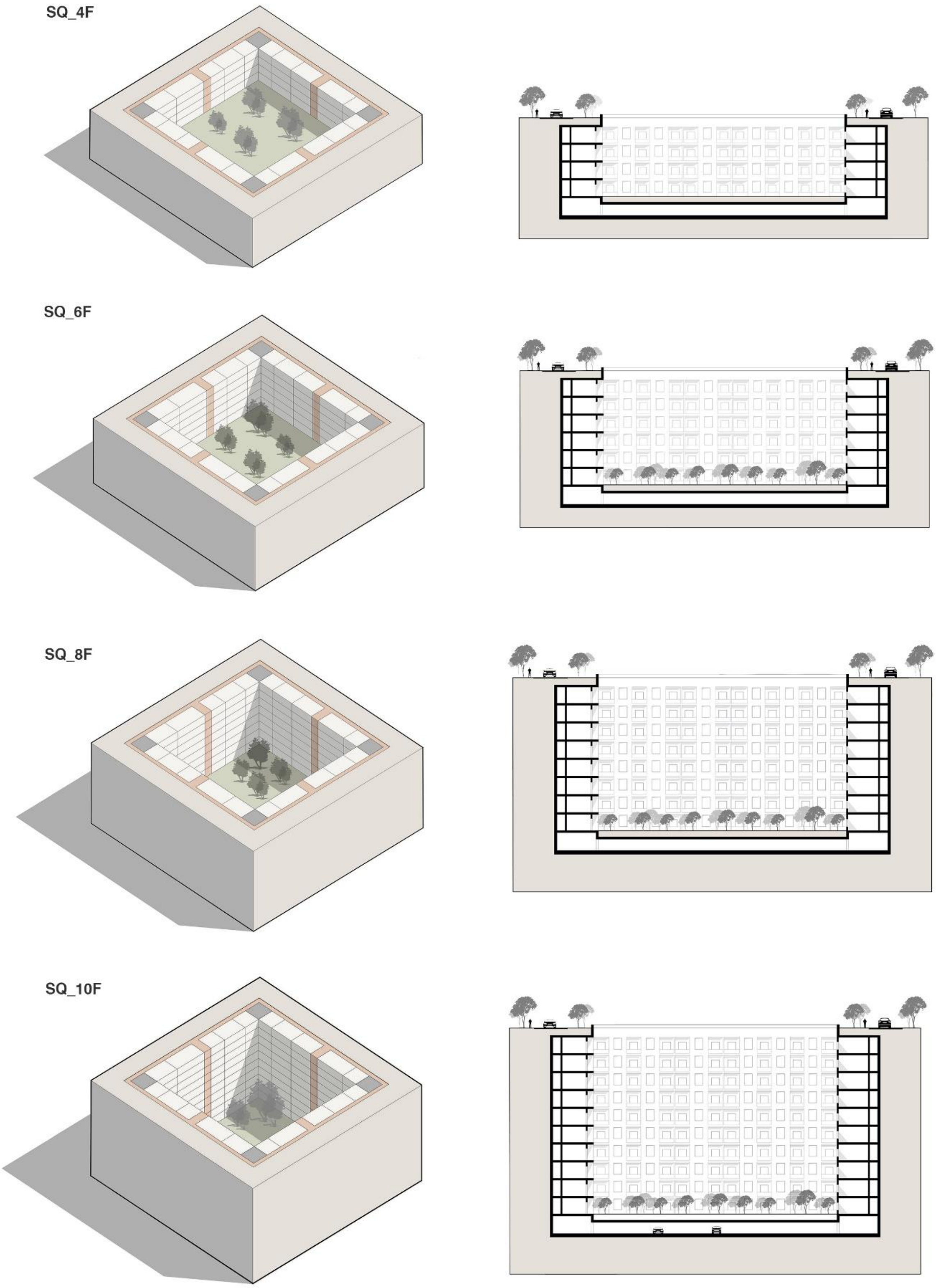



***Figure 27.*** Square morphology

### 3.4.3 Rectangle Morphology (1:2 ratio)

The second morphology is rectangle shape plan, with a courtyard. The ground floor is dedicated to parking, while the other floors are residential. The courtyard geometry is kept clean, with a 1:2 ratio, and its dimensions are 40 x 80 m.

The total floor area is 2800 $m^2$. In total there are 20 apartments per floor (*Figure 28*). 40% or 8 apartments are of the 1+1 typology. 40% or 8 apartments are of the 2+1 typology. 20% or 4 apartments are of the 3+1 typology (*Figure 29*).


***Figure 28.*** RC_1:2 morphology layout

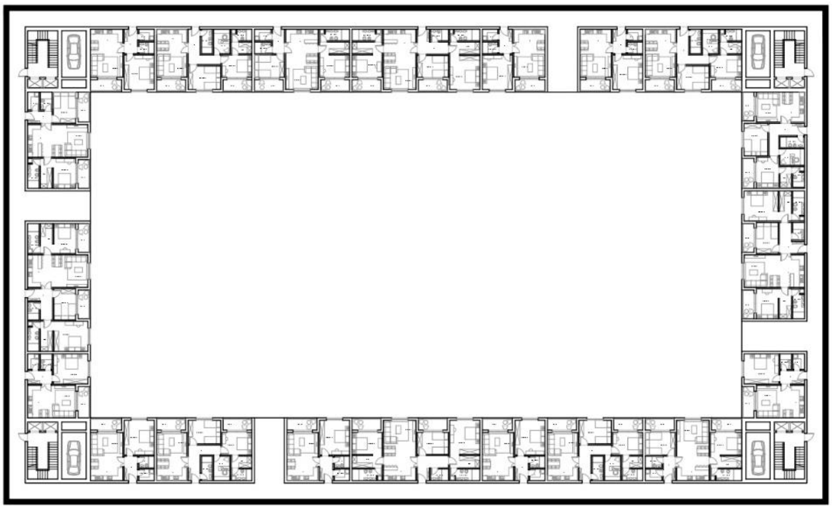


***Figure 29.*** RC_1:2 morphology typical floor plan

The morphology is developed in 4 different heights, 4 floors, 6 floors, 8 floors and 10 floors (*Figure 30*). The height of the floor is 4 m, so that the interior spaces are spacious. The design of the interior spaces is simple, and the arrangement is similar to the commonly used domestic concepts within the context.

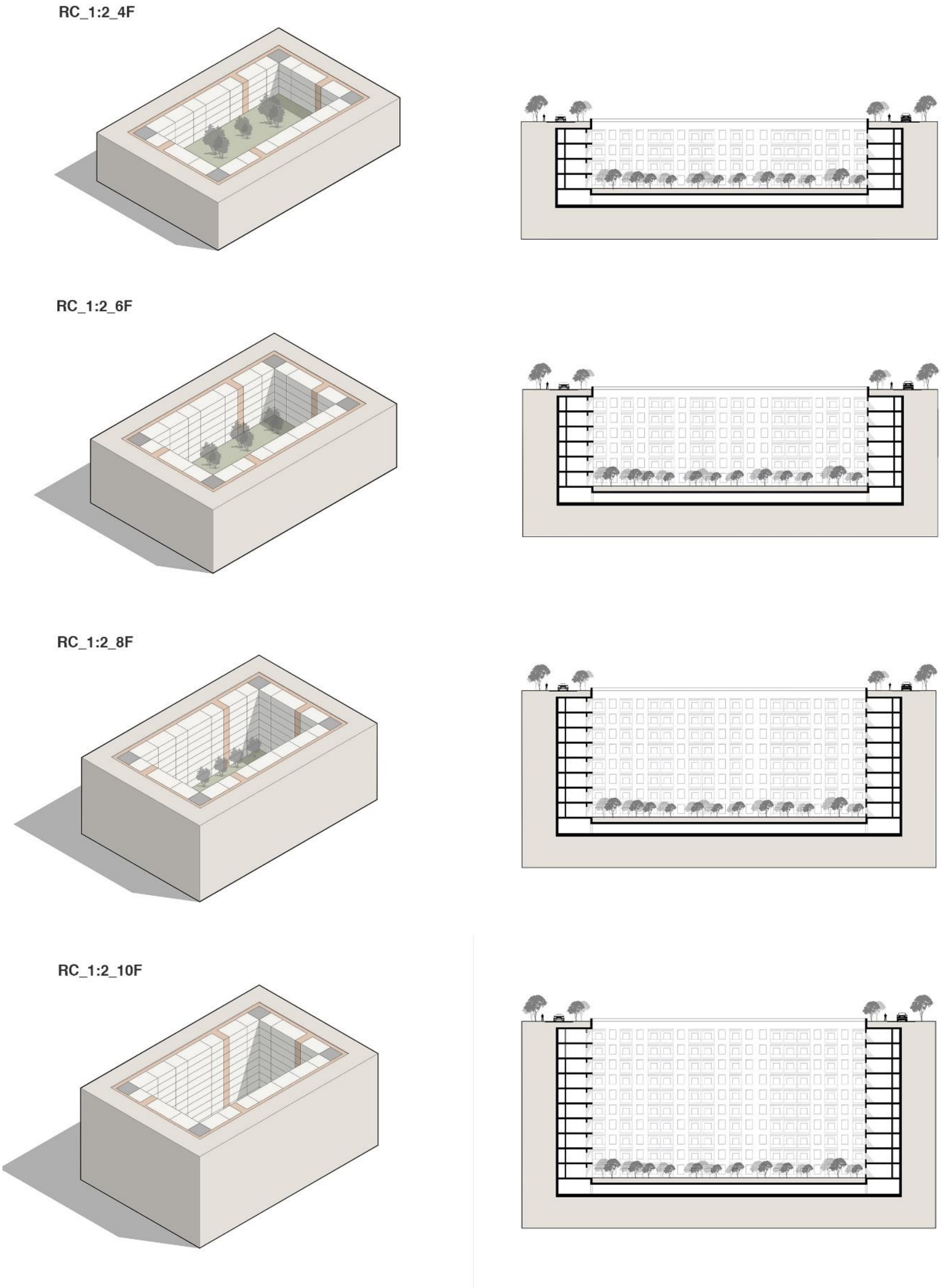



***Figure 30.*** Rectangle (1:2 ratio) morphology

### 3.4.4 Circular Morphology (40m radius)

The fifth morphology is circular shape plan, with a courtyard. The ground floor is dedicated to parking, while the other floors are residential. The courtyard geometry is kept clean, and its radius is 40m.

The total floor area is 2800 $m^2$. In total there are 19 apartments per floor (*Figure 37*). 36% or 7 apartments are of the 1+1 typology. 43% or 8 apartments are of the 2+1 typology. 21% or 4 apartments are of the 3+1 typology (*Figure 38*).

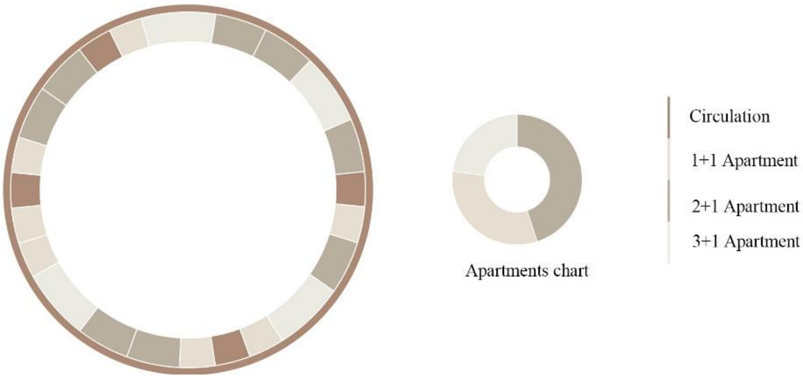



***Figure 31***. CI_R40 morphology layout

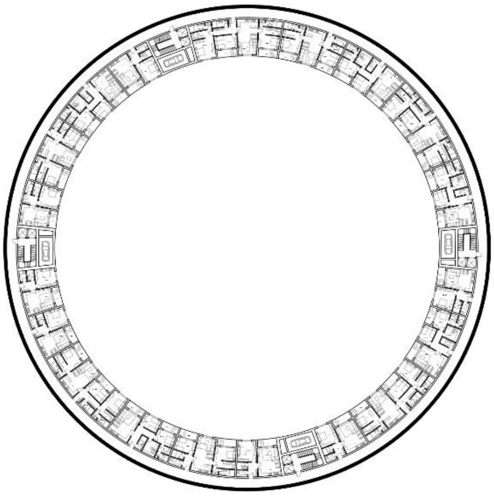


***Figure 32.*** CI_R40 morphology typical floor plan

The morphology is developed in 4 different heights, 4 floors, 6 floors, 8 floors and 10 floors (*Figure 39*). The height of the floor is 4 m, so that the interior spaces are spacious. The design of the interior spaces is simple, and the arrangement is similar to the commonly used domestic concepts within the context.

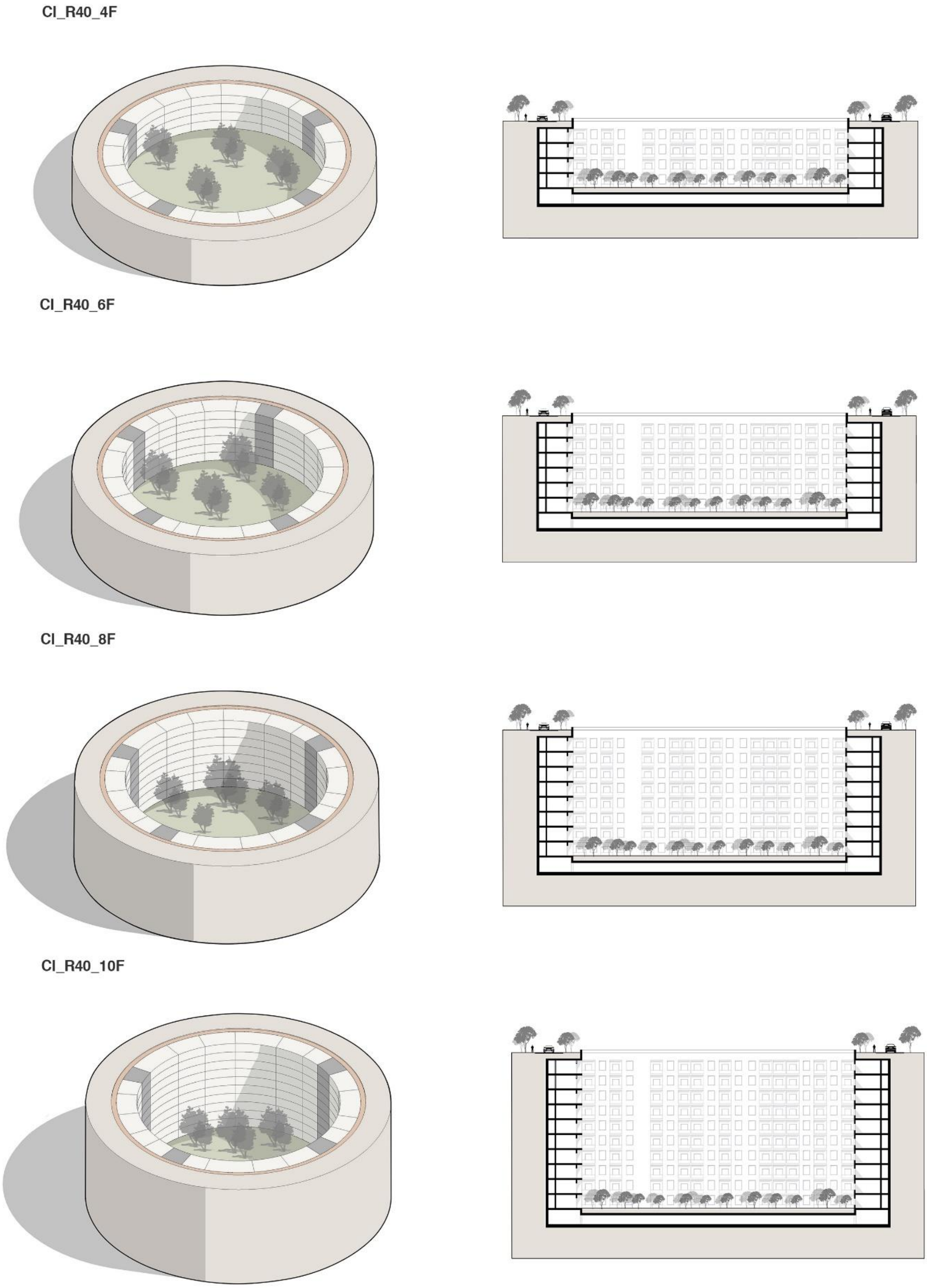



***Figure 33.*** Circular (radius 40m) morphology

### 3.4.5 Rectangle Morphology (2:3 ratio)

The third morphology is rectangle shape plan, with a courtyard. The ground floor is dedicated to parking, while the other floors are residential. The courtyard geometry is kept clean, with a 2:3 ratio, and its dimensions are 60 x 80 m.

The total floor area is 3200 m$^2$. In total there are 22 apartments per floor ***(Error! Reference source not found.)***. 36% or 8 apartments are of the 1+1 typology. 45% or 10 apartments are of the 2+1 typology. 19% or 4 apartments are of the 3+1 typology (***Error! Reference source not found.***).


***Figure 34.*** RC_2:3 morphology layout

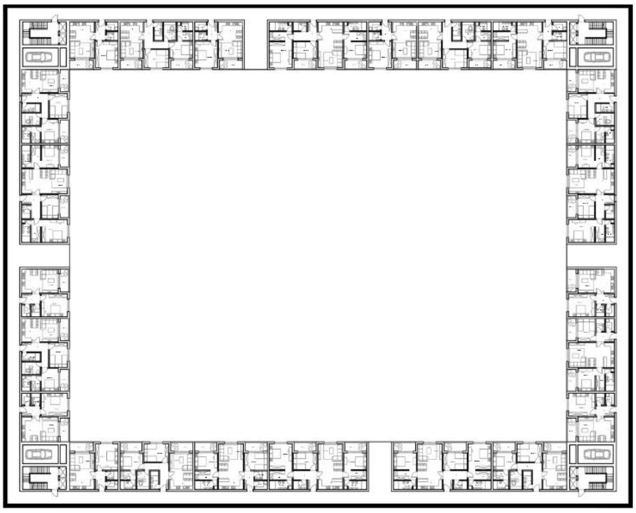


***Figure 35.*** RC_2:3 morphology typical floor plan

The morphology is developed in 4 different heights, 4 floors, 6 floors, 8 floors and 10 floors (***Error! Reference source not found.***). The height of the floor is 4 m, so that the interior spaces are spacious. The design of the interior spaces is simple, and the arrangement is similar to the commonly used domestic concepts within the context.

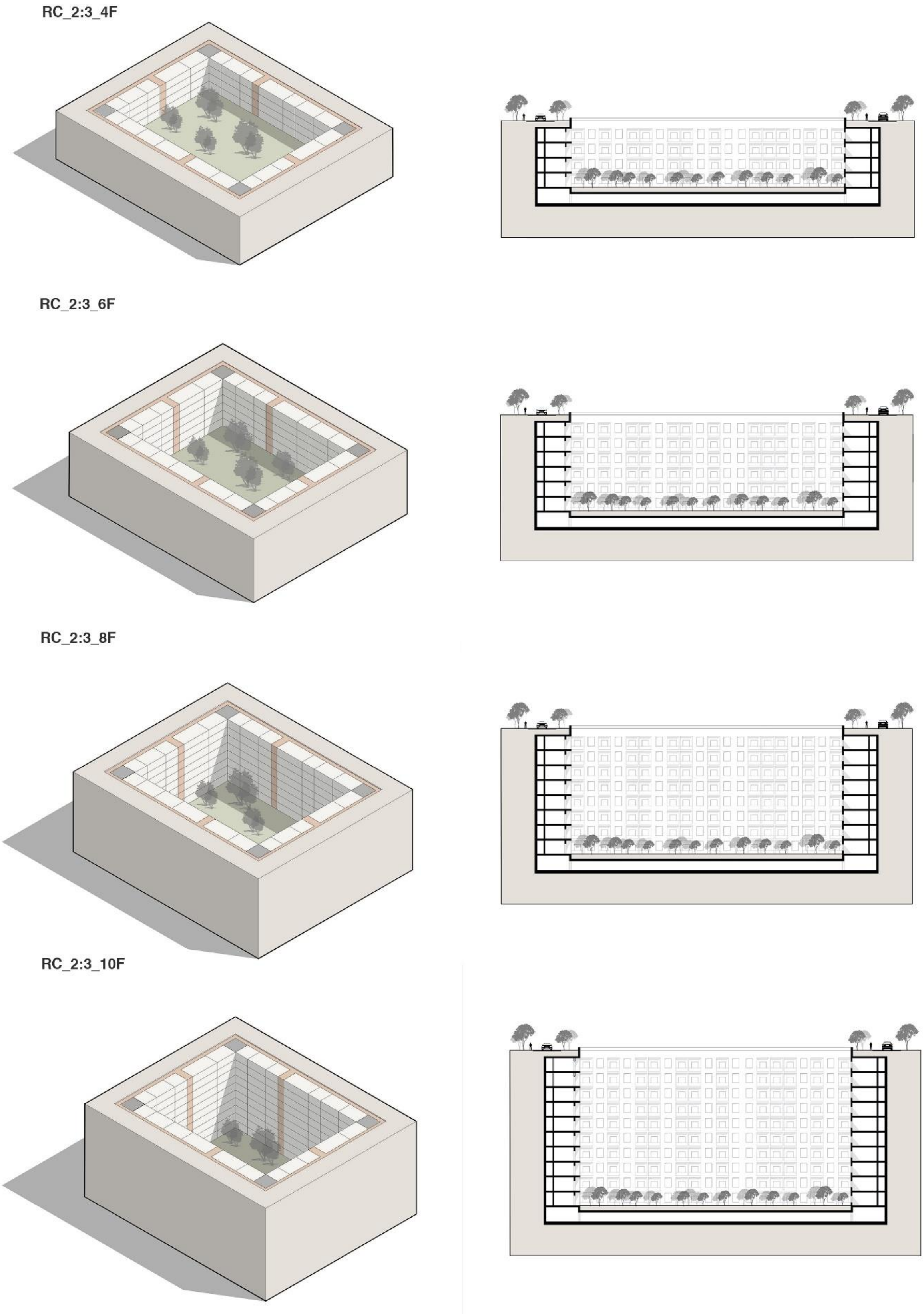



***Figure 36.*** Rectangle (2:3 ratio) morphology.

### 3.4.5 Circular Morphology (40m radius)

The fifth morphology is circular shape plan, with a courtyard. The ground floor is dedicated to parking, while the other floors are residential. The courtyard geometry is kept clean, and its radius is 40m.

The total floor area is 2800 $m^2$. In total there are 19 apartments per floor (*Figure 37*). 36% or 7 apartments are of the 1+1 typology. 43% or 8 apartments are of the 2+1 typology. 21% or 4 apartments are of the 3+1 typology (*Figure 38*).

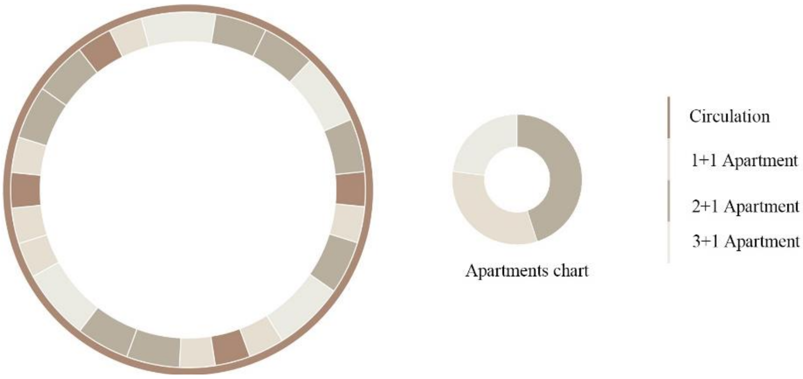



***Figure 37***. CI_R40 morphology layout

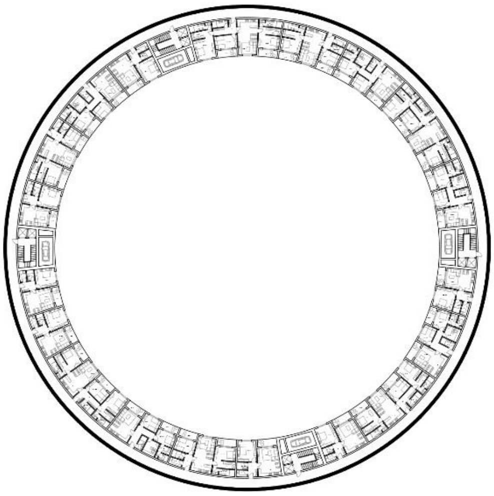


***Figure 38.*** CI_R40 morphology typical floor plan

The morphology is developed in 4 different heights, 4 floors, 6 floors, 8 floors and 10 floors (*Figure 39*). The height of the floor is 4 m, so that the interior spaces are spacious. The design of the interior spaces is simple, and the arrangement is similar to the commonly used domestic concepts within the context.

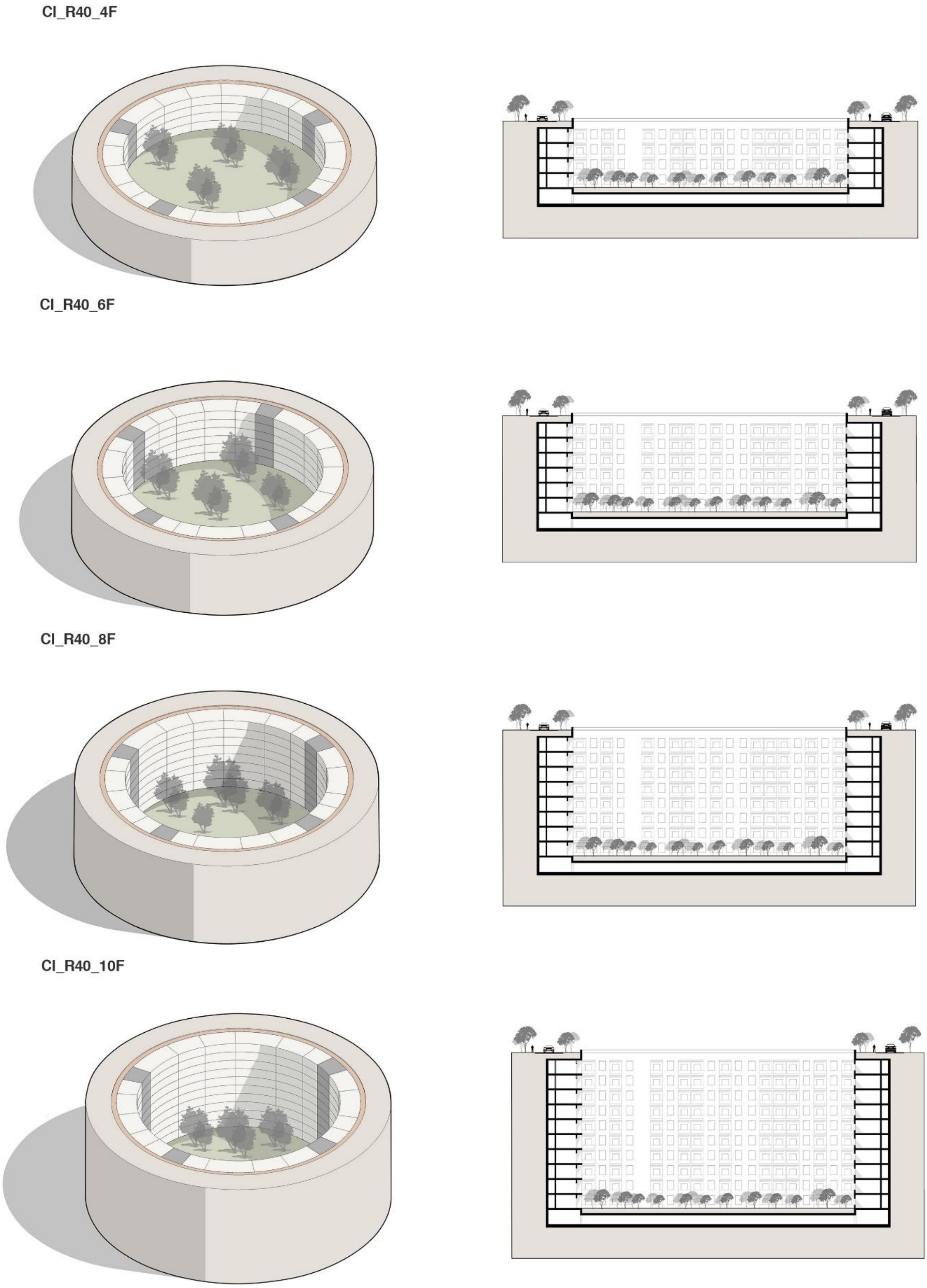



***Figure 39.*** Circular (radius 40m) morphology

### 3.4.6 Apartments' typology

For the development of the floor plans of each morphology, a 1+1 typology, two 2+1 typologies and a 3+1 typology have been designed. These apartments are spacious, to soften the effect of being underground. Due to the location underground, the apartments are all oriented to one side.

#### 3.4.6.1 One-bedroom apartment

One-bedroom apartment is organized into one living room and kitchen, one bedroom, one toilet and a laundry. The total area of the apartment is $60m^2$ and it has a depth of 8 meters (*Figure 40*).

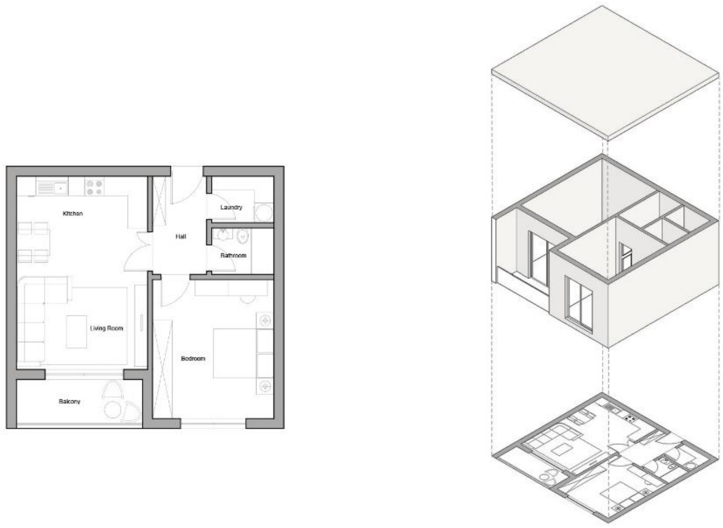



***Figure 40.*** 1+1 apartment typology

#### 3.4.6.2 Two-bedroom apartments

For these typical floor plans, two two-bedroom typology apartments have been designed. The first apartment is organized in a living room and kitchen, a master bedroom with a walk-in closet and an en-suite bathroom, a double bedroom, a toilet and an office (*Figure 41*).

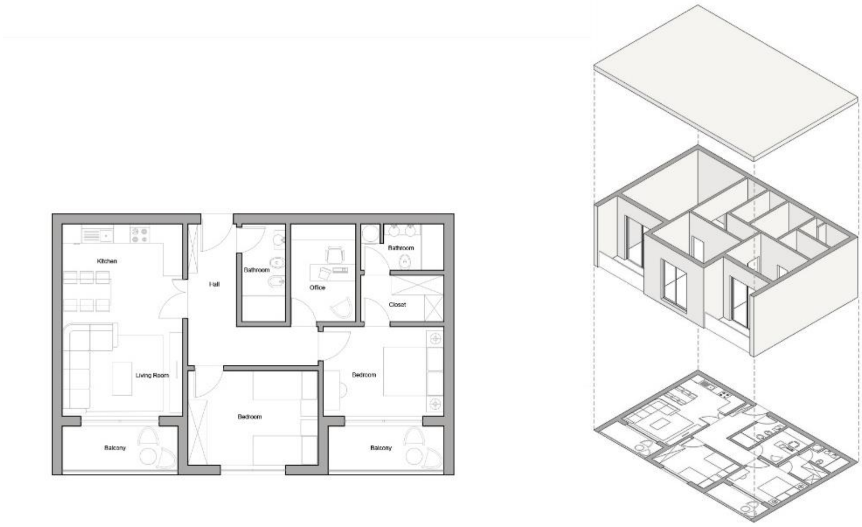



***Figure 41.*** 2+1 apartment typology

The second apartment is organized into a living room and kitchen, a master bedroom with a walk-in closet and an en-suite bathroom, a double bedroom, a toilet and laundry space (*Figure 42*).


***Figure 42***. 2+1 apartment typology

Of all the spaces, the living room with the kitchen, and the two bedrooms receive natural light. The total area of both apartments is $96m^2$ and they have a depth of 8 meters.

### 3.4.6.2 Three-bedroom apartments

Three-bedroom apartment is organized into one living room and kitchen, one master bedroom with a walk-in closet and an en-suite bathroom, one bedroom with a walk-in closet and a en-suite bathroom and one double bedroom, one toilet and a laundry. The total area of the apartment is 128m$^2$ and it has a depth of 8 meters (*Figure 43*).


***Figure 43.*** 3+1 apartment typology

## 3.5 Relative Compactness (RC)

Many studies have examined how the shape of a building has a great importance in its energy performance. Various studies have investigated how the morphology of a building, specifically relative compactness, has influenced energy efficiency. Relative compactness is defined as the ratio of the volume (V) to the external wall surface (A) of the building by *Equation 18* (Ourghi, Al-Anzi , & Krarti, 2007).

$$RC = 6 \times V^{0.66} \times A^{-1} \qquad \text{(Eq 18)}$$

Ourghi, Al-Anzi & Krarti (2007) have developed a study to predict the impact of the building form on annual cooling and heating. Their results showed that the more compact a building is, the lower the annual cooling and heating demands are (Ourghi, Al-Anzi , & Krarti, 2007). Roaf (2016), also studied the relationship of form with energy performance, focusing on winter energy needs. The author found a strong correlation between energy consumption and the shape coefficient. He concluded that the architectural design can disregard the shape of buildings in medium climates. Relative compactness is a ratio of the volume of the external walls, measuring the compactness of a building (Raof, 2016).

*Figure 44.* shows how the energy performance of five UGB morphologies has been examined in this study, using the building energy consumption formula. In order to study the overall energy consumption of morphology, the formula takes into consideration aspects such as the building envelope surface gross roof area and overall object volume. To get a result, this formula will be applied to all morphologies, considering the number of floors, allowing for a comparison of the energy efficiency of different building designs (*Table 1*).

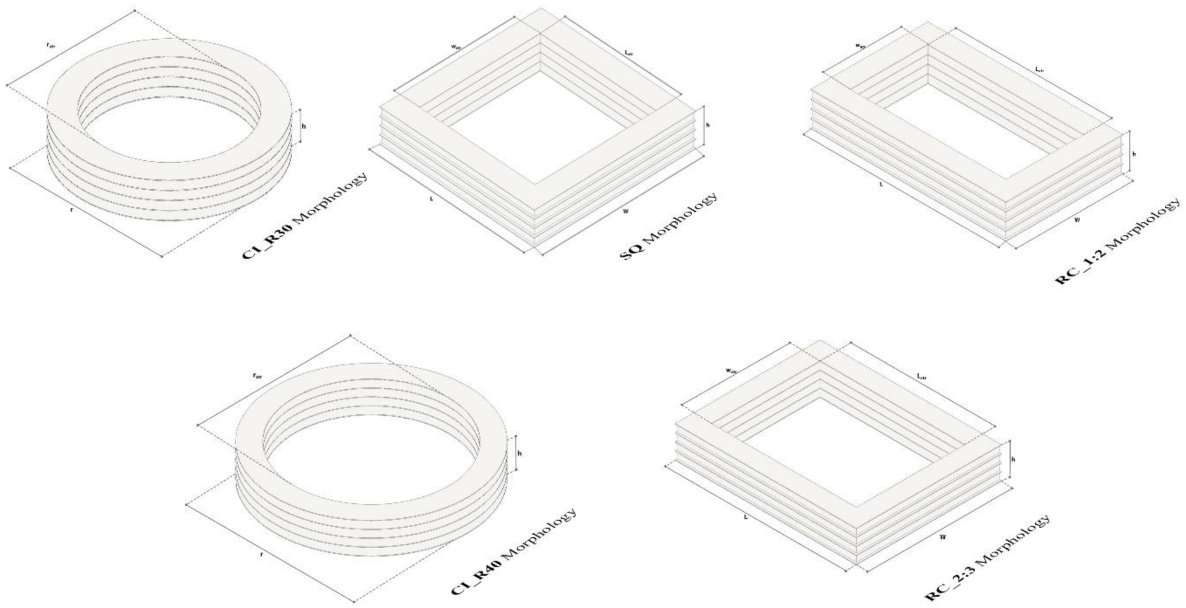



***Figure 44.*** UGB morphologies: An Illustration of RC Values and Building Dimension

***Table 2.*** Relative Compactness Calculation.

| Code | Footprint Area | Lateral Wall Surface | Area | Volume | W | $W_{atr}$ | L | $L_{atr}$ | H | RC |
|---|---|---|---|---|---|---|---|---|---|---|
| CI_R30 | 2200 | 7680 | 10416 | 35200 | r=40 | r=30 | | | 16 | **0.58** |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| SQ | 2800 | 7680 | 13280 | 44800 | 80 | 80 | 80 | 60 | 16 | **0.53** |
| RC_1:2 | 2800 | 7680 | 13280 | 44800 | 100 | 80 | 60 | 40 | 16 | **0.53** |
| CI_R40 | 2800 | 7680 | 44800 | 44800 | r=50 | r=40 | | | 16 | **0.52** |
| RC_2:3 | 3200 | 7680 | 14080 | 51200 | 100 | 80 | 80 | 60 | 16 | **0.50** |

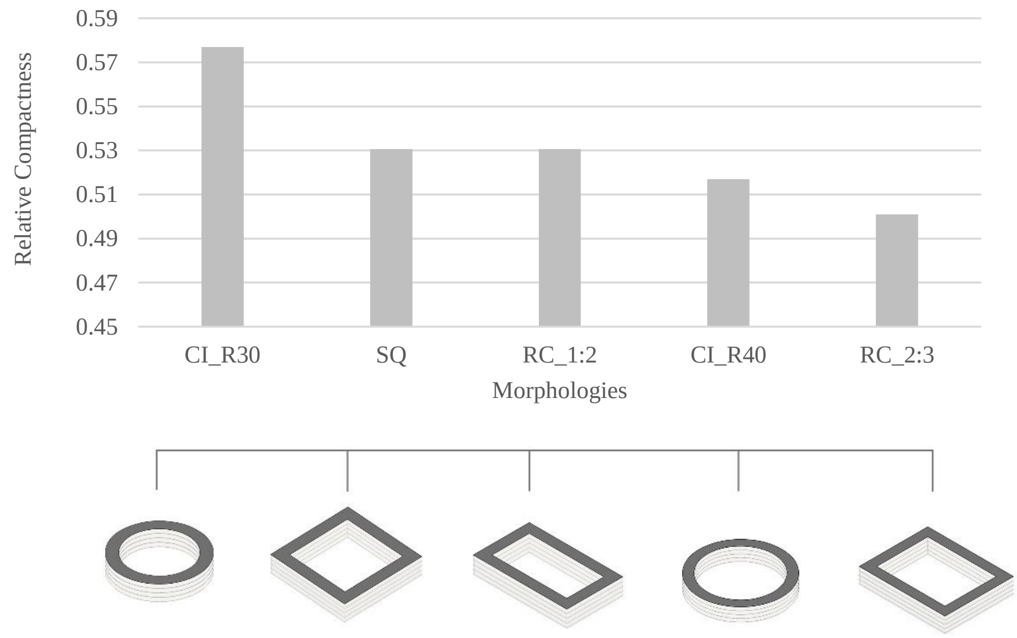



***Figure 45.*** Comparison of building morphologies RC

Based on the calculations performed on the shapes of the morphologies as shown in *Figure 45*, the circular morphology with radius of 30m (CI_R30) is the most compact morphology. Compared to other morphologies, the less compact building is the rectangular morphology RC_2:3 with has the biggest surface, which means a bigger wall surface and less exposure to climatic conditions, eventually expected to result in decreased energy usage. Meanwhile, the other morphologies, square, rectangular with a ratio of 1:2 have the same RC value, followed by the circular morphology with a radius of 40, CI_R40.

## 3.6 Modelling and simulation

### 3.6.1 Building models

Common configurations of floor plans will be modeled using DesignBuilder software, for the examination of energy-efficient designs of UGB buildings. The objective is to assess their energy performance in different climates and to determine the best energy-efficient arrangement. As shown in *Figure 46* the study focuses on plans of five morphologies: square. rectangular (1:2 ratio), rectangular (2:3 ratio), circular (R=30m), circular (R=40m). Hypothetical models that vary in four types of heights, 4 floors, 6 floors, 8 floors, and 10 floors, have been selected for this research in order to study the efficiency of different morphologies. The structure of the residential areas has a floor-to-floor height of 4 meters and a footprint that varies between: 2200, 2800 and 3200 square meters. Although all spaces have the same condition area, the surface-to-volume ratio changes depending on the shape.

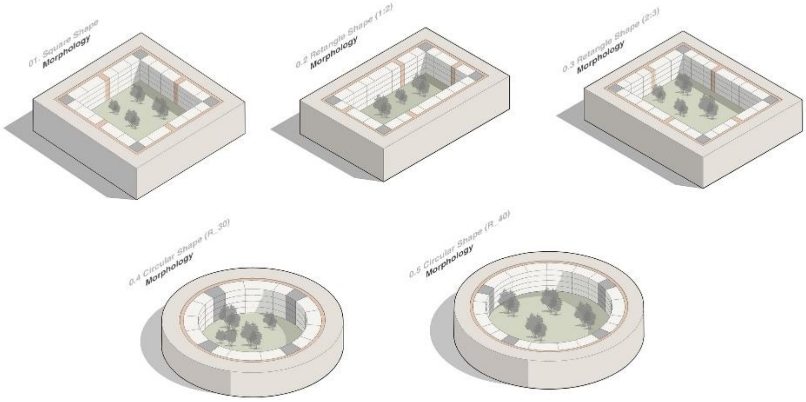



***Figure 46.*** Studied morphologies

The occupancy schedules as shown in *Figure 47* reflect a logical establishment to meet space behavioral patterns.

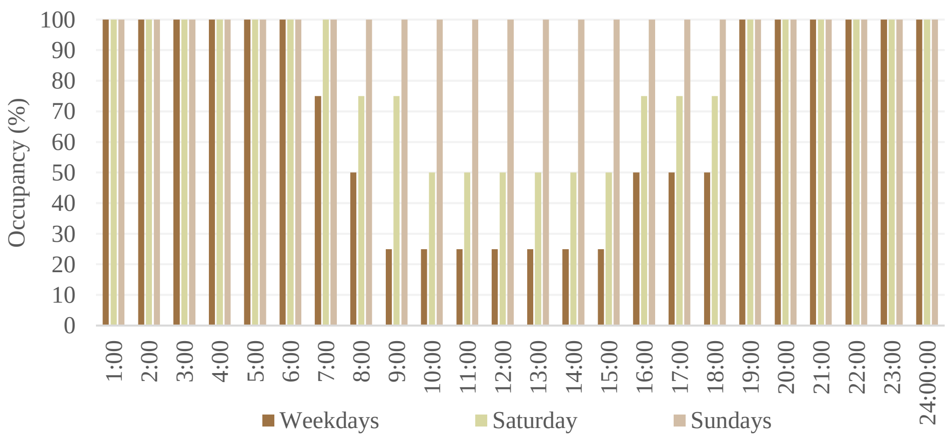



***Figure 47.*** Occupancy schedule

The building construction parameters, glass type, illumination, HVAC characteristics, and internal loads remain unaltered, as shown in *Table 3*, *Table 4*, *Table 5*, *Table 6* and *Figure 48* depicts the specifics of the building attributes.

***Table 3.*** Construction properties

| | | Density [kg/m$^3$] | Conductivity [W/m ºC] | Specific Heat [J/kg ºC] | Thickness [m] |
|---|---|---|---|---|---|
| **External Wall** U-Value = 0.352 [W/m$^2$. K] | Stone – basalt | 2880 | 3.49 | 840 | 0.02 |
| | Air gap 30 mm | | | | 0.03 |
| | MW Stone Wool (standard board) | 40 | 0.038 | 840 | 0.1 |
| | Brickwork | 1700 | 0.84 | 800 | 0.25 |
| | Cement plaster | 1760 | 0.72 | 840 | 0.01 |
| **Internal Wall** U-Value = 0.515 [W/m$^2$. K] | Cement Plaster | 1760 | 0.72 | 840 | 0.01 |
| | Brickwork | 1700 | 0.62 | 800 | 0.12 |
| | MW Stone Wool (standard board) | 40 | 0.038 | 840 | 0.05 |
| | Brickwork | 1700 | 0.62 | 800 | 0.12 |
| | Cement plaster | 1760 | 0.72 | 840 | 0.01 |
| **Ground-facing Wall** U-Value = 0.325 [W/m$^2$. K] | Brickwork | 1700 | 0.84 | 800 | 0.05 |
| | MW Stone Wool (standard board) | 40 | 0.038 | 840 | 0.1 |
| | Bituminous Membrane | 1700 | 0.5 | 1000 | 0.02 |
| | Reinforced concrete, 2% steel | 2400 | 2.5 | 1000 | 0.4 |
| | Cement plaster | 1760 | 0.72 | 840 | 0.01 |
| **Green Roof** U-Value = 0.119 [W/m$^2$. K] | Earth | 1460 | 1.28 | 880 | 1.5 |
| | Porous stone | 1600 | 0.55 | 1000 | 0.03 |
| | Bitumen | 1050 | 0.17 | 1000 | 0.01 |
| | Gravel | 1840 | 0.36 | 840 | 0.04 |
| | Bitumen | 1050 | 0.17 | 1000 | 0.02 |
| | Cement sand render | 1800 | 1 | 1000 | 0.05 |
| | MW Stone Wool (standard board) | 40 | 0.038 | 840 | 0.1 |
| | OUR Polyurethane board | 35 | 0.028 | 1590 | 0.01 |
| | Screed | 1200 | 0.41 | 840 | 0.1 |
| | Reinforced concrete, 2% steel | 2400 | 2.5 | 1000 | 0.25 |
| | Cement plaster | 1760 | 0.72 | 840 | 0.01 |
| **Ground Floor** U-Value = 0.245 [W/m$^2$. K] | Ceramic floor tiles | 1700 | 0.8 | 850 | 0.02 |
| | Screed | 2100 | 1.4 | 650 | 0.1 |
| | MW Stone Wool (standard board) | 40 | 0.038 | 840 | 0.1 |
| | Reinforced concrete, 2% steel | 2400 | 2.5 | 1000 | 0.6 |
| | Bitumen | 1050 | 0.17 | 1000 | 0.02 |
| | Screed | 2100 | 1.4 | 650 | 0.1 |
| | Gravel | 1840 | 0.36 | 840 | 0.1 |
| | Earth | 2050 | 0.52 | 180 | 0.2 |
| **Inner Slab** U-Value = 2.082 [W/m$^2$. K] | Ceramic floor tiles | 1700 | 0.8 | 850 | 0.02 |
| | Screed | 2100 | 1.4 | 650 | 0.1 |
| | Reinforced concrete, 2% steel | 2400 | 2.5 | 1000 | 0.25 |
| | Cement Plaster | 1760 | 0.72 | 840 | 0.01 |

***Table 4.*** Input parameters for HVAC operation

| Input Parameters |
|---|

| | |
|---|---|
| Fan coil unit | (4 pipe) water cooled chiller, waterside economizer |
| Heating/ Cooling system | Electricity from grid |
| Coefficient of Performance for Heating [CoP] | 3.8 |
| Coefficient of Performance for Cooling [CoP] | 3.4 |
| Heating set back [ºC] | 12 |
| Cooling set back [ºC] | 28 |
| Natural ventilation setpoint [ºC] | 15 |

***Table 5.*** Brief for the spatial program.

| Areas | Size $m^2$ | Number | Fresh Air (L/S-Person) | Air Exchange Rate (Ac/h) | Power density ($W/m^2$-100 lux) | Heating temperature set points °C | Cooling temperature set points °C | Occupancy density [$P/m^2$] |
|---|---|---|---|---|---|---|---|---|
| Apartment | 100 | 20 | 10 | 10 | 300 | 20 | 24 | 0.4 |
| Corridors | 96 | 1 | 5 | 5 | 100 | 20 | 28 | 0.02 |

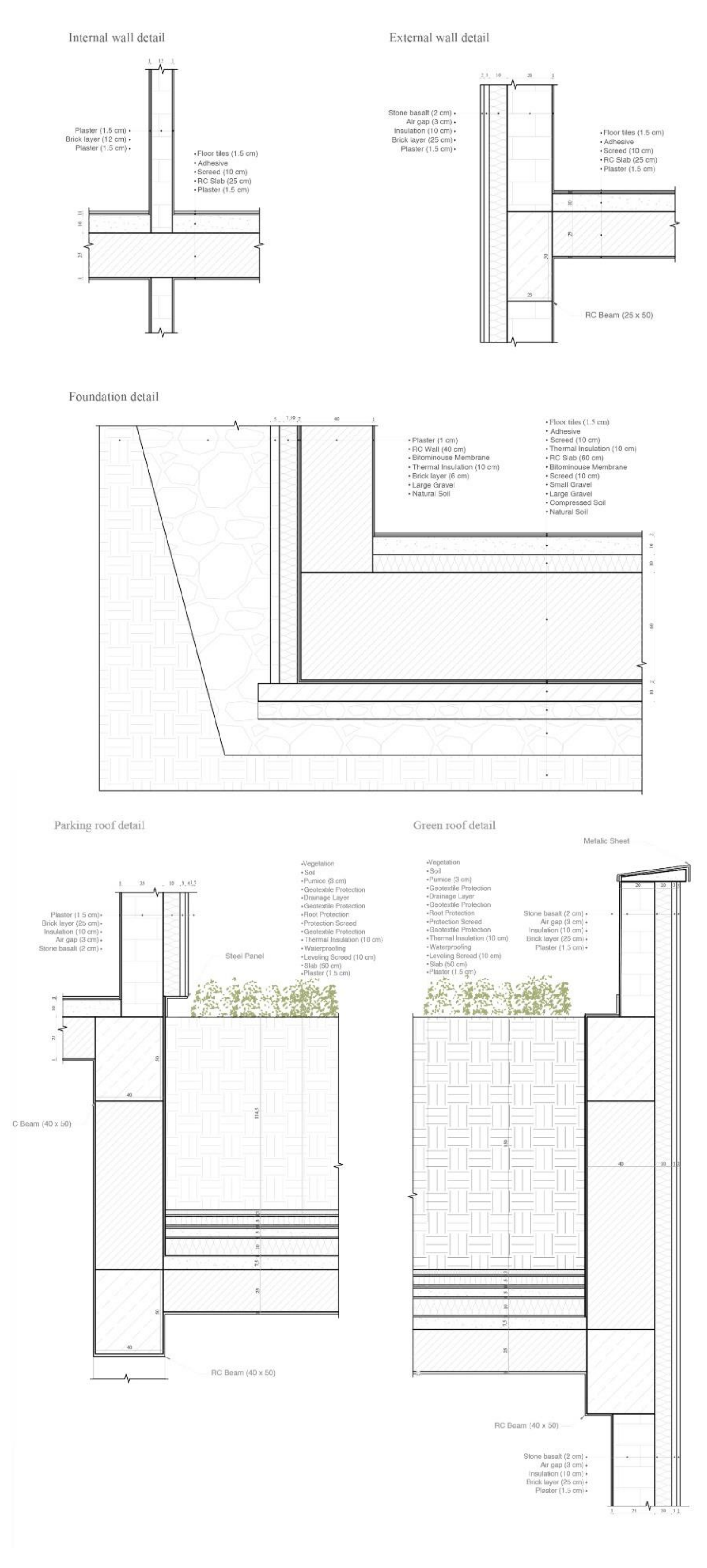



***Figure 48.*** Section details of simulation models

***Table 6.*** Glazing properties

| Glazing properties | |
|---|---|
| Glazing type | Double Low-E (e2=1) clear 6mm/ 13mm Air |
| Frame properties | Aluminum window frame with thermal break |
| SHGC (Total solar transmission) | 0.563 |
| U-value of glass (W/m$^2$. K) | 1.772 |
| Opening position | Side |
| Glazing area openness (%) | 70 |
| Air tightness (ac/h) | 0.5 |

### 3.6.2 Simulation Scenarios

A variety of design parameters are considered in the energy performance calculation for five morphologies. The models are analyzed in four types of floor numbers in advance: 4, 6, 8 and 10 floors scenarios; 3 types of WWR, which are: WWR_60%, WWR_75% and WWR_90%; as well as four different types of balcony widths, such as: no balconies, 1.5m wide, 2m wide and 2.5m wide balconies. The process is repeated for various climatic contexts as illustrated in *Figure 49.* Simulation scenarios are shown in *Table 7.*

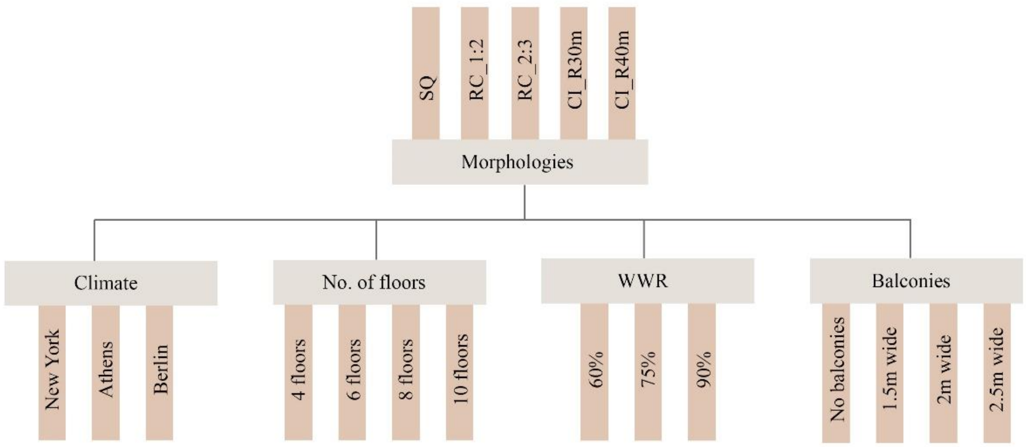



***Figure 49.*** Simulation scenarios

***Table 7.*** Scenario description

| **Code** | **Scenario** | **Description** |
|---|---|---|
| CI_R30 | Circular morphology, four different no. of residential floors, central courtyard, south-oriented | Circular plan morphology, organized a central courtyard with a radius of 30m, developed in 4 floors, 6 floors, 8 floors, 10 floors, south-oriented. |
| SQ | Square morphology, four different no. of residential floors, central courtyard, south-oriented | Square plan morphology, organized a central courtyard with 1:1 ratio, developed in 4 floors, 6 |

| | | |
|---|---|---|
| | | floors, 8 floors, 10 floors, south-oriented. |
| RC_1:2 | Rectangle morphology, four different no. of residential floors, central courtyard, south-oriented | Rectangle plan morphology, organized a central courtyard with 1:2 ratio, developed in 4 floors, 6 floors, 8 floors, 10 floors, south-oriented. |
| CI_R40 | Circular morphology, four different no. of residential floors, central courtyard, south-oriented | Circular plan morphology, organized a central courtyard with a radius of 40m, developed in 4 floors, 6 floors, 8 floors, 10 floors, south-oriented. |
| RC_2:3 | Rectangle morphology, four different no. of residential floors, central courtyard, south-oriented | Rectangle plan morphology, organized a central courtyard with 2:3 ratio, developed in 4 floors, 6 floors, 8 floors, 10 floors, south-oriented. |

### 3.6.3 Simulation Software

The DesignBuilder software version 7 for EnergyPlus is utilized to develop UGB simulations in selected climates. This program makes possible, through an interface, the virtual modeling of different geometric shapes, incorporating specific architectural features, occupants' activities, glazing, HVAC systems, and energy load. Climatic data are generated by Meteonorm Software veriosni 7.2, and these data are integrated into the DesignBuilder program. EnergyPlus is the program that made it possible to transfer hourly data from Meteonorm's software to DesignBuilder's, allowing us comprehensive simulations for the special conditions of UGB.

# CHAPTER 4

# RESULTS AND DISCUSSIONS

The results generated by the software are evaluated and presented in charts. Computer simulations, combining five morphologies, with different number of floors, and WWR, have been calculated computationally. The results obtained show the correlation that exists between different morphologies and the energy performance of UGB.

## 4.1 Climate of New York

A comparison between annual cooling, annual heating and annual total energy consumption inside the apartments is illustrated in the figures below, to determine the impact of the humid subtropical climate of New York on the recommended morphologies.

### 4.1.1 WWR 60%

The following figures illustrate the correlation of annual consumption for cooling, heating and total, for five UGB morphologies and for four different floor numbers, studied for WWR 60%.

*Figure 50* illustrates the annual cooling demand for all typologies with different number of floors. Apparently, the deeper the morphologies go, they display a poor performance in a subtropical climate. CI_R30 morphology, performs poorer, competed to the other morphologies, since it has the smallest area of the courtyard and ground contact surface and is the most compact building. The best performance was obtained by SQ due to its large courtyard area, ground contact surface and equal orientation of the facade. *Figure 51* illustrates the annual heating demand for all typologies with different number of floors. RC_1:2 morphology, performs poorer competed to the other morphologies. The best performance was obtained by CI_R40 due to its large courtyard area, ground contact surface and better ventilation.

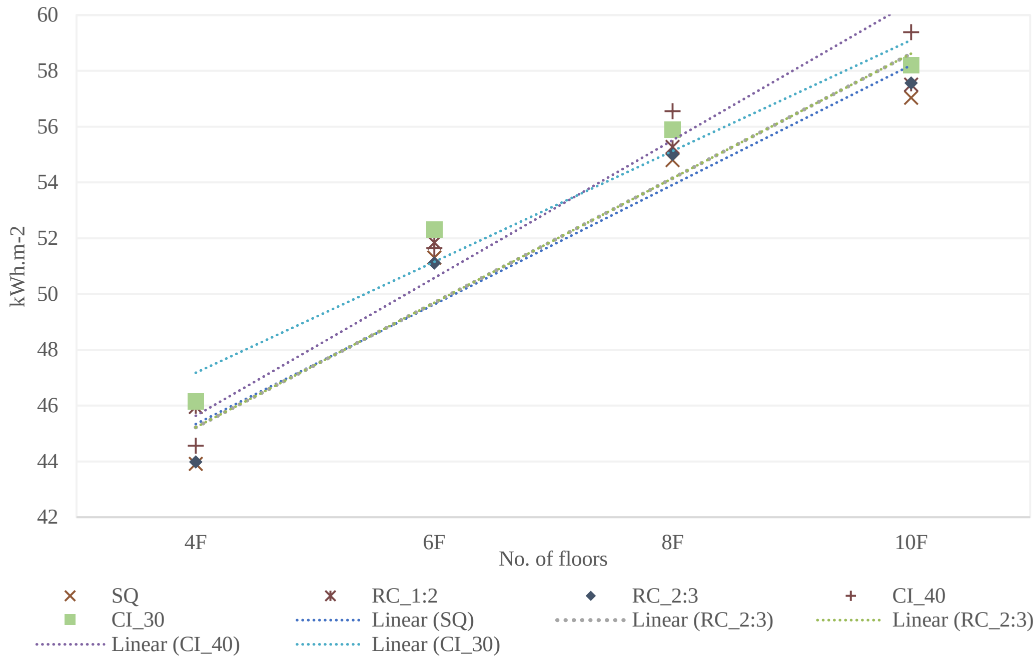



***Figure 50***. Comparison of simulated cooling demand (kWh.m$^2$) of UGB morphologies

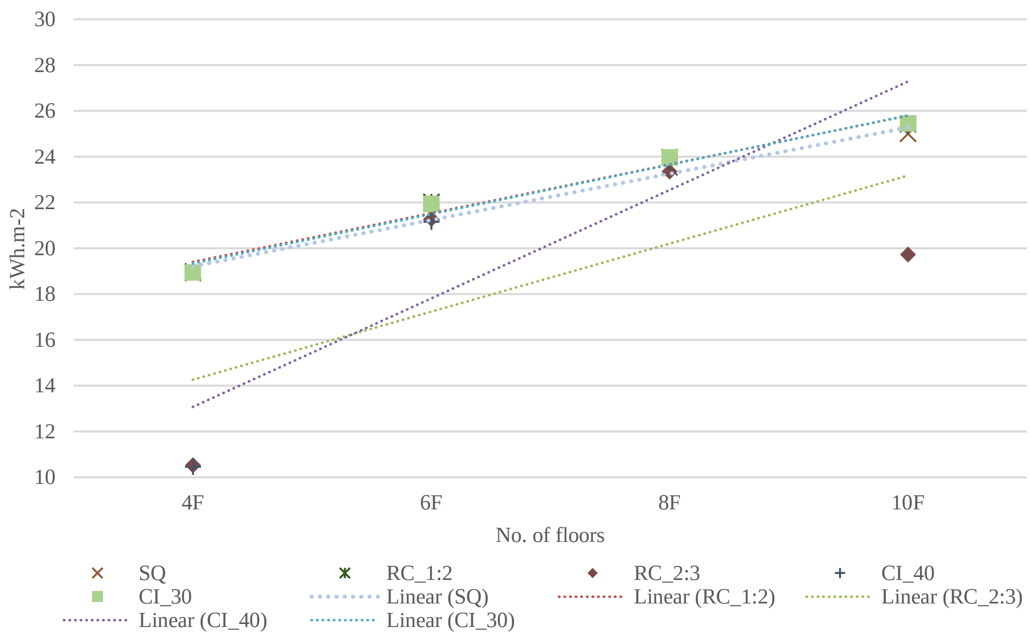



***Figure 51.*** Comparison of simulated heating demand (kWh.m$^2$) of UGB morphologies

*Figure 52* illustrates the annual total of cooling and heating demand for all typologies with different number of floors. In the total annual energy consumption, CI_R30 morphology, performs poorer competed to the other morphologies, since it has the smallest area of the courtyard, ground contact surface and is the less compact building. The best total performance was obtained by RC_2:3 due to its largest courtyard area, largest ground surface contact and because it have the smallest compactness value, followed by CI_R40.

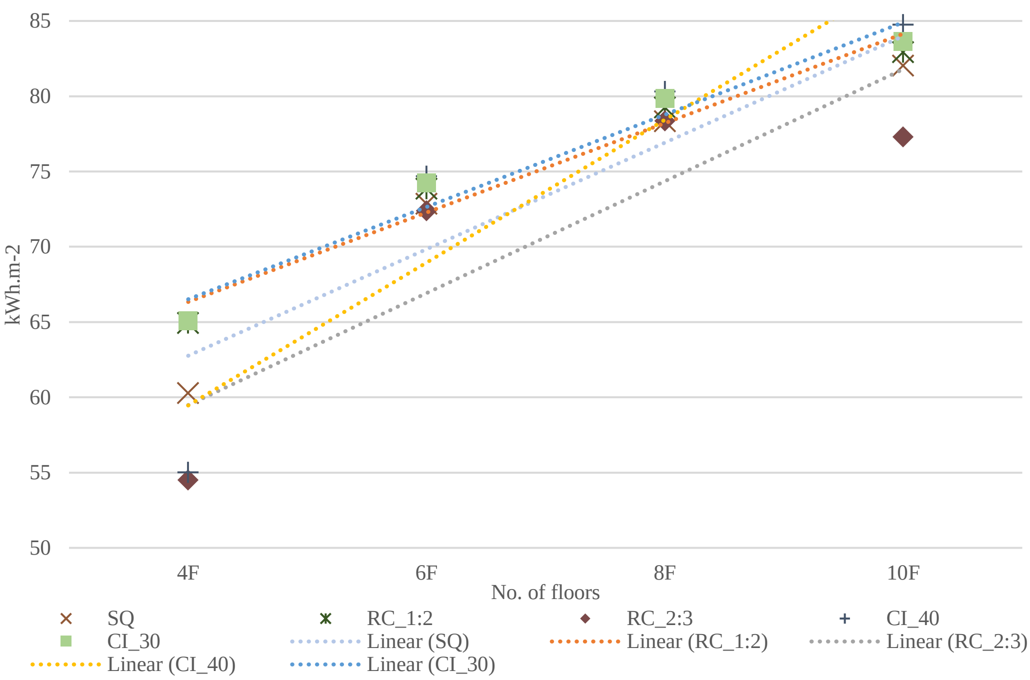



***Figure 52.*** Comparison of simulated total annual demand (kWh.m2) of UGB morphologies

### 4.1.2 WWR 75%

The following figures illustrate the correlation of annual consumption for cooling, heating and total, for five UGB morphologies and for four different floor numbers, studied for WWR 75%.

*Figure 53* illustrates the annual cooling demand for all typologies with different number of floors. Apparently, the deeper the morphologies go, they display a poor performance in a subtropical climate. CI_R30 morphology, performs poorer, competed to the other morphologies, since it has the smallest area of the courtyard and ground contact surface and it is the most compact building. The best performance was obtained by SQ due to its large courtyard area, ground contact surface and equal orientation of the facade. *Figure 54* illustrates the annual heating demand for all typologies with different number of floors. SQ, RC_1:2 and CI_R30 morphology, performs poorer competed to the other two morphologies. The best performance was obtained by RC_2:3 and CI_R40 due to their large courtyard area, ground contact surface and because it is the least compact building.

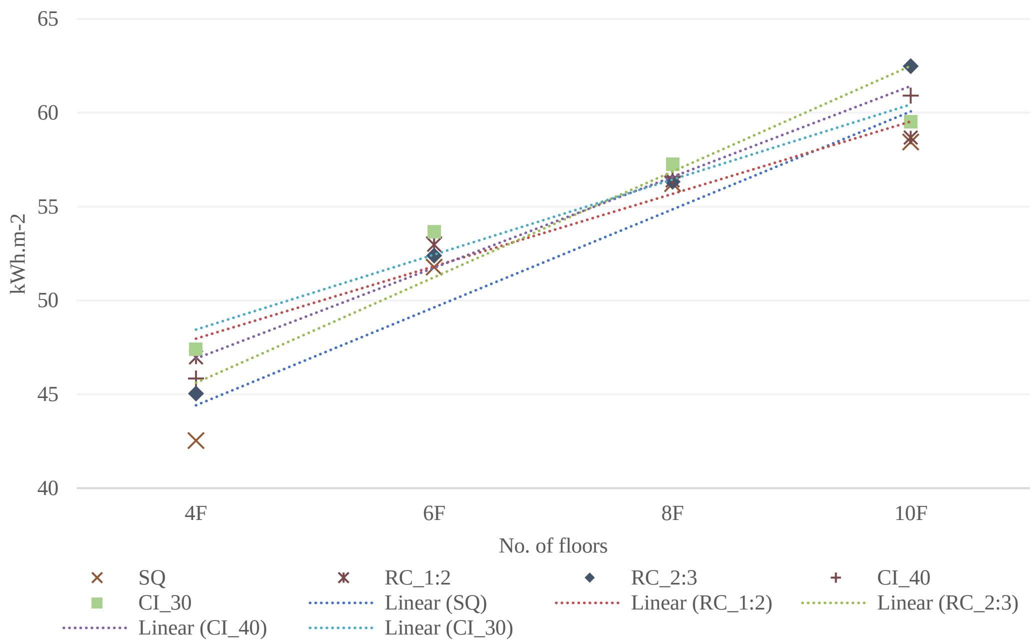



***Figure 53.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies

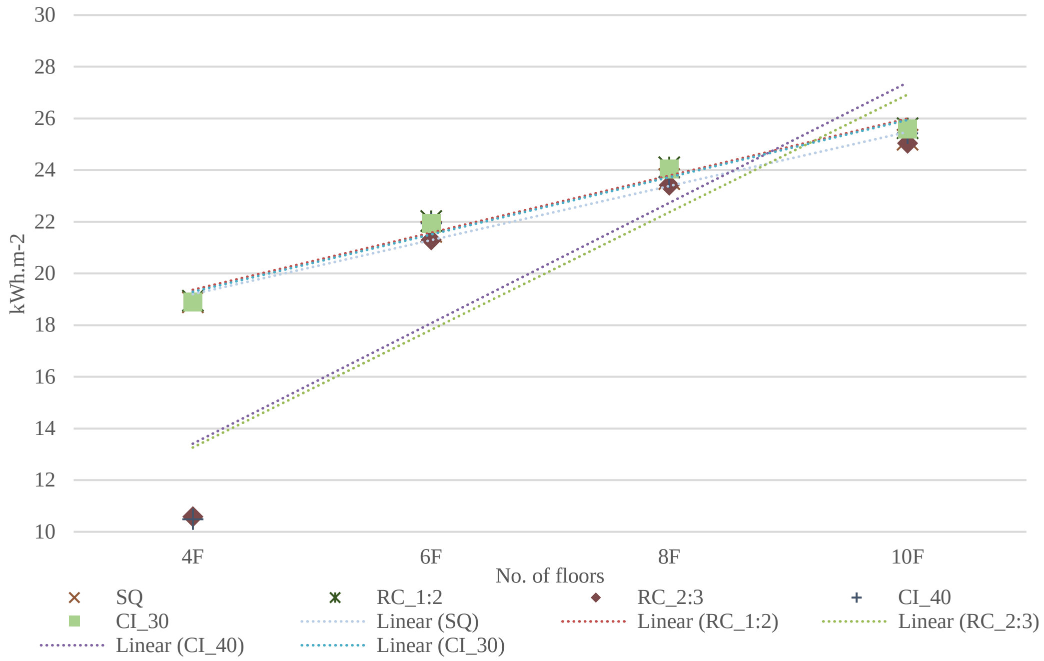



***Figure 54.*** Comparison of simulated heating demand (kWh.m$^2$) of UGB morphologies

***Figure 55*** illustrates the annual total of cooling and heating demand for all typologies with different number of floors. In the total annual energy consumption, CI_R30 morphology, performs poorer competed to the other morphologies, since it has the smallest area of the courtyard. The best total performance was obtained by RC_2:3 due to its large courtyard area, ground surface contact and because it is the least compact building.

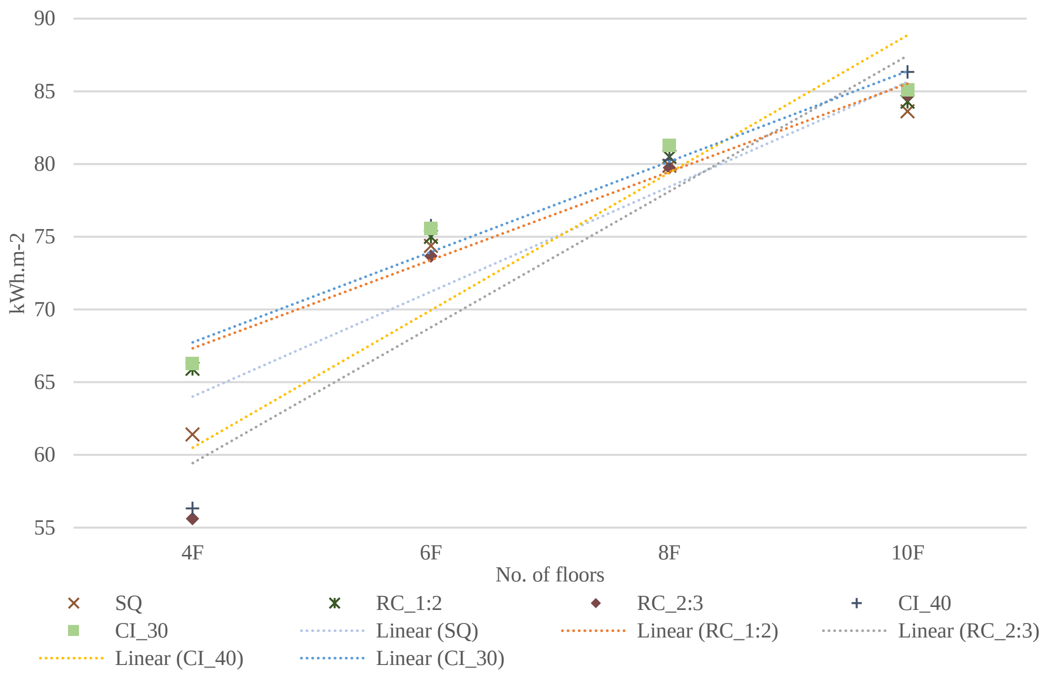



***Figure 55.*** Comparison of simulated total annual demand (kWh.m2) of UGB morphologies

### 4.1.3 WWR 90%

The following figures illustrate the correlation of annual consumption for cooling, heating and total, for five UGB morphologies and for four different floor numbers, studied for WWR 90%.

*Figure 56* illustrates the annual cooling demand for all typologies with different number of floors. Apparently, the deeper the morphologies go, they display a poor performance in a subtropical climate. CI_R30 morphology, performs poorer, competed to the other morphologies, since it has the smallest area of the courtyard and ground contact surface. The best performance was obtained by SQ due to its large courtyard area, ground contact surface and equal orientation of the facade. *Figure 57* illustrates the annual heating demand for all typologies with different number of floors. RC_1:2 morphology, performs poorer competed to the other morphologies. With a slight difference, best performance was obtained by CI_R40, followed by RC_2:3.

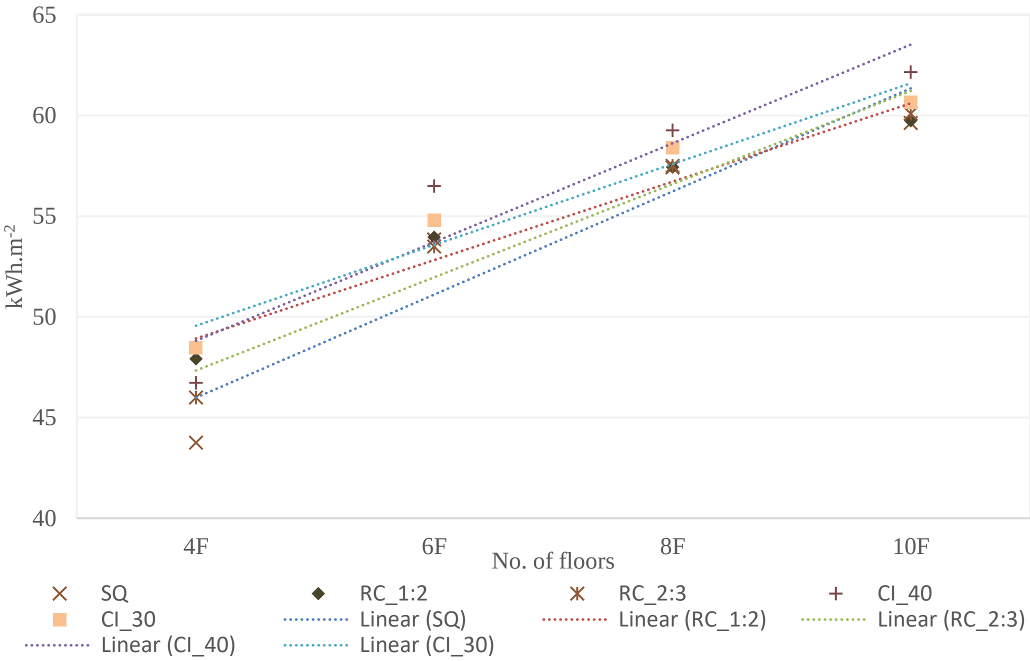



***Figure 56.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies

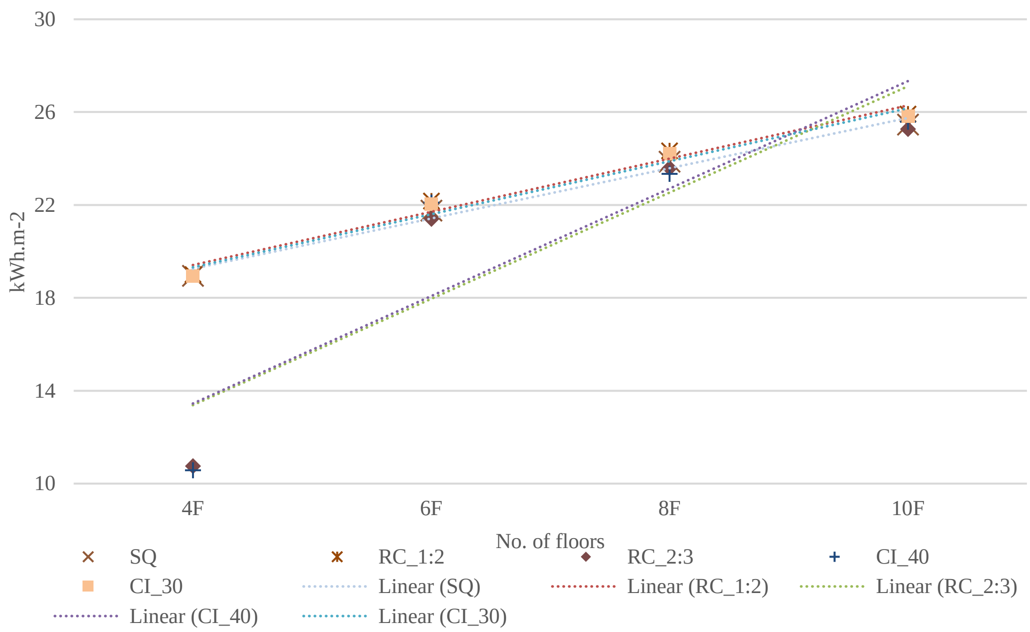



***Figure 57.*** Comparison of simulated heating demand (kWh.$m^2$) of UGB morphologies

*Figure 58* illustrates the annual total of cooling and heating demand for all typologies with different number of floors. In the total annual energy consumption, CI_R30 morphology, performs poorer competed to the other morphologies, since it has the smallest area of the courtyard and ground contact area. The best total performance was obtained by RC_2:3 due to its large courtyard area, ground surface contact and because it is the least compact building.

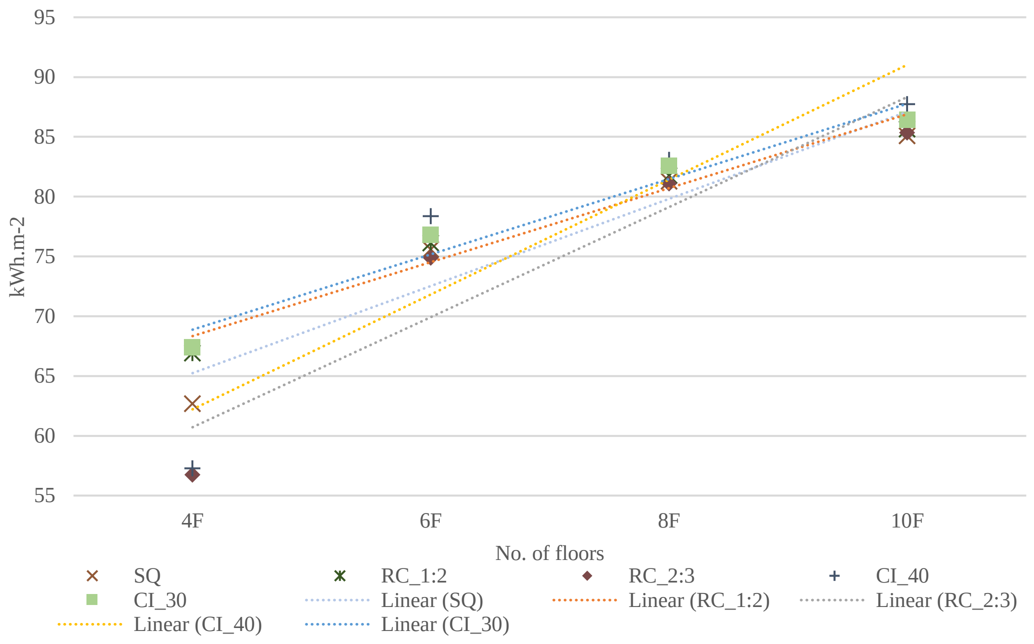
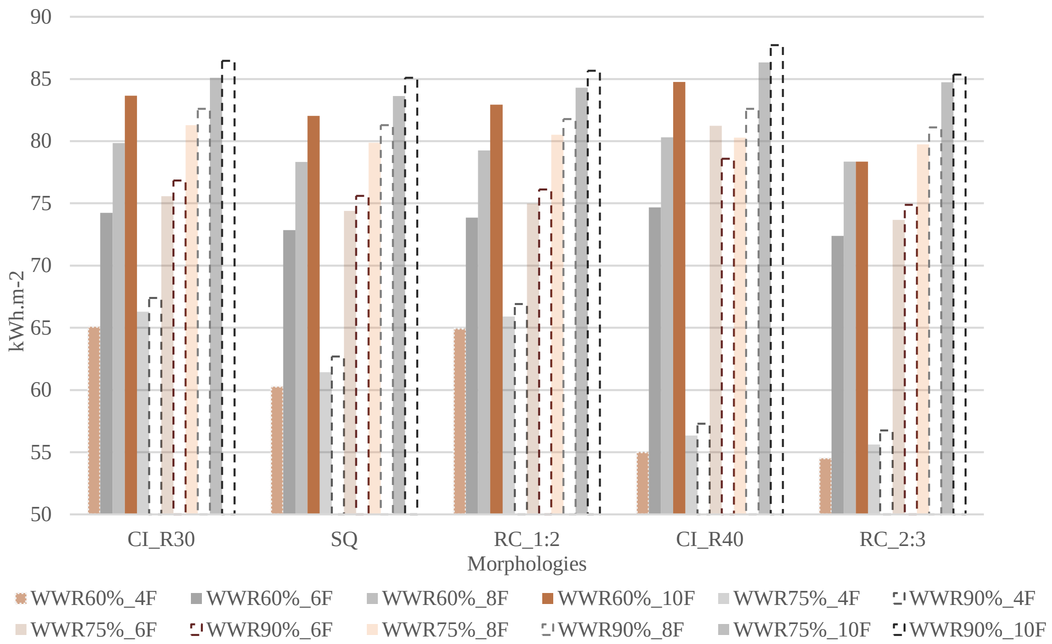



***Figure 58.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies

### 4.1.4 Morphological comparison

In *Figure 59* the comparison of the total annual energy demand of the morphologies for the climate of New York is illustrated, in terms of no. of floors and the transparency of the facades. As it is shown, in the annual energy demand, the trend decreases as the surface of the courtyard, the surface of contact with the ground and the compactness of the building is larger. From the results, it is clear that the deeper you go underground, the worse the building performs. For typology CI_R40 energy consumption is subject to an increase of 30.4 kWh.m$^{-2}$y-1, when it goes from four floors to ten underground floors, for WWR 60%. Small changes are observed with the increase in the transparency of the facade, where for each morphology, as the WWR increases, we have an increase in energy consumption by 1.1-2.4 kWh.m$^{-2}$y$^{-1}$.



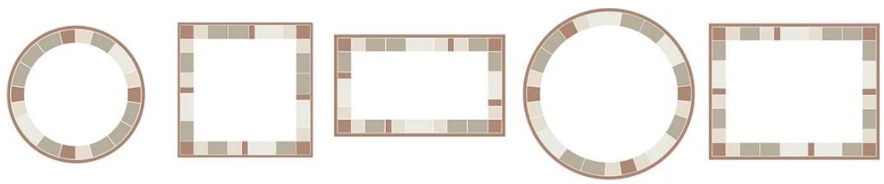



**Figure 59.** *Morphological comparation of annual energy demand (kWh.m$^{-2}$y$^{-1}$)*

*Table 8* summarizes the simulation results obtained for all the scenarios in the climate of New York. A maximum of 16.3% of the total annual energy consumption can be reduced by choosing the right morphology for the selected climatic context. The morphology that performs worse is CI_R30, due to its smaller surface in contact with the ground, the smaller surface of the courtyard and because it is a less compact building. Based on transparency, this morphology consumes 14% more energy, while based on the number of floors, it consumes 25.8% more energy. The morphology that has the best energy performance is RC_2:3, which has a morphology effectiveness of 15.8-16.3% in terms of transparency. The reason for this result is the fact that this morphology has the largest contact surface with the ground, the largest courtyard surface and is the least compact morphology, compared to other morphologies. The second morphology with the best performance is CI_R40, with a morphology effectiveness of 15.5%.

***Table 8.*** Results of simulations for all morphologies.

| Scenarios | | | Annual cooling demand | | | Annual heating demand | | | Annual energy demand | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Total Heating [kWh] | Total heating [kWh.m$^2$] | ME | Total Heating [kWh] | Total heating [kWh.m$^2$] | Morph. | Total Heating [kWh] | Total heating [kWh.m$^2$] | ME |
| WWR_60% | CI_R30 | 4F | 564430.5 | 46.2 | - | 231622.0 | 18.9 | - | 796052.4 | 65.1 | - |
| | | 6F | 832660.4 | 52.3 | **-13.3** | 349045.9 | 21.9 | **-15.8** | 1181706.3 | 74.2 | **-14.0** |
| | | 8F | 1096032.8 | 55.9 | **-21.1** | 469891.4 | 24.0 | **-26.5** | 1565924.2 | 79.9 | **-22.7** |
| | | 10F | 1356138.4 | 58.2 | **-26.1** | 592862.6 | 25.4 | **-34.4** | 1949001.1 | 83.7 | **-28.5** |
| | SQ | 4F | 646855.9 | 41.4 | **10.4** | 295760.5 | 18.9 | **0.1** | 942616.4 | 60.3 | **7.4** |
| | | 6F | 1049335.4 | 51.3 | **-9.9** | 440724.5 | 21.5 | **-13.8** | 1490059.9 | 72.9 | **-11.9** |
| | | 8F | 1381040.6 | 54.8 | **-18.8** | 592872.1 | 23.5 | **-24.2** | 1973912.7 | 78.3 | **-20.3** |
| | | 10F | 1708066.0 | 57.0 | **-23.6** | 748212.6 | 25.0 | **-31.9** | 2456278.6 | 82.0 | **-26.0** |
| | RC_1:2 | 4F | 701090.2 | 46.0 | **0.4** | 289559.1 | 19.0 | **-0.2** | 990649.3 | 64.9 | **0.2** |
| | | 6F | 1035679.5 | 51.8 | **-12.3** | 1475350.7 | 22.0 | **-16.2** | 2511030.2 | 73.9 | **-13.5** |
| | | 8F | 1364953.5 | 55.3 | **-19.8** | 592135.4 | 24.0 | **-26.6** | 1957088.9 | 79.2 | **-21.7** |
| | | 10F | 1691698.1 | 57.5 | **-24.6** | 747745.8 | 25.4 | **-34.2** | 2439443.9 | 82.9 | **-27.4** |
| | CI_R40 | 4F | 763501.3 | 44.6 | **3.4** | 178963.8 | 10.4 | **44.8** | 942465.0 | 55.0 | **15.5** |
| | | 6F | 1173584.6 | 53.6 | **-16.2** | 460847.4 | 21.1 | **-11.2** | 1634432.0 | 74.7 | **-14.7** |
| | | 8F | 1506918.5 | 56.6 | **-22.6** | 632953.4 | 23.8 | **-25.4** | 2139871.8 | 80.3 | **-23.4** |
| | | 10F | 1864797.5 | 59.4 | **-28.7** | 796120.6 | 25.4 | **-33.9** | 2660918.1 | 84.8 | **-30.2** |
| | RC_2:3 | 4F | 817946.4 | 44.0 | **4.7** | 195543.2 | 10.5 | **44.5** | 1013489.6 | 54.5 | **16.3** |
| | | 6F | 1226699.5 | 51.1 | **-10.8** | 510657.0 | 21.3 | **-12.3** | 1737356.5 | 72.4 | **-11.2** |
| | | 8F | 1617349.4 | 55.0 | **-19.2** | 686540.0 | 23.4 | **-23.3** | 2303889.4 | 78.4 | **-20.4** |
| | | 10F | 2003522.1 | 57.6 | **-24.7** | 866711.4 | 19.7 | **-4.2** | 2870233.5 | 77.3 | **-18.7** |
| WWR_75% | CI_R30 | 4F | 579550.9 | 47.4 | - | 231148.5 | 18.9 | - | 810699.3 | 66.3 | - |
| | | 6F | 853936.6 | 53.6 | **-13.2** | 349208.0 | 21.9 | **-16.1** | 1203144.6 | 75.6 | **-14.0** |
| | | 8F | 1122412.3 | 57.2 | **-20.8** | 471403.1 | 24.0 | **-27.2** | 1593815.4 | 81.3 | **-22.6** |
| | | 10F | 1386778.8 | 59.5 | **-25.6** | 596173.9 | 25.6 | **-35.4** | 1982952.7 | 85.1 | **-28.4** |
| | SQ | 4F | 665149.5 | 42.5 | **10.3** | 295397.2 | 18.9 | **0.1** | 960546.7 | 61.4 | **7.3** |
| | | 6F | 1079381.9 | 52.8 | **-11.4** | 442004.0 | 21.6 | **-14.3** | 1521385.9 | 74.4 | **-12.2** |
| | | 8F | 1416821.4 | 56.2 | **-18.7** | 596109.6 | 23.7 | **-25.2** | 2012931.0 | 79.9 | **-20.5** |
| | | 10F | 1750027.8 | 57.0 | **-20.4** | 754087.1 | 25.2 | **-33.2** | 2504114.9 | 82.2 | **-24.0** |
| | RC_1:2 | 4F | 716561.2 | 47.0 | **0.9** | 289085.4 | 18.9 | **-0.3** | 1005646.5 | 65.9 | **0.6** |
| | | 6F | 1057966.3 | 53.0 | **-11.8** | 440152.2 | 22.0 | **-16.6** | 1498118.5 | 75.0 | **-13.1** |
| | | 8F | 1392738.7 | 56.4 | **-19.0** | 595431.6 | 24.1 | **-27.6** | 1988170.3 | 80.5 | **-21.4** |
| | | 10F | 1726230.8 | 58.7 | **-23.8** | 753692.1 | 25.6 | **-35.6** | 2479922.9 | 84.3 | **-27.2** |
| | CI_R40 | 4F | 785381.5 | 45.8 | **3.3** | 229631.1 | 10.5 | **44.5** | 1015012.6 | 56.3 | **15.0** |
| | | 6F | 1207770.0 | 55.2 | **-16.4** | 570433.1 | 26.1 | **-37.9** | 1778203.1 | 81.2 | **-22.6** |
| | | 8F | 1546660.7 | 56.6 | **-19.4** | 631891.8 | 23.7 | **-25.5** | 2178552.6 | 80.3 | **-21.1** |
| | | 10F | 1912333.4 | 60.9 | **-28.5** | 798529.6 | 25.4 | **-34.6** | 2710863.0 | 86.3 | **-30.2** |
| | RC_2:3 | 4F | 837481.5 | 45.0 | **5.0** | 196866.0 | 10.6 | **44.0** | 1034347.5 | 55.6 | **16.1** |
| | | 6F | 1257092.5 | 53.5 | **-12.9** | 511113.4 | 21.3 | **-12.7** | 1768205.9 | 74.8 | **-12.8** |
| | | 8F | 1656058.9 | 56.3 | **-18.9** | 688788.5 | 23.4 | **-23.9** | 2344847.4 | 79.8 | **-20.3** |
| | | 10F | 1957723.4 | 84.7 | **-78.8** | 871813.0 | 25.0 | **-32.5** | 2829536.4 | 109.8 | **-65.6** |
| WWR_90% | CI_R30 | 4F | 592793.9 | 48.5 | - | 231456.8 | 18.9 | - | 824250.7 | 67.4 | - |
| | | 6F | 872462.5 | 54.8 | **-13.1** | 350644.2 | 22.0 | **-16.4** | 1223106.6 | 76.8 | **-14.0** |
| | | 8F | 1144993.5 | 58.4 | **-20.5** | 474559.1 | 24.2 | **-27.9** | 1619552.5 | 82.6 | **-22.5** |
| | | 10F | 1413311.3 | 60.7 | **-25.1** | 601344.2 | 25.8 | **-36.4** | 2014655.5 | 86.5 | **-28.3** |
| | SQ | 4F | 684360.4 | 43.8 | **9.7** | 296188.0 | 18.9 | **-0.1** | 980548.4 | 62.7 | **7.0** |
| | | 6F | 1101422.0 | 53.9 | **-11.1** | 444827.7 | 21.7 | **-14.9** | 1546249.7 | 75.6 | **-12.2** |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 8F | 1446941.3 | 57.4 | **-18.5** | 601290.8 | 23.9 | **-26.1** | 2048232.0 | 81.3 | **-20.6** |
| | 10F | 1785743.8 | 59.6 | **-23.0** | 762073.5 | 25.5 | **-34.5** | 2547817.3 | 85.1 | **-26.2** |
| RC_1:2 | 4F | 731147.3 | 47.9 | **1.1** | 289793.7 | 19.0 | **-0.4** | 1020941.0 | 66.9 | **0.7** |
| | 6F | 1077826.1 | 54.0 | **-11.3** | 442690.3 | 22.2 | **-17.1** | 1520516.4 | 76.1 | **-12.9** |
| | 8F | 1418702.9 | 57.4 | **-18.5** | 600875.9 | 24.3 | **-28.6** | 2019578.8 | 81.8 | **-21.3** |
| | 10F | 1757277.3 | 59.7 | **-23.2** | 762225.7 | 25.9 | **-36.9** | 2519503.0 | 85.7 | **-27.1** |
| CI_R40 | 4F | 800681.8 | 46.7 | **3.6** | 180958.2 | 10.6 | **44.2** | 981640.0 | 57.3 | **15.0** |
| | 6F | 1236654.3 | 56.5 | **-16.6** | 483491.4 | 22.1 | **-16.7** | 1720145.7 | 78.6 | **-16.6** |
| | 8F | 1579218.7 | 59.3 | **-22.3** | 621575.8 | 23.3 | **-23.3** | 2200794.5 | 82.6 | **-22.6** |
| | 10F | 1951431.0 | 62.2 | **-28.2** | 803061.4 | 25.6 | **-35.1** | 2754492.4 | 87.7 | **-30.2** |
| RC_2:3 | 4F | 855594.1 | 46.0 | **5.1** | 199721.7 | 10.7 | **43.3** | 1055315.8 | 56.7 | **15.8** |
| | 6F | 1283972.4 | 53.5 | **-10.4** | 513299.7 | 21.4 | **-13.0** | 1797272.1 | 74.9 | **-11.1** |
| | 8F | 1690897.2 | 57.5 | **-18.6** | 693436.6 | 23.6 | **-24.6** | 2384333.8 | 81.1 | **-20.3** |
| | 10F | 2091489.4 | 59.7 | **-36.5** | 879230.5 | 25.3 | **-33.5** | 2970719.9 | 85.0 | **-26.1** |

## 4.2 Climate of Athens

A comparison between annual cooling, annual heating and annual total energy consumption inside the apartments is illustrated in the figures below, to determine the impact of the hot-summer Mediterranean climate of Athens on the recommended morphologies.

### 4.2.1 WWR 60%

The following figures illustrate the correlation of annual consumption for cooling, heating and total, for five UGB morphologies and for four different floor numbers, studied for WWR 60%.

*Figure 60* illustrates the annual cooling demand for all typologies with different number of floors. Apparently, the deeper the morphologies go, they display a poor performance in a hot-summer Mediterranean climate. CI_R30 morphology, performs poorer, competed to the other morphologies, since it has the smallest area of the courtyard and ground contact surface and is the less compact building. The best performance was obtained by SQ due to its large courtyard area, ground contact surface and equal orientation of the façade, and since in this climate it offers better ventilation and more balanced shading. *Figure 51* illustrates the annual heating demand for all typologies with different number of floors. SQ morphology, performs poorer competed to the other morphologies, because it brings colder winds to the building. The best performance was obtained by RC_2:3 and CI_R40 due to their large courtyard area and ground contact surface and better ventilation and highest relative compactness value.

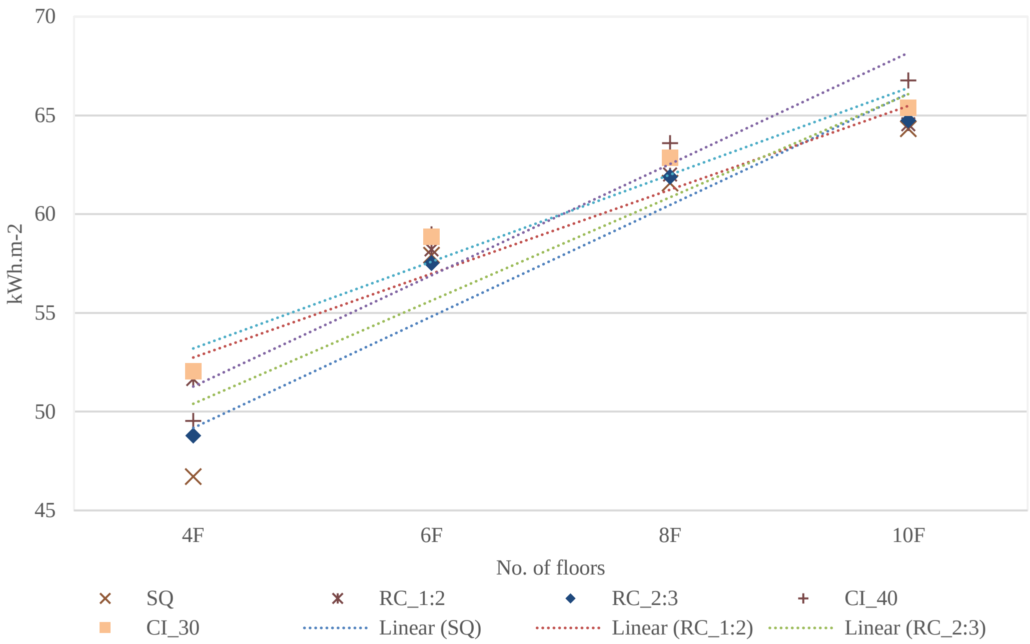



***Figure 60***. Comparison of simulated cooling demand (kWh.m$^2$) of UGB morphologies

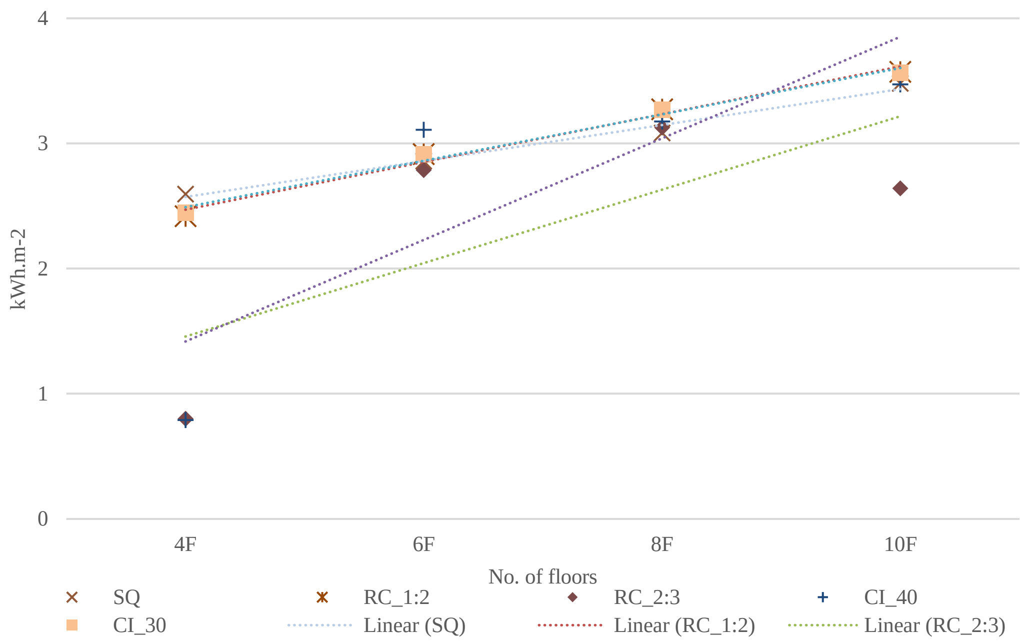



***Figure 61.*** Comparison of simulated heating demand (kWh.m$^2$) of UGB morphologies

*Figure 62* illustrates the annual total of cooling and heating demand for all typologies with different number of floors. In the total annual energy consumption, CI_R30 morphology, performs poorer competed to the other morphologies, since it has the smallest area of the courtyard. With a slight difference, best total performance was obtained by SQ morphology, followed by RC_2:3.

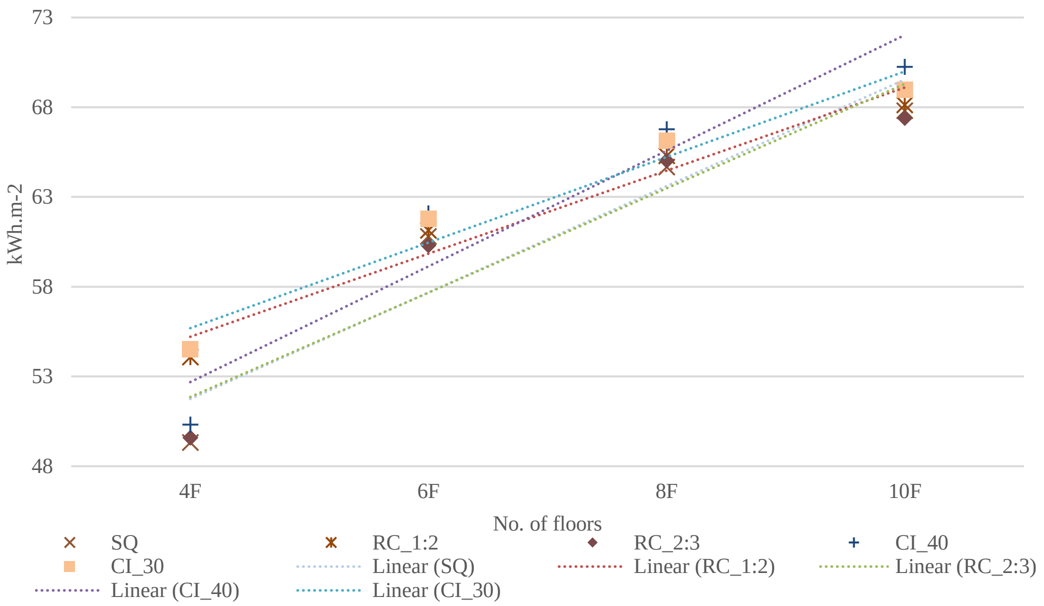



***Figure 62.*** Comparison of simulated total annual demand (kWh.m2) of UGB morphologies

### 4.2.2 WWR 75%

The following figures illustrate the correlation of annual consumption for cooling, heating and total, for five UGB morphologies and for four different floor numbers, studied for WWR 75%.

*Figure 63* illustrates the annual cooling demand for all typologies with different number of floors. As shown by the figure below, the deeper the morphologies go, they display a poor performance in a hot-summer Mediterranean climate. CI_R30 morphology, performs poorer competed to the other morphologies, since it has the smallest area of the courtyard. The best performance was obtained by SQ due to its large courtyard area and equal oriented façade, and since in this climate it offers better ventilation and more balanced shading. *Figure 64* illustrates the annual heating demand for all typologies with different number of floors. SQ morphology, performs poorer competed to the other morphologies because its exposure the building to colder winds. The best performance was obtained by CI_R40 due to its large courtyard area, and ground contact area.

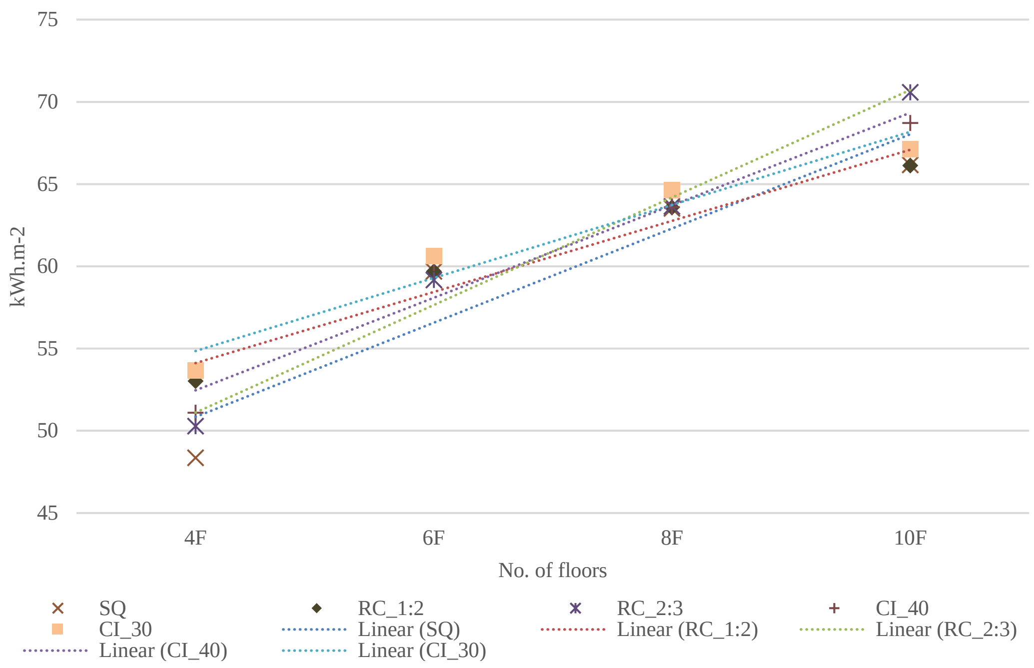



***Figure 63.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies

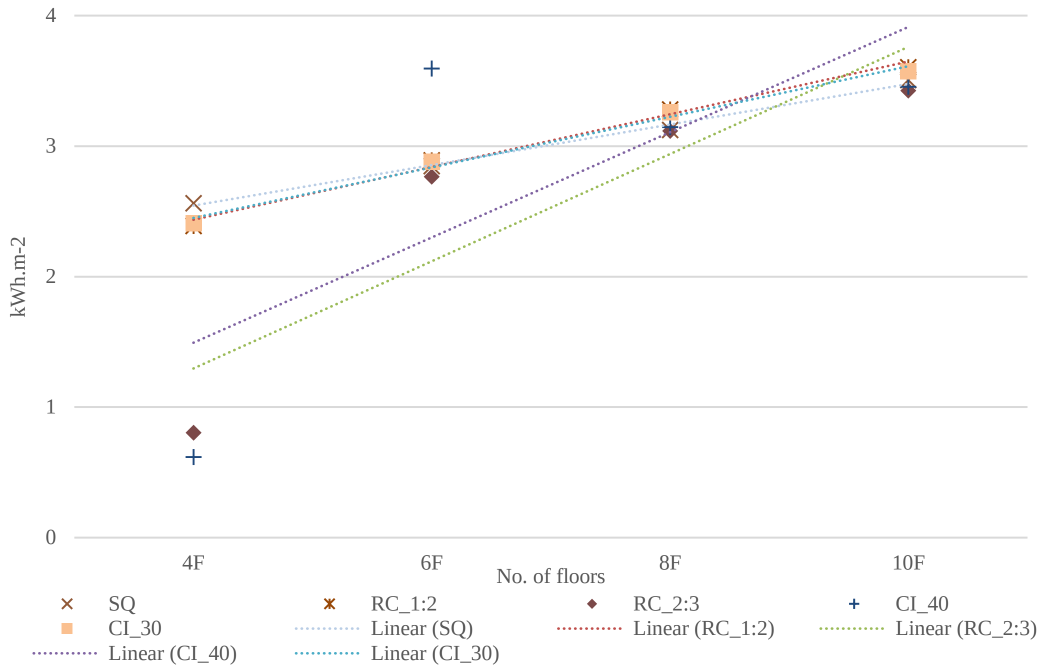



***Figure 64.*** Comparison of simulated heating demand (kWh.m$^2$) of UGB morphologies

*Figure 65* illustrates the annual total of cooling and heating demand for all typologies with different number of floors. In the total annual energy consumption, CI_R30 morphology, performs poorer competed to the other morphologies, since it has the smallest area of the courtyard, and ground contact surface. With a slight change, the best total performance was obtained by SQ morphology, followed with a slight difference by RC_2:3.

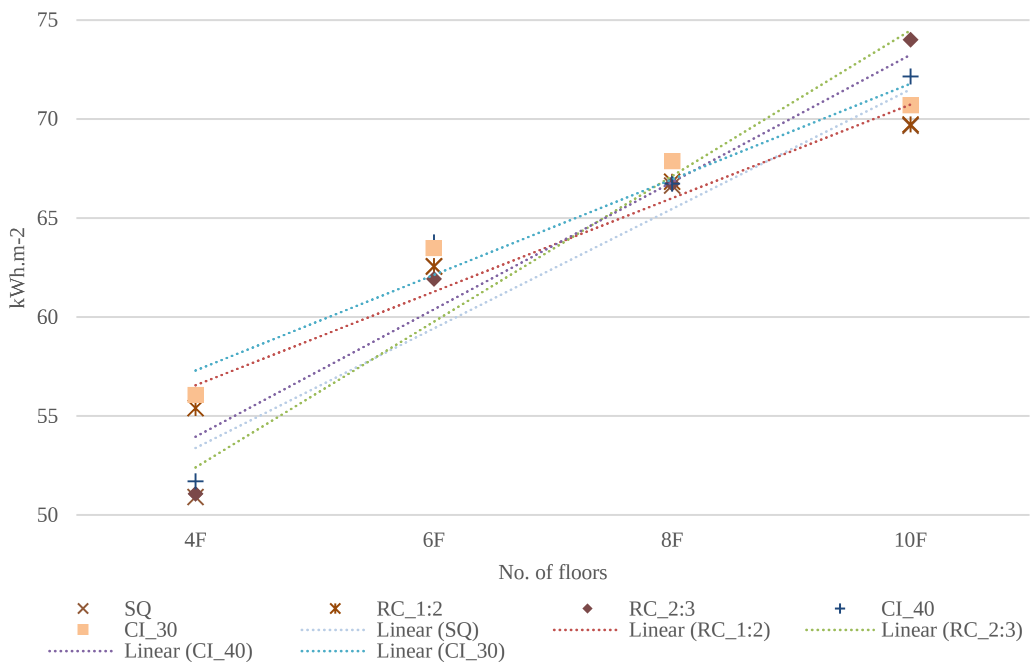



***Figure 65.*** Comparison of simulated total annual demand (kWh.m2) of UGB morphologies

### 4.2.3 WWR 90%

The following figures illustrate the correlation of annual consumption for cooling, heating and total, for five UGB morphologies and for four different floor numbers, studied for WWR 90%.

*Figure 66* illustrates the annual cooling demand for all typologies with different number of floors. As shown by the figure below, the deeper the morphologies go, they display a poor performance in a subtropical climate. CI_R30 morphology, performs poorer competed to the other morphologies, since it has the smallest area of the courtyard and ground contact surface. The best performance was obtained by SQ, since in this climate it offers better ventilation and more balanced shading. *Figure 67* illustrates the annual heating demand for all typologies with different number of floors. SQ morphology, performs poorer competed to the other morphologies. The best performance was obtained by RC_2:3 and CI_R40 due to their large courtyard area, ground contact surface and low relative compactness value.

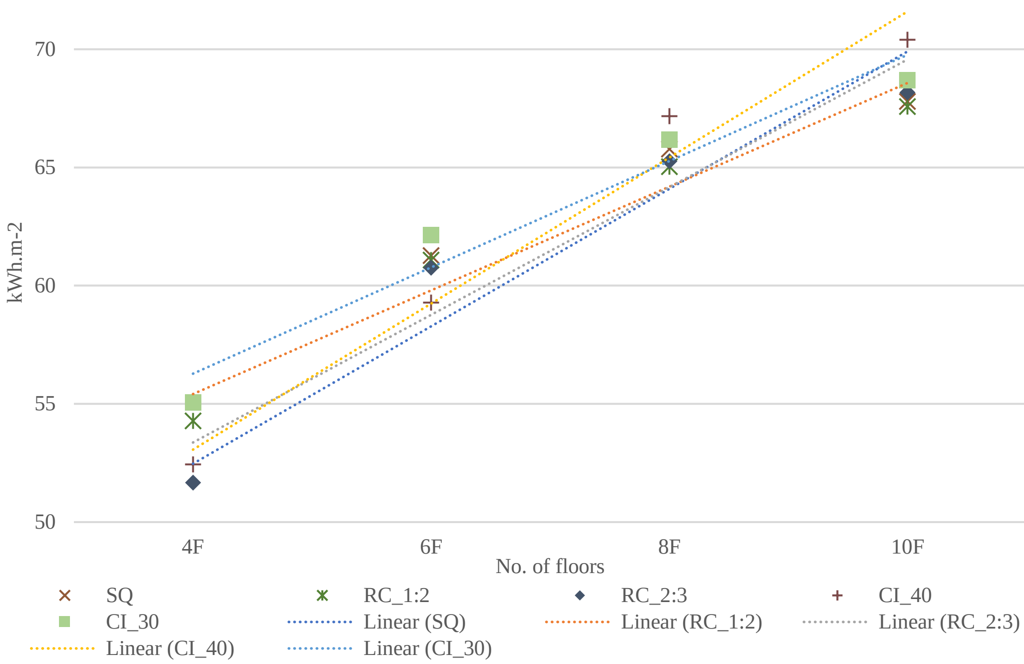



***Figure 66.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies

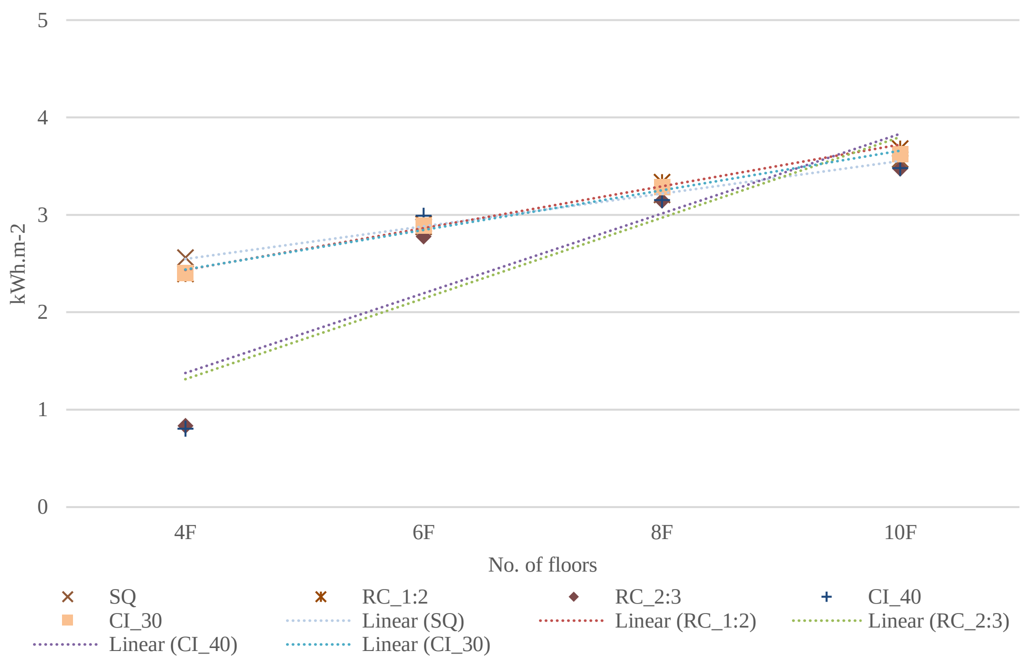



***Figure 67.*** Comparison of simulated heating demand (kWh.m$^2$) of UGB morphologies

*Figure 68* illustrates the annual total of cooling and heating demand for all typologies with different number of floors. In the total annual energy consumption, CI_R30 morphology, performs poorer competed to the other morphologies, since it has the smallest area of the courtyard and ground contact surface. The best total performance was obtained by SQ due to its large courtyard area.

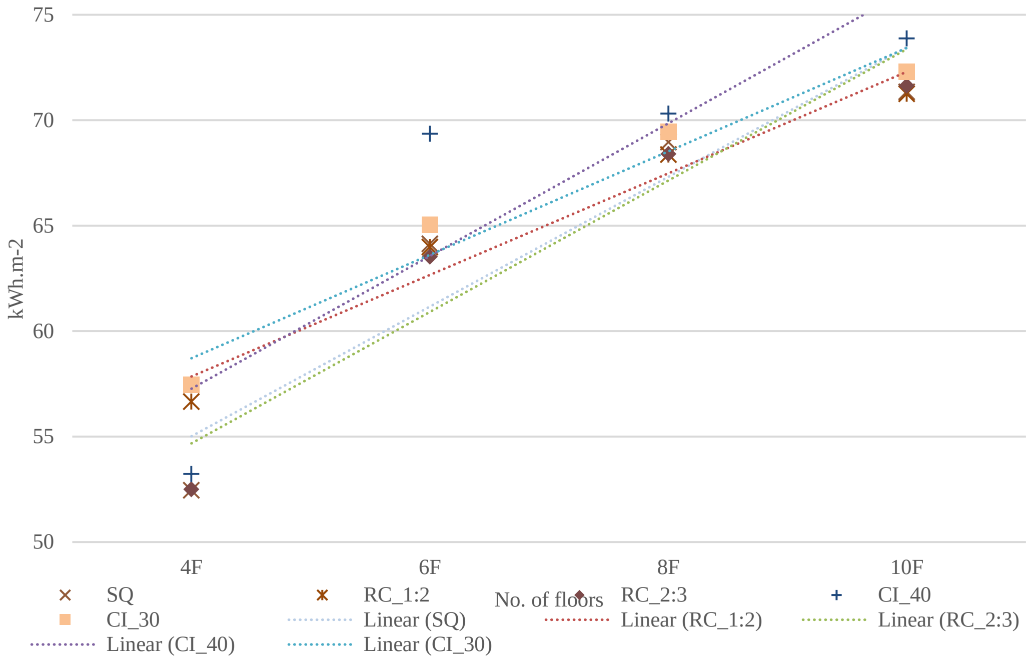



***Figure 68.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies

### 4.2.4 Morphological comparison

In *Figure 69* the comparison of the total annual energy demand of the morphologies for the climate of Athens is illustrated, in terms of no. of floors and the transparency of the facades. As it is shown, in the annual energy demand, the trend decreases as the surface of the courtyard, the surface of contact with the ground and the more ventilation the building receives. From the results, it is clear that the deeper you go underground, the worse the building performs. For typology CI_R40 energy consumption is subject to an increase of 19.9 kWh.m$^{-2}$y-1, when it goes from four floors to ten underground floors, for WWR 60%. Small changes are observed with the increase in the transparency of the facade, where for each morphology, as the WWR increases, we have an increase in energy consumption by 1.3-3.2 kWh.m$^{-2}$y$^{-1}$.

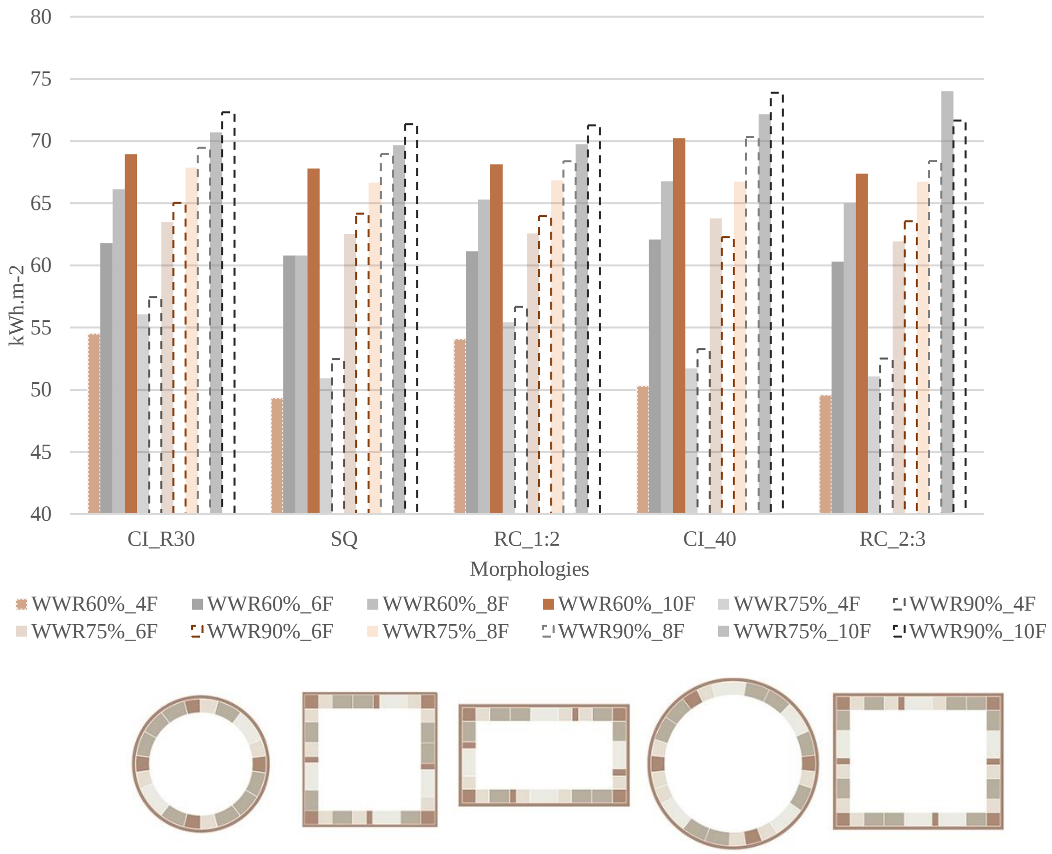



***Figure 69.*** Morphological comparation of annual energy demand (kWh.m-2y-1)

*Table 9* summarizes the simulation results obtained for all the scenarios in the climate of Athens. A maximum of 9.5% of the total annual energy consumption can be reduced by choosing the right morphology for the selected climatic context. The morphology that performs worse is CI_R30, due to its smaller surface in contact with the ground, the smaller surface of the courtyard, building compactness and the shadow and lack of ventilation that this morphology offers for this climate. Based on transparency, this morphology consumes 13.2-13.4% more energy, while based on the number of floors, it consumes 25.9-26.5% more energy. The morphology that has the best energy performance is SQ. The reason for this result is the fact that this morphology has the largest contact surface with the ground, the largest courtyard surface and is a compact building compared to RC_1:2 and CI_R30, but it also gives a better ventilation performance compared with the others. With a slight difference of

0.5%, the second morphology with the best performance is RC_2:3, because this morphology has the largest contact surface with the ground, the largest courtyard surface and is more compact compared to other morphologies. CI_R40 compared with the two abovementioned morphologies performs 1.5-2% worse.

***Table 9.*** Results of simulations for all morphologies.

| Scenarios | | | Annual cooling demand | | | Annual heating demand | | | Annual energy demand | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Total Heating [kWh] | Total heating [kWh.m$^2$] | ME | Total Heating [kWh] | Total heating [kWh.m$^2$] | Morph. | Total Heating [kWh] | Total heating [kWh.m$^2$] | ME |
| WWR_60% | CI_R30 | 4F | 636681.9 | 52.1 | - | 29912.8 | 2.4 | - | 666594.6 | 54.5 | - |
| | | 6F | 937262.0 | 58.9 | **-13.1** | 46331.4 | 2.9 | **-19.0** | 983593.3 | 61.8 | **-13.4** |
| | | 8F | 1232465.5 | 62.9 | **-20.7** | 64105.4 | 3.3 | **-33.7** | 1296570.9 | 66.1 | **-21.3** |
| | | 10F | 1523665.2 | 65.4 | **-25.6** | 82987.9 | 3.6 | **-45.6** | 1606653.1 | 69.0 | **-26.5** |
| | SQ | 4F | 730717.4 | 46.7 | **10.3** | 40582.9 | 2.6 | **-6.1** | 771300.3 | 49.3 | **9.5** |
| | | 6F | 1184930.1 | 57.9 | **-11.3** | 58458.7 | 2.9 | **-16.9** | 1243388.8 | 60.8 | **-11.5** |
| | | 8F | 1551700.9 | 61.6 | **-18.3** | 77690.7 | 3.1 | **-26.1** | 1629391.6 | 64.7 | **-18.6** |
| | | 10F | 1925981.2 | 64.3 | **-23.6** | 104134.9 | 3.5 | **-42.2** | 2030116.1 | 67.8 | **-24.4** |
| | RC_1:2 | 4F | 788026.9 | 51.7 | **0.8** | 36877.0 | 2.4 | **1.2** | 824903.9 | 54.1 | **0.8** |
| | | 6F | 1163138.8 | 58.2 | **-11.8** | 58193.9 | 2.9 | **-19.1** | 1221332.7 | 61.1 | **-12.2** |
| | | 8F | 1531567.3 | 62.0 | **-19.1** | 80801.8 | 3.3 | **-33.8** | 1612369.1 | 65.3 | **-19.8** |
| | | 10F | 1898751.9 | 64.5 | **-24.0** | 105009.0 | 3.6 | **-45.9** | 2003761.0 | 68.1 | **-25.0** |
| | CI_R40 | 4F | 848621.6 | 49.5 | **4.9** | 13497.3 | 0.8 | **67.8** | 862119.0 | 50.3 | **7.7** |
| | | 6F | 1290849.9 | 59.0 | **-13.3** | 68009.2 | 3.1 | **-27.0** | 1358859.1 | 62.1 | **-13.9** |
| | | 8F | 1694411.4 | 63.6 | **-22.2** | 84576.0 | 3.2 | **-29.8** | 1778987.5 | 66.8 | **-22.5** |
| | | 10F | 2096354.1 | 66.8 | **-28.3** | 108957.9 | 3.5 | **-41.9** | 2205312.0 | 70.2 | **-28.9** |
| | RC_2:3 | 4F | 907248.3 | 48.8 | **6.3** | 14851.2 | 0.8 | **67.4** | 922099.5 | 49.6 | **9.0** |
| | | 6F | 1380403.4 | 57.5 | **-10.5** | 66827.2 | 2.8 | **-13.8** | 1447230.6 | 60.3 | **-10.6** |
| | | 8F | 1820064.8 | 61.9 | **-18.9** | 91902.6 | 3.1 | **-27.8** | 1911967.5 | 65.0 | **-19.3** |
| | | 10F | 2253368.8 | 64.7 | **-24.4** | 118835.2 | 2.6 | **-8.0** | 2372204.0 | 67.4 | **-23.6** |
| WWR_75% | CI_R30 | 4F | 656293.1 | 53.7 | - | 29445.1 | 2.4 | - | 685738.1 | 56.1 | - |
| | | 6F | 965068.9 | 60.6 | **-13.0** | 45880.9 | 2.9 | **-19.7** | 1010949.8 | 63.5 | **-13.3** |
| | | 8F | 1267141.0 | 64.6 | **-20.4** | 63911.7 | 3.3 | **-35.4** | 1331052.7 | 67.9 | **-21.1** |
| | | 10F | 1564213.3 | 67.1 | **-25.1** | 65300.0 | 3.6 | **-50.4** | 1629513.2 | 70.8 | **-26.2** |
| | SQ | 4F | 756158.9 | 48.4 | **9.9** | 40075.4 | 2.6 | **-18.3** | 796234.3 | 50.9 | **9.2** |
| | | 6F | 1220791.5 | 59.7 | **-11.2** | 58251.1 | 2.8 | **-18.3** | 1279042.6 | 62.5 | **-11.5** |
| | | 8F | 1600624.7 | 63.5 | **-18.4** | 78709.3 | 3.1 | **-29.7** | 1679333.9 | 66.6 | **-18.9** |
| | | 10F | 1981144.2 | 66.2 | **-23.3** | 104977.3 | 3.5 | **-45.6** | 2086121.4 | 69.7 | **-24.2** |
| | RC_1:2 | 4F | 808834.5 | 53.0 | **1.2** | 36448.3 | 2.4 | **0.8** | 845282.7 | 55.4 | **1.2** |
| | | 6F | 1192240.0 | 59.7 | **-11.2** | 57749.7 | 2.9 | **-20.1** | 1249989.6 | 62.6 | **-11.6** |
| | | 8F | 1569812.9 | 63.6 | **-18.5** | 81052.6 | 3.3 | **-36.3** | 1650865.5 | 66.8 | **-19.2** |
| | | 10F | 1945305.2 | 66.1 | **-23.2** | 106075.4 | 3.6 | **-49.8** | 2051380.6 | 69.7 | **-24.4** |
| | CI_R40 | 4F | 875366.9 | 51.1 | **4.8** | 13513.5 | 0.6 | **74.4** | 888880.4 | 51.7 | **7.8** |
| | | 6F | 1317300.0 | 60.2 | **-12.2** | 78665.8 | 3.6 | **-49.3** | 1395965.7 | 63.8 | **-13.7** |
| | | 8F | 1745258.0 | 63.6 | **-18.5** | 83823.8 | 3.1 | **-30.7** | 1829081.8 | 66.7 | **-19.0** |
| | | 10F | 2156994.5 | 68.7 | **-28.0** | 108479.3 | 3.5 | **-43.5** | 2265473.8 | 72.2 | **-28.7** |
| | RC_2:3 | 4F | 934940.0 | 50.3 | **6.3** | 14965.4 | 0.8 | **66.6** | 949905.4 | 51.1 | **8.9** |
| | | 6F | 1420064.7 | 59.2 | **-10.3** | 66376.5 | 2.8 | **-14.9** | 1486441.1 | 61.9 | **-10.5** |
| | | 8F | 1870644.0 | 63.6 | **-18.6** | 91635.5 | 3.1 | **-29.4** | 1962279.5 | 66.7 | **-19.0** |
| | | 10F | 2315276.8 | 70.6 | **-31.5** | 119238.6 | 3.4 | **-42.3** | 2434515.4 | 74.0 | **-32.0** |
| WWR_90% | CI_R30 | 4F | 673287.9 | 55.1 | - | 29335.7 | 2.4 | - | 702623.5 | 57.5 | - |
| | | 6F | 989392.2 | 62.1 | **-12.9** | 45982.7 | 2.9 | **-20.4** | 1035375.0 | 65.0 | **-13.2** |
| | | 8F | 1297908.1 | 66.2 | **-20.2** | 64443.3 | 3.3 | **-37.0** | 1362351.5 | 69.5 | **-20.9** |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 10F | 1600543.1 | 68.7 | **-24.8** | 84385.6 | 3.6 | **-51.0** | 1684928.7 | 72.3 | **-25.9** |
| SQ | 4F | 780583.3 | 49.9 | **9.3** | 40014.4 | 2.6 | **-6.7** | 820597.7 | 52.5 | **8.7** |
| | 6F | 1253265.1 | 61.3 | **-11.3** | 58771.0 | 2.9 | **-19.8** | 1312036.0 | 64.2 | **-11.7** |
| | 8F | 1657423.2 | 65.8 | **-19.5** | 80672.3 | 3.2 | **-33.5** | 1738095.5 | 69.0 | **-20.1** |
| | 10F | 2029852.6 | 67.8 | **-23.1** | 106834.0 | 3.6 | **-48.7** | 2136686.5 | 71.4 | **-24.2** |
| RC_1:2 | 4F | 828079.1 | 54.3 | **1.4** | 36476.0 | 2.4 | **0.3** | 864555.2 | 56.7 | **1.4** |
| | 6F | 1220170.1 | 61.1 | **-10.9** | 58115.6 | 2.9 | **-21.3** | 1278285.8 | 64.0 | **-11.4** |
| | 8F | 1606255.9 | 65.0 | **-18.1** | 82313.4 | 3.3 | **-39.0** | 1688569.3 | 68.4 | **-19.0** |
| | 10F | 1987914.4 | 67.6 | **-22.8** | 108268.3 | 3.7 | **-53.4** | 2096182.6 | 71.3 | **-24.0** |
| CI_R40 | 4F | 898481.9 | 52.4 | **4.7** | 13738.4 | 0.8 | **66.6** | 912220.3 | 53.2 | **7.3** |
| | 6F | 1297817.3 | 59.3 | **-7.7** | 65437.7 | 3.0 | **-24.6** | 1363255.0 | 62.3 | **-8.4** |
| | 8F | 1789796.4 | 67.2 | **-22.0** | 83923.6 | 3.2 | **-31.3** | 1873720.1 | 70.3 | **-22.4** |
| | 10F | 2210622.4 | 70.4 | **-27.9** | 109187.8 | 3.5 | **-45.0** | 2319810.2 | 73.9 | **-28.6** |
| RC_2:3 | 4F | 960964.3 | 51.7 | **6.1** | 15471.8 | 0.8 | **65.3** | 976436.1 | 52.5 | **8.6** |
| | 6F | 1458217.3 | 60.8 | **-10.4** | 66627.4 | 2.8 | **-15.7** | 1524844.7 | 63.5 | **-10.6** |
| | 8F | 1918932.4 | 65.3 | **-18.6** | 92469.1 | 3.1 | **-31.1** | 2011401.5 | 68.4 | **-19.1** |
| | 10F | 2372709.5 | 68.2 | **-23.8** | 120846.3 | 3.5 | **-44.8** | 2493555.8 | 71.6 | **-24.7** |

## 4.3 Climate of Berlin

A comparison between annual cooling, annual heating and annual total energy consumption inside the apartments is illustrated in the figures below, to determine the impact of the oceanic climate of Berlin on the recommended morphologies.

### 4.3.1 WWR 60%

The following figures illustrate the correlation of annual consumption for cooling, heating and total, for five UGB morphologies and for four different floor numbers, studied for WWR 60%.

*Figure 70* illustrates the annual cooling demand for all typologies with different number of floors. Apparently, the deeper the morphologies go, they display a poor performance in a oceanic climate. CI_R40 morphology, performs poorer competed to the other morphologies. The best performance was obtained by SQ due to its large courtyard area, ground contact surface and equal oriented façade. *Figure 71* illustrates the annual heating demand for all typologies with different number of floors. RC_1:2 morphology, performs poorer competed to the other morphologies. With a slight difference, the best performance was obtained by CI_R40 due to its large courtyard area, followed by RC_2:3.

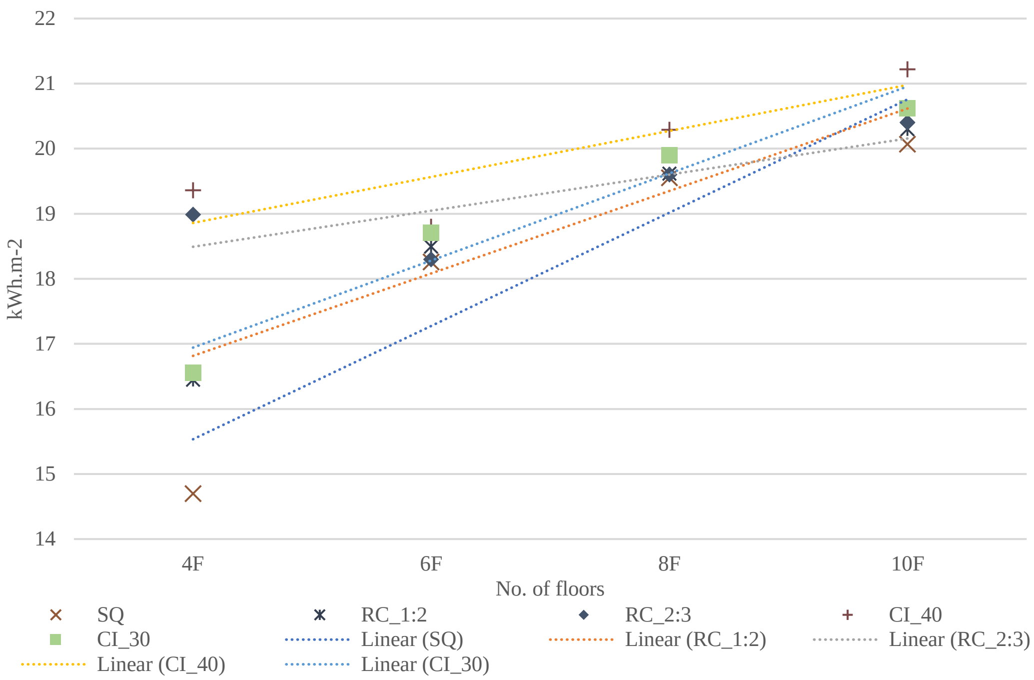



***Figure 70***. Comparison of simulated cooling demand (kWh.m$^2$) of UGB morphologies

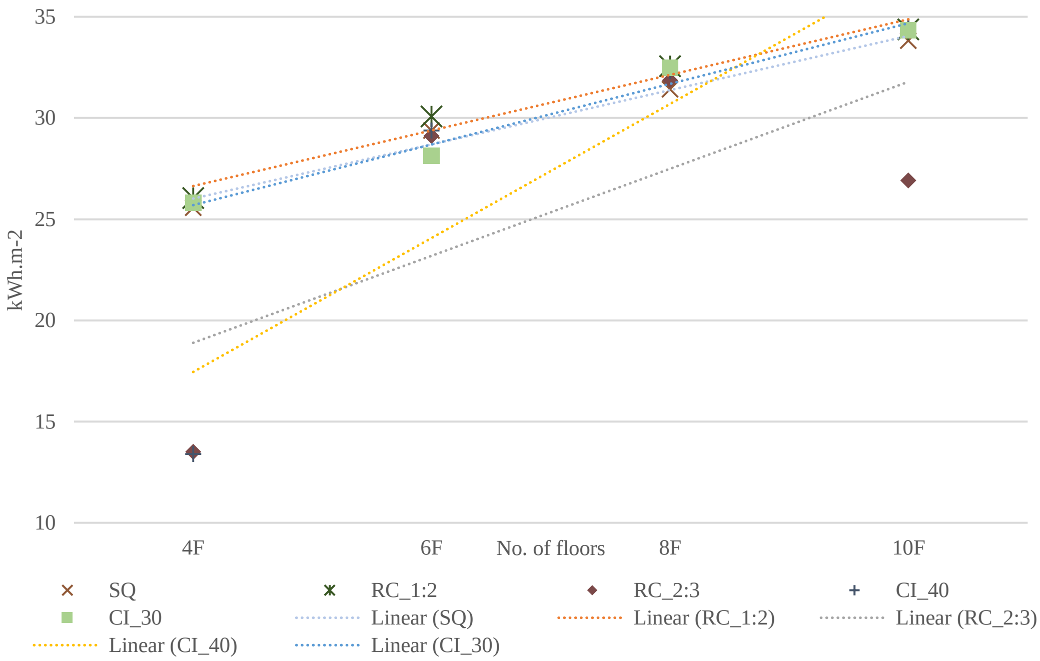



***Figure 71.*** Comparison of simulated heating demand (kWh.m$^2$) of UGB morphologies

*Figure 72* illustrates the annual total of cooling and heating demand for all typologies with different number of floors. In the total annual energy consumption, CI_R30 morphology, performs poorer competed to the other morphologies, since it has the smallest area of the courtyard and ground contact surface. The best total performance was obtained by RC_2:3 due to its large courtyard area, due to its larger courtyard area, ground contact surface and building compactness.

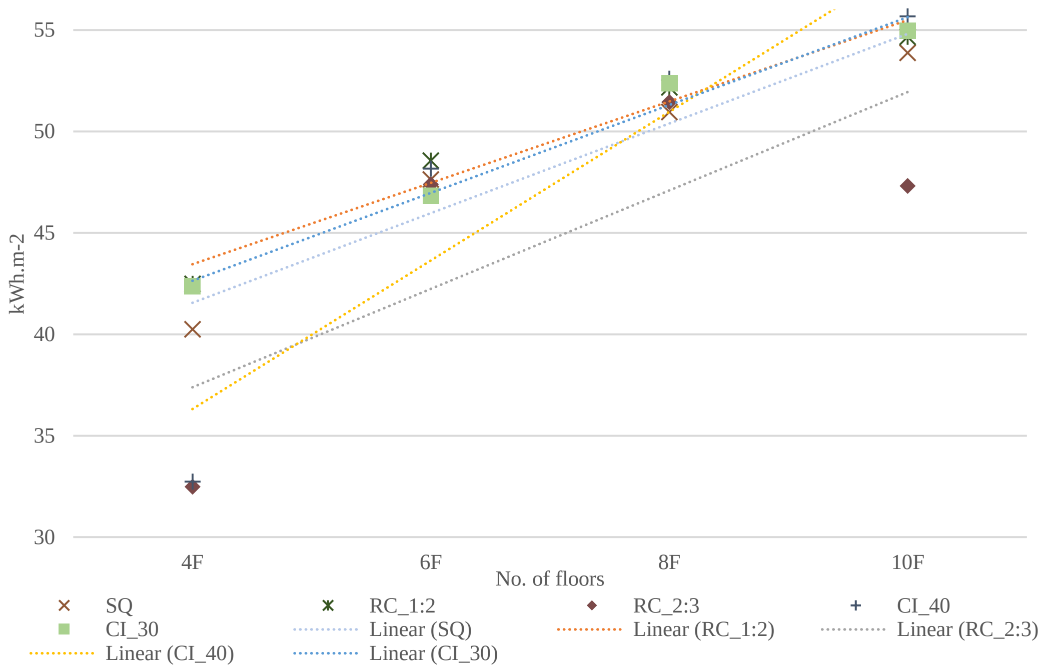



***Figure 72.*** Comparison of simulated total annual demand (kWh.m2) of UGB morphologies

### 4.3.2 WWR 75%

The following figures illustrate the correlation of annual consumption for cooling, heating and total, for five UGB morphologies and for four different floor numbers, studied for WWR 75%.

*Figure 73* illustrates the annual cooling demand for all typologies with different number of floors. As shown by the figure below, the deeper the morphologies go, they display a poor performance in a oceanic climate. CI_R40 morphology, performs poorer competed to the other morphologies, since it has the smallest area of the courtyard. The best performance was obtained by SQ. *Figure 74* illustrates the annual heating demand for all typologies with different number of floors. RC_1:2 morphology, performs poorer competed to the other morphologies. The best performance was obtained by CI_R40 due to its large courtyard area, ground contact surface and building compactness.

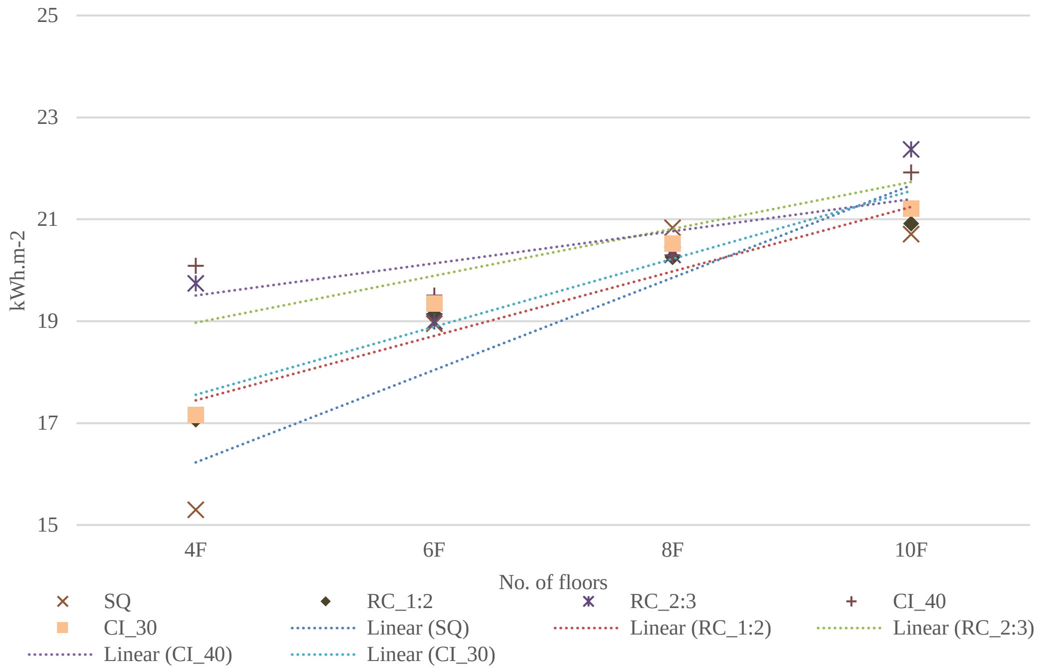



***Figure 73.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies

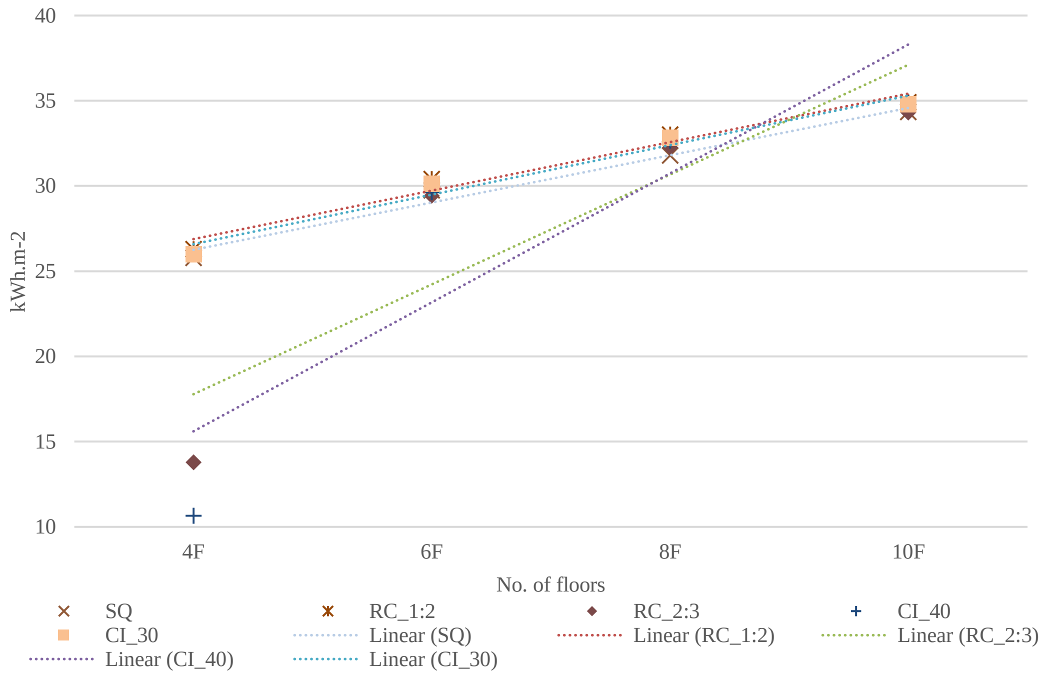


***Figure 74.*** Comparison of simulated heating demand (kWh.m$^2$) of UGB morphologies

*Figure 75* illustrates the annual total of cooling and heating demand for all typologies with different number of floors. In the total annual energy consumption, RC_1:2 morphology performs poorer. The best total performance was obtained by CI_R40 due to its large courtyard area, ground contact surface and building compactness.

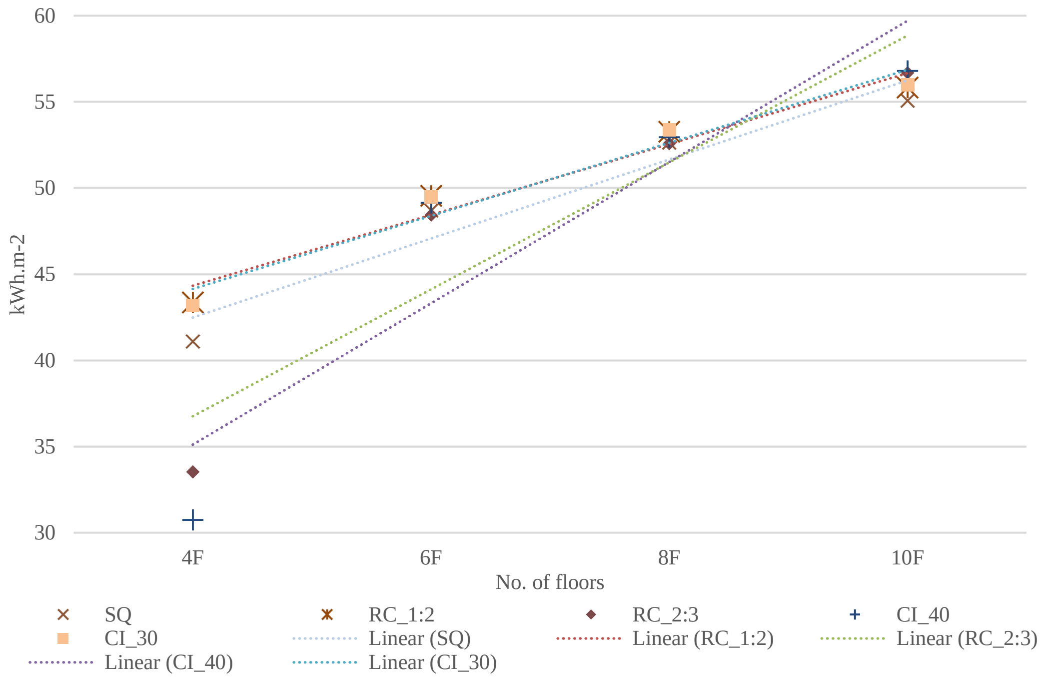



***Figure 75.*** Comparison of simulated total annual demand (kWh.m2) of UGB morphologies

### 4.1.3 WWR 90%

The following figures illustrate the correlation of annual consumption for cooling, heating and total, for five UGB morphologies and for four different floor numbers, studied for WWR 90%.

*Figure 76* illustrates the annual cooling demand for all typologies with different number of floors. As shown by the figure below, the deeper the morphologies go, they display a poor performance in an oceanic climate. CI_R40 morphology, performs poorer competed to the other morphologies. The best performance was obtained by SQ due to its largest courtyard area. *Figure 77* illustrates the annual heating demand for all typologies with different number of floors. RC_1:2 morphology, performs poorer competed to the other morphologies. The best performance was obtained by CI_R40 due to its large courtyard area, ground contact surface and building compactness.

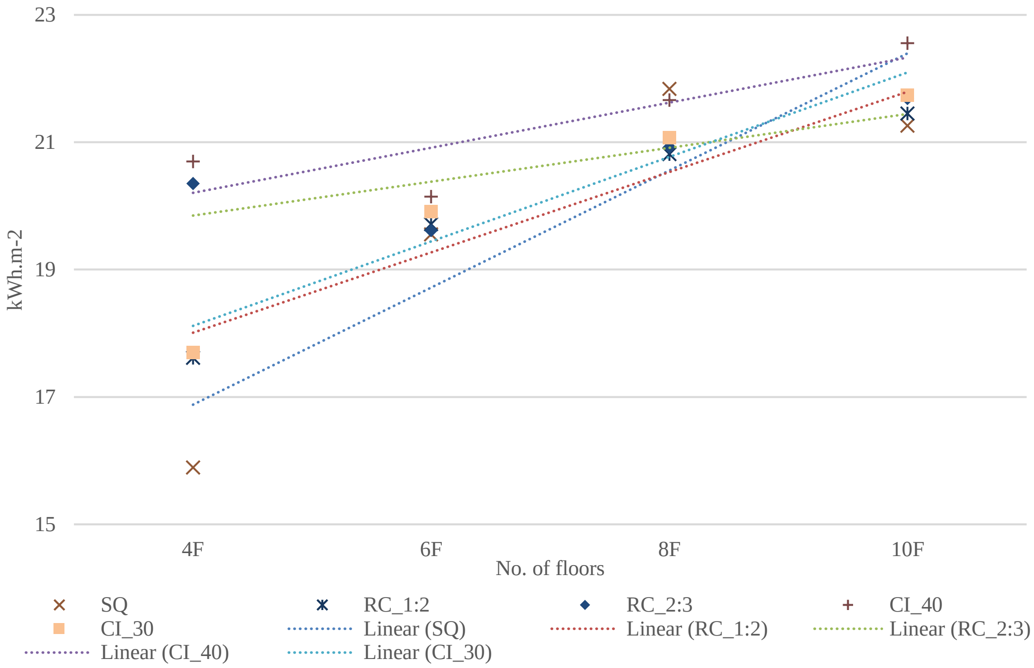



***Figure 76.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies

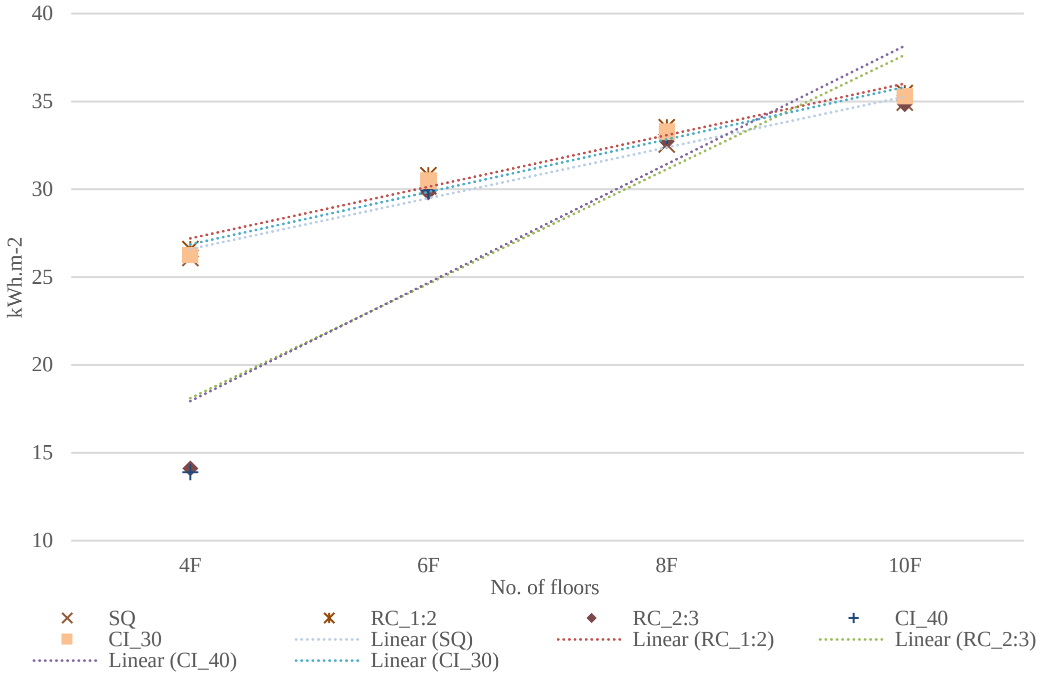



***Figure 77.*** Comparison of simulated heating demand (kWh.m$^2$) of UGB morphologies

*Figure 78* illustrates the annual total of cooling and heating demand for all typologies with different number of floors. In the total annual energy consumption, RC_1:2 morphology, performs poorer competed to the other morphologies. With a slight difference, the best total performance was obtained by CI_R40, followed by RC_2:3 morphology.

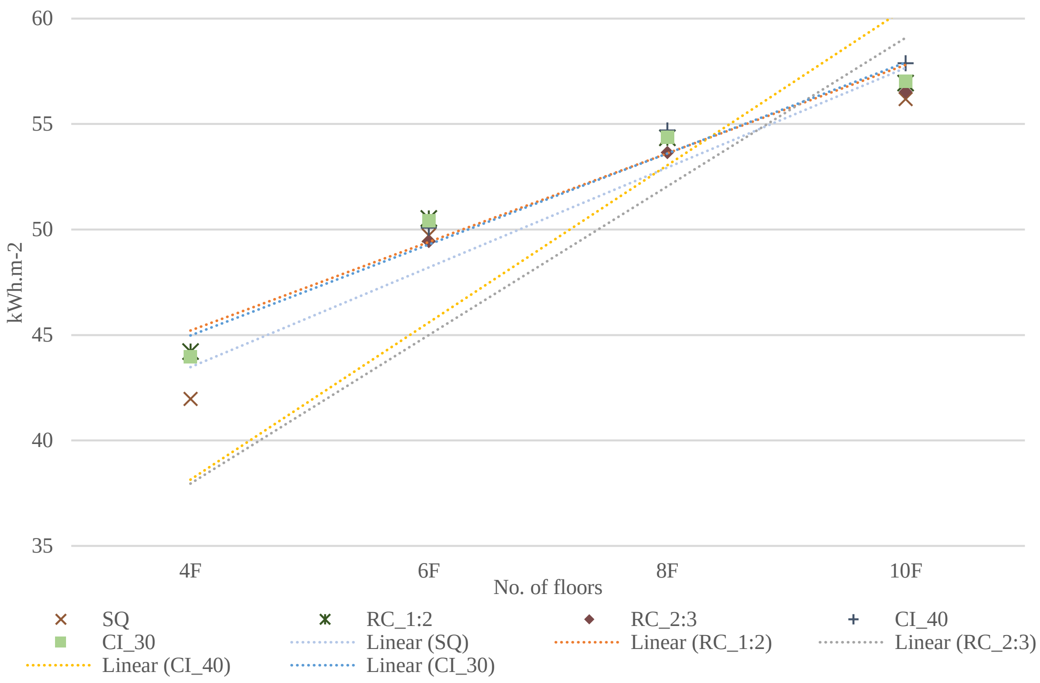



***Figure 78.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies

### 4.2.4 Morphological comparison

In *Figure 79* the comparison of the total annual energy demand of the morphologies for the climate of Berlin is illustrated, in terms of no. of floors and the transparency of the facades. As it is shown, in the annual energy demand, the trend decreases as the surface of the courtyard, the surface of contact with the ground and the compactness of the building is larger. From the results, it is clear that the deeper you go underground, the worse the building performs. For typology CI_R40 energy consumption is subject to an increase of 23 kWh.m$^{-2}$y-1, when it goes from four floors to ten underground floors, for WWR 60%. Small changes are observed with the increase in the transparency of the facade, where for each morphology, as the WWR increases, we have an increase in energy consumption by 0.8-1.9 kWh.m$^{-2}$y$^{-1}$.

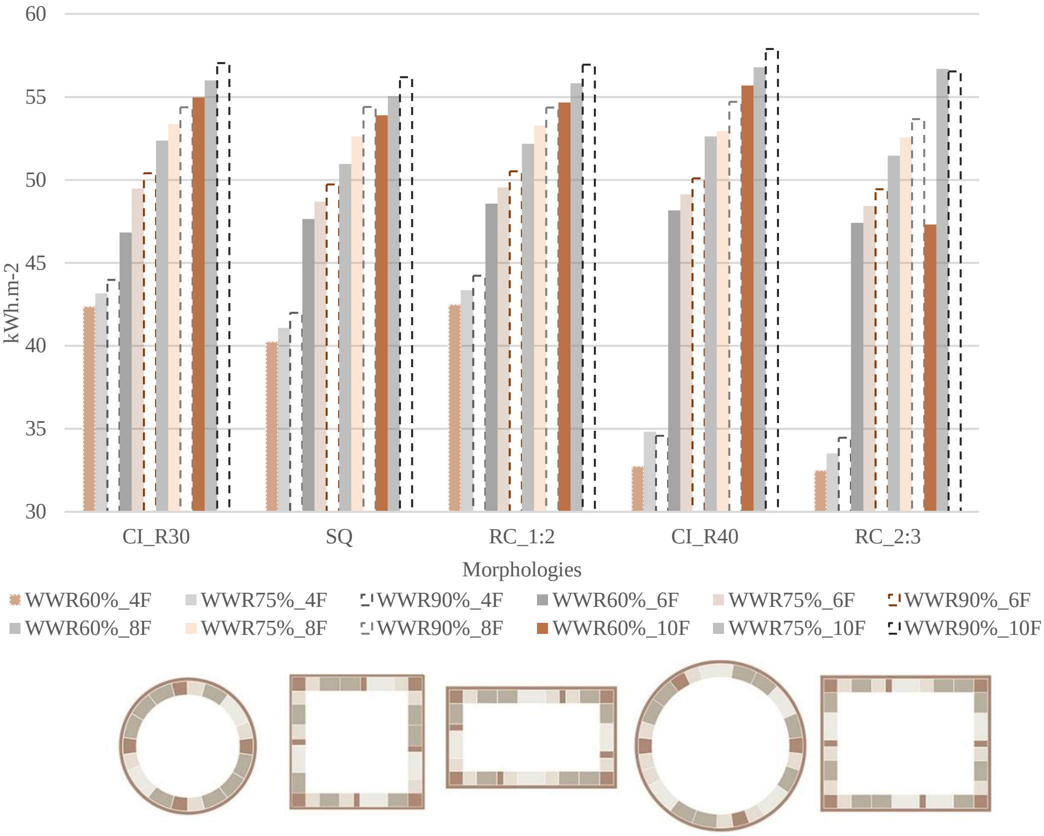



**Figure 79**. Morphological comparation of annual energy demand (kWh.m-2y-1)

*Table 10* summarizes the simulation results obtained for all the scenarios in the climate of Berlin. A maximum of 19.3% of the total annual energy consumption can be reduced by choosing the right morphology for the selected climatic context. The morphology that performs worse is RC_1:2, even though it has a bigger courtyard surface and ground contact surface compared to CI_R30, its longitudinal courtyard brings cooler air into the building. Based on transparency, this morphology consumes 5.3-5.6% more energy, while based on the number of floors, it consumes 34.7-35.8% more energy. The morphology that has the best energy performance is RC_2:3, which has a morphology effectiveness of 17.9-19.3% in terms of transparency. The reason for this result is the fact that this morphology has the largest contact surface with the ground, the largest courtyard surface and is more compact compared to other morphologies. The second morphology with the best performance is CI_R40, with a morphology effectiveness of 17.6-25.2%.

*Table 10.* Results of simulations for all morphologies.

| Scenarios | | | Annual cooling demand | | | Annual heating demand | | | Annual energy demand | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Total Heating [kWh] | Total heating [kWh.m$^2$] | ME | Total Heating [kWh] | Total heating [kWh.m$^2$] | Morph. | Total Heating [kWh] | Total heating [kWh.m$^2$] | ME |
| WWR_60% | CI_R30 | 4F | 202519.7 | 16.6 | - | 315666.4 | 25.8 | - | 518186.1 | 42.4 | - |
| | | 6F | 297908.4 | 18.7 | -13.0 | 475004.4 | 36.5 | -41.3 | 772912.8 | 55.2 | -30.2 |
| | | 8F | 390251.3 | 19.9 | -20.2 | 636801.5 | 32.5 | -25.8 | 1027052.8 | 52.4 | -23.6 |
| | | 10F | 480542.5 | 20.6 | -24.5 | 800194.8 | 34.3 | -33.1 | 1280737.3 | 55.0 | -29.7 |
| | SQ | 4F | 229851.9 | 14.7 | 11.2 | 399726.5 | 25.6 | 1.0 | 629578.4 | 40.3 | 5.0 |
| | | 6F | 373498.2 | 18.3 | -10.3 | 600674.7 | 29.4 | -13.8 | 974172.9 | 47.6 | -12.4 |
| | | 8F | 492664.3 | 19.6 | -18.1 | 791325.1 | 31.4 | -21.7 | 1283989.4 | 51.0 | -20.3 |
| | | 10F | 601017.6 | 20.1 | -21.2 | 1012459.9 | 33.8 | -31.0 | 1613477.4 | 53.9 | -27.2 |
| | RC_1:2 | 4F | 250961.7 | 16.5 | 0.7 | 397287.1 | 26.0 | -0.9 | 648248.8 | 42.5 | -0.3 |
| | | 6F | 369507.1 | 18.5 | -11.7 | 600552.9 | 30.1 | -16.5 | 970059.9 | 48.6 | -14.6 |
| | | 8F | 484444.5 | 19.6 | -18.5 | 803989.6 | 32.6 | -26.1 | 1288434.1 | 52.2 | -23.1 |
| | | 10F | 597190.1 | 20.3 | -22.6 | 1010912.6 | 34.4 | -33.1 | 1608102.6 | 54.7 | -29.0 |
| | CI_R40 | 4F | 331707.9 | 19.4 | -16.9 | 229267.5 | 13.4 | 48.2 | 560975.3 | 32.7 | 22.7 |
| | | 6F | 642745.3 | 18.8 | -13.5 | 642745.3 | 29.4 | -13.8 | 1285490.5 | 48.2 | -13.7 |
| | | 8F | 540646.6 | 20.3 | -22.5 | 861008.2 | 32.3 | -25.2 | 1401654.8 | 52.6 | -24.2 |
| | | 10F | 666267.8 | 21.2 | -28.1 | 1082040.8 | 34.5 | -33.5 | 1748308.6 | 55.7 | -31.4 |
| | RC_2:3 | 4F | 353167.8 | 19.0 | -14.7 | 250978.6 | 13.5 | 47.7 | 604146.4 | 32.5 | 23.3 |
| | | 6F | 439150.0 | 18.3 | -10.5 | 698527.5 | 29.1 | -12.8 | 1137677.5 | 47.4 | -11.9 |
| | | 8F | 576360.8 | 19.6 | -18.4 | 936526.1 | 31.9 | -23.4 | 1512886.8 | 51.5 | -21.4 |
| | | 10F | 710173.3 | 20.4 | -23.2 | 1177205.1 | 26.9 | -4.3 | 1887378.4 | 47.3 | -11.7 |
| WWR_75% | CI_R30 | 4F | 202519.7 | 17.2 | - | 318114.1 | 26.0 | - | 520633.8 | 43.2 | - |
| | | 6F | 307945.8 | 19.3 | -12.8 | 479662.7 | 30.1 | -15.8 | 787608.4 | 49.5 | -14.6 |
| | | 8F | 402302.6 | 20.5 | -19.6 | 644154.7 | 32.8 | -26.3 | 1046457.3 | 53.4 | -23.6 |
| | | 10F | 494167.3 | 21.2 | -23.6 | 810519.4 | 34.8 | -33.7 | 1304686.7 | 56.0 | -29.7 |
| | SQ | 4F | 239189.3 | 15.3 | 10.8 | 403282.3 | 25.8 | 0.9 | 642471.6 | 41.1 | 4.8 |
| | | 6F | 387574.5 | 19.0 | -10.5 | 608237.7 | 29.7 | -14.3 | 995812.2 | 48.7 | -12.8 |
| | | 8F | 525001.5 | 20.8 | -21.4 | 801069.7 | 31.8 | -22.2 | 1326071.1 | 52.6 | -21.9 |
| | | 10F | 620041.6 | 20.7 | -20.7 | 1028490.0 | 34.3 | -32.0 | 1648531.6 | 55.1 | -27.5 |
| | RC_1:2 | 4F | 260374.1 | 17.1 | 0.5 | 401049.2 | 26.3 | -1.1 | 661423.3 | 43.4 | -0.4 |
| | | 6F | 382353.1 | 19.1 | -11.6 | 607319.4 | 30.4 | -16.9 | 989672.5 | 49.5 | -14.8 |
| | | 8F | 500155.9 | 20.3 | -18.1 | 815282.8 | 33.0 | -26.9 | 1315438.7 | 53.3 | -23.4 |
| | | 10F | 615214.3 | 20.9 | -21.9 | 1026646.6 | 34.9 | -34.2 | 1641861.0 | 55.8 | -29.3 |
| | CI_R40 | 4F | 414061.8 | 24.2 | -40.9 | 233345.8 | 10.7 | 59.0 | 647407.6 | 34.8 | 19.3 |
| | | 6F | 426883.2 | 19.5 | -13.7 | 648482.4 | 29.6 | -13.9 | 1075365.6 | 49.1 | -13.8 |
| | | 8F | 559735.2 | 20.3 | -18.3 | 870033.1 | 32.7 | -25.5 | 1429768.3 | 52.9 | -22.7 |
| | | 10F | 688253.2 | 21.9 | -27.8 | 1094888.4 | 34.9 | -34.1 | 1783141.6 | 56.8 | -31.6 |
| | RC_2:3 | 4F | 367073.5 | 19.7 | -15.1 | 256271.3 | 13.8 | 47.0 | 623344.8 | 33.5 | 22.4 |
| | | 6F | 455842.1 | 19.0 | -10.7 | 706368.1 | 29.4 | -13.2 | 1162210.2 | 48.4 | -12.2 |
| | | 8F | 596888.5 | 20.3 | -18.3 | 948662.3 | 32.3 | -24.0 | 1545550.8 | 52.6 | -21.8 |
| | | 10F | 733814.3 | 22.4 | -30.4 | 1194134.6 | 34.3 | -31.9 | 1927948.8 | 56.7 | -31.3 |
| WWR_90% | CI_R30 | 4F | 216473.6 | 17.7 | - | 321336.4 | 26.3 | - | 537810.0 | 44.0 | - |
| | | 6F | 317037.2 | 19.9 | -12.5 | 485452.1 | 30.5 | -16.1 | 802489.3 | 50.4 | -14.6 |
| | | 8F | 413216.2 | 21.1 | -19.0 | 652874.6 | 33.3 | -26.7 | 1066090.8 | 54.4 | -23.6 |
| | | 10F | 506467.3 | 21.7 | -22.8 | 822429.9 | 35.3 | -25.6 | 1328897.2 | 57.0 | -29.7 |
| | SQ | 4F | 248563.4 | 15.9 | 10.2 | 407964.9 | 26.1 | 0.7 | 656528.3 | 42.0 | 4.5 |
| | | 6F | 399933.8 | 19.6 | -10.5 | 616993.7 | 30.2 | -14.8 | 1016927.4 | 49.7 | -13.1 |
| | | 8F | 550274.0 | 21.8 | -23.4 | 820130.9 | 32.5 | -23.9 | 1370404.9 | 54.4 | -23.7 |
| | | 10F | 636674.2 | 21.3 | -20.1 | 1045910.2 | 34.9 | -32.9 | 1682584.4 | 56.2 | -27.8 |
| | RC_1:2 | 4F | 268772.5 | 17.6 | 0.5 | 405867.9 | 26.6 | -1.3 | 674640.4 | 44.2 | -0.6 |
| | | 6F | 393826.2 | 19.7 | -11.4 | 615451.4 | 30.8 | -17.3 | 1009277.6 | 50.5 | -14.9 |
| | | 8F | 514089.7 | 20.8 | -17.6 | 828091.1 | 33.5 | -27.6 | 1342180.9 | 54.3 | -23.6 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 10F | 631114.0 | 21.5 | -21.2 | 1044032.0 | 35.5 | -35.1 | 1675146.0 | 56.9 | -29.5 |
| CI_R40 | 4F | 354671.8 | 20.7 | -17.0 | 237914.6 | 13.9 | 47.1 | 592586.4 | 34.6 | 21.3 |
| | 6F | 441013.9 | 20.1 | -13.8 | 655293.7 | 29.9 | -13.9 | 1096307.6 | 50.1 | -13.9 |
| | 8F | 577136.6 | 21.7 | -22.4 | 880439.7 | 33.0 | -25.8 | 1457576.3 | 54.7 | -24.4 |
| | 10F | 708255.8 | 22.6 | -27.4 | 1109310.4 | 35.3 | -34.5 | 1817566.2 | 57.9 | -31.6 |
| RC_2:3 | 4F | 378510.2 | 20.4 | -15.0 | 262315.8 | 14.1 | 46.3 | 640826.0 | 34.5 | 21.6 |
| | 6F | 470779.6 | 19.6 | -10.8 | 715564.5 | 29.8 | -13.5 | 1186344.1 | 49.4 | -12.4 |
| | 8F | 615257.0 | 20.9 | -18.2 | 962387.4 | 32.7 | -24.6 | 1577644.4 | 53.7 | -22.0 |
| | 10F | 754900.3 | 21.7 | -22.5 | 1212833.2 | 34.8 | -32.6 | 1967733.5 | 56.5 | -28.6 |

## 4.4 Climate comparison

*Figure 80* compares the simulated energy demand (kWh.m$^{-2}$Y$^{-1}$) for five morphologies, in 6 floors, with 60% transparency, in four climatic contexts. New York's humid subtropical climate displays the highest energy demand. Ranked second, with a considerable difference from the climate of New York, is the hot-summer Mediterranean climate of Athens. The best energy performance is shown by Berlin's oceanic climate, realizing that the underground has a better effect in colder climates. For the RC_2:3 morphology, Berlin performs 50.1% better than New York, while Athens performs 24.2% better. The RC_2:3 morphology performs better for the New York and Berlin climates, while with a very small difference from the SQ morphology, it performs second for the Athens climate. For all three climates, the morphology that performs the worst is CI_R30.

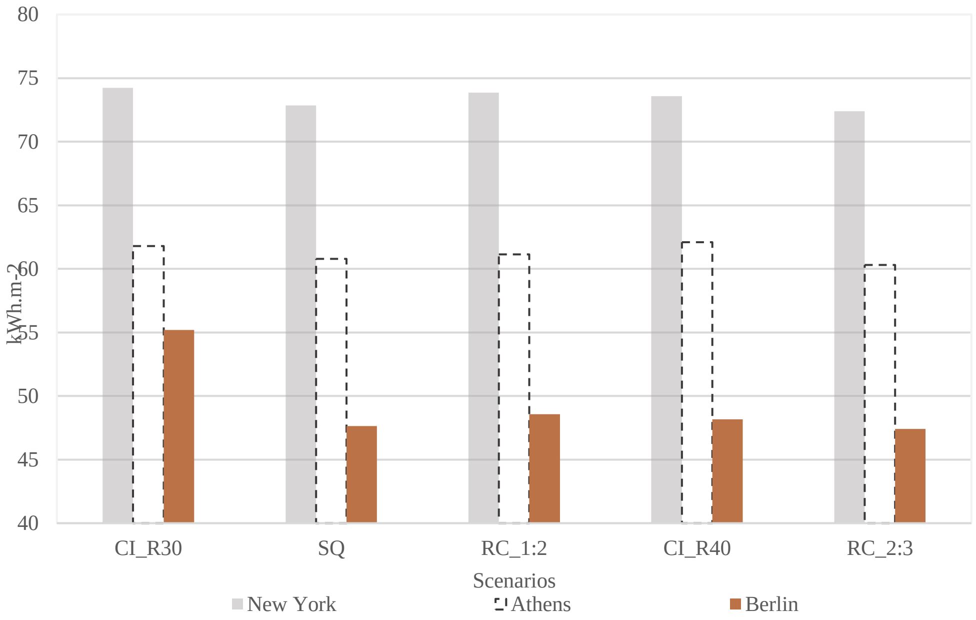


*Figure 80*. Comparison of annual simulation energy demand (kWh.m$^{-2}$y$^{-1}$) for 6 floors morphologies, with a WWR 60%, in 3 climatic contexts

According to the suitability gradient shown in *Figure 81* set based on the results of the simulation scenarios, CI_R30 is not suitable for any climate. The RC_2:3 morphology is more suitable for subcontinental and oceanic climates, but for the Mediterranean hot-summer climate the morphology that performs better is that of SQ.

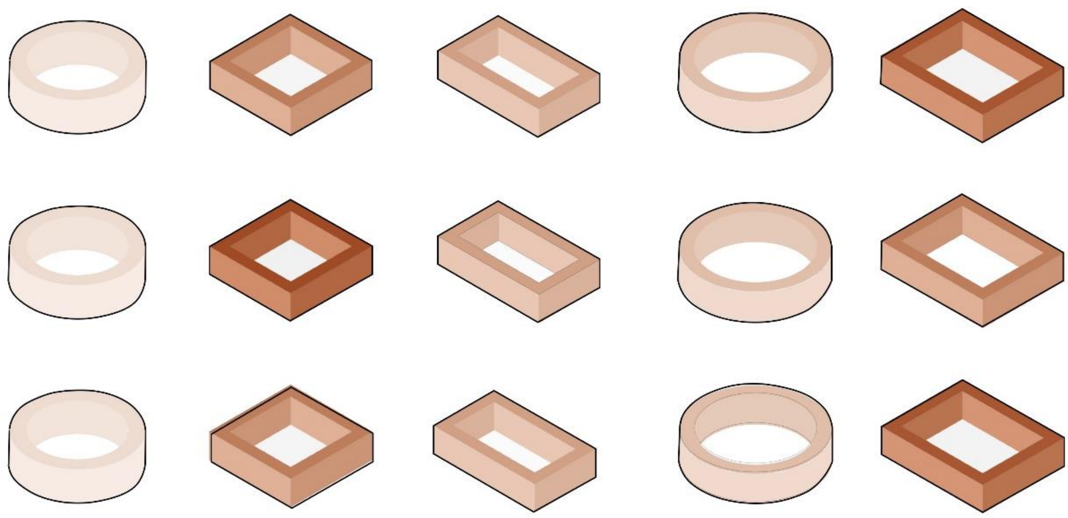


***Figure 81.*** Suitability gradient for UGB morphologies in the studied climatic context

A higher optimization of energy consumption in terms of morphology selection can be reached in oceanic climatic regions, as displayed in *Table 11*.

***Table 11.*** Total morphology effectiveness (%)

| | | **WWR 60%** | | | **WWR 75%** | | | **WWR 90%** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Scenarios | | New York | Athens | Berlin | New York | Athens | Berlin | New York | Athens | Berlin |
| CI_R30 | 4F | - | 16.3 | 34.9 | - | 34.9 | 34.9 | - | 14.8 | 34.8 |
| | 6F | -14.0 | 5.1 | 15.2 | -14.0 | 25.4 | 25.4 | -14.0 | 3.5 | 25.2 |
| | 8F | -22.7 | -1.6 | 19.5 | -22.6 | 19.5 | 19.5 | -22.5 | -3.1 | 19.3 |
| | 10F | -28.5 | -5.9 | 15.6 | -28.4 | 15.5 | 15.5 | -28.3 | -7.3 | 15.4 |
| SQ | 4F | 7.4 | 24.2 | 38.2 | 7.3 | 23.2 | 38.0 | 7.0 | 22.1 | 37.7 |
| | 6F | -11.9 | 6.6 | 26.8 | -12.2 | 5.7 | 26.6 | -12.2 | 4.8 | 26.2 |
| | 8F | -20.3 | 0.7 | 21.7 | -20.5 | -0.5 | 20.6 | -20.6 | -2.3 | 19.3 |
| | 10F | -30.3 | -7.7 | 17.2 | -26.2 | -5.1 | 16.9 | -26.2 | -5.9 | 16.6 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| RC_1:2 | 4F | 0.2 | 16.9 | 34.7 | 0.6 | 16.4 | 34.6 | 0.7 | 15.9 | 34.4 |
| | 6F | -13.5 | 6.1 | 25.4 | -13.1 | 5.6 | 25.3 | -12.9 | 5.1 | 25.0 |
| | 8F | -21.7 | -0.3 | 17.3 | -21.4 | -0.8 | 19.6 | -21.3 | -1.4 | 19.4 |
| | 10F | -27.4 | -4.6 | 16.0 | -27.2 | -5.2 | 15.8 | -27.1 | -5.7 | 15.5 |
| CI_R40 | 4F | 15.5 | 22.7 | 49.7 | 15.0 | 22.0 | 47.5 | 15.0 | 21.0 | 48.7 |
| | 6F | -14.7 | 4.6 | 26.0 | -14.3 | 3.8 | 25.9 | -16.6 | 7.6 | 25.7 |
| | 8F | -23.4 | -4.8 | 19.2 | -21.1 | -0.7 | 20.1 | -22.6 | -4.3 | 18.8 |
| | 10F | -30.2 | -3.5 | 14.5 | -30.2 | -8.8 | 14.3 | -30.2 | -9.6 | 14.1 |
| RC_2:3 | 4F | 16.3 | 23.8 | 50.1 | 16.1 | 10.7 | 49.4 | 15.8 | 22.1 | 48.9 |
| | 6F | -11.2 | 7.4 | 27.2 | -11.1 | 6.6 | 28.5 | -11.1 | 5.7 | 26.7 |
| | 8F | -24.2 | 0.1 | 20.9 | -20.3 | -0.7 | 20.7 | -20.3 | -1.5 | 20.4 |
| | 10F | -18.7 | -3.5 | 27.3 | -27.8 | -11.6 | 14.5 | -26.6 | -6.3 | 16.1 |

# CHAPTER 5

# BALCONIES SCENARIOS

The results generated by the software are evaluated and presented in charts. Computer simulations, combining five morphologies of four floors, with different WWR and balcony width, have been calculated computationally. The results for all morphologies of six, eight and ten floors, with a different WWR and balcony width. The results obtained show the correlation that exists between different morphologies and the energy performance of UGB.

## 5.1 New York

A comparison between annual cooling, annual heating and annual total energy consumption inside the apartments for four different balcony scenarios is illustrated in the figures below, to determine the impact of the humid subtropical climate of New York on the recommended morphologies.

### 5.1.1 WWR 60%

The following figures illustrate the correlation of annual consumption for cooling, heating and total, for five UGB morphologies, 4F scenario and four different balcony scenarios, studied for WWR 60%.

*Figure 82* illustrates the annual cooling demand for all typologies for 4F scenarios and balcony scenarios. Apparently, the wider the balcony, the better the energy performance shown by the morphologies is. CI_R30 morphology, performs poorer, competed to the other morphologies, since it has the smallest area of the courtyard and ground contact surface and is the most compact building. The best performance was obtained by SQ. *Figure 83* illustrates the annual heating demand for all typologies with different number of floors. Unlike the cooling case, for heating, the wider the balcony, the weaker the energy performance of the morphology. RC_1:2 morphology, performs poorer competed to the other morphologies. The best performance was obtained by RC_2:3 and CI_R40, with a significant difference from the rest of morphologies.

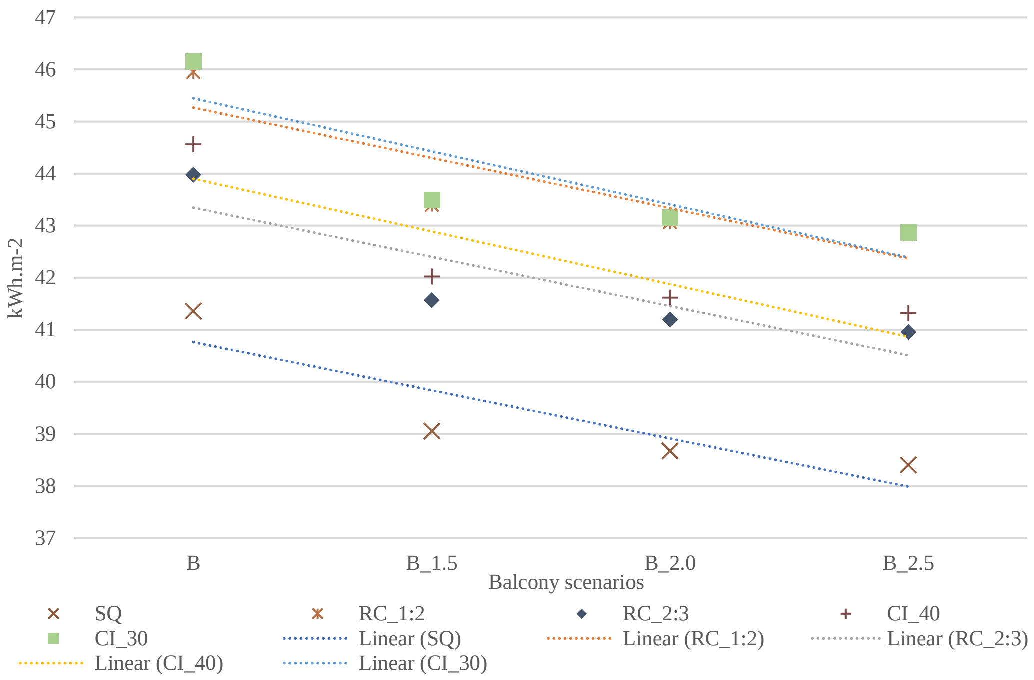



***Figure 82.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for balconies' scenarios

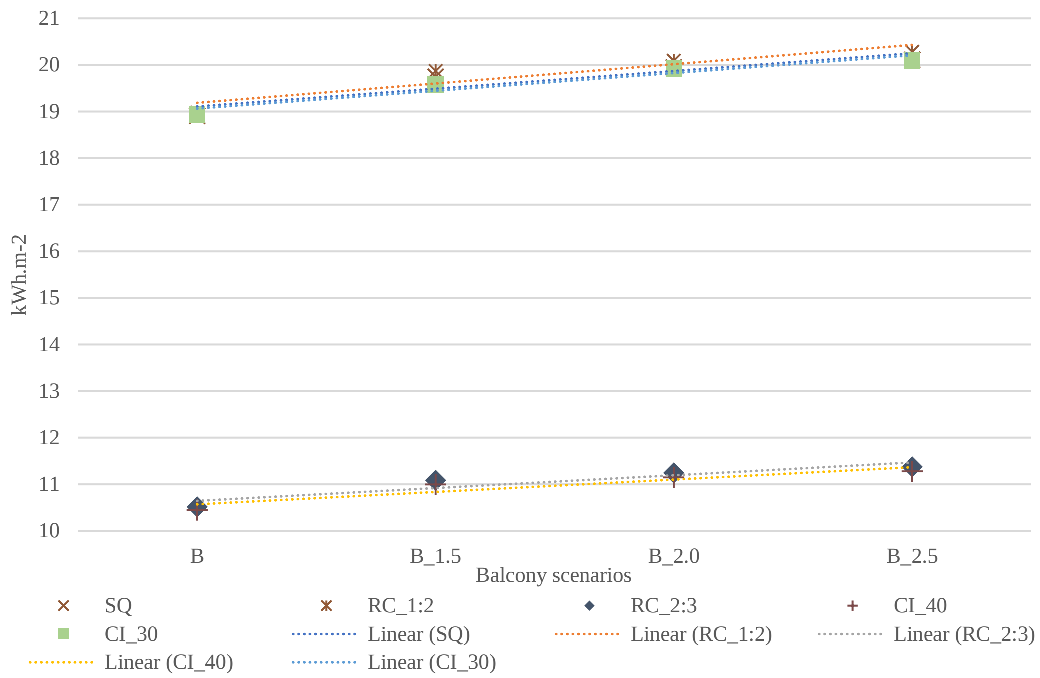



***Figure 83.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for balconies' scenarios

*Figure 84* illustrates the annual total of cooling and heating demand for all typologies, for 4F and balconies scenario. Apparently, although with a very small difference, the wider the balcony, the better a morphology performs. In the total annual energy consumption, CI_R30 morphology performs poorer. The best total performance was obtained by RC_2:3.

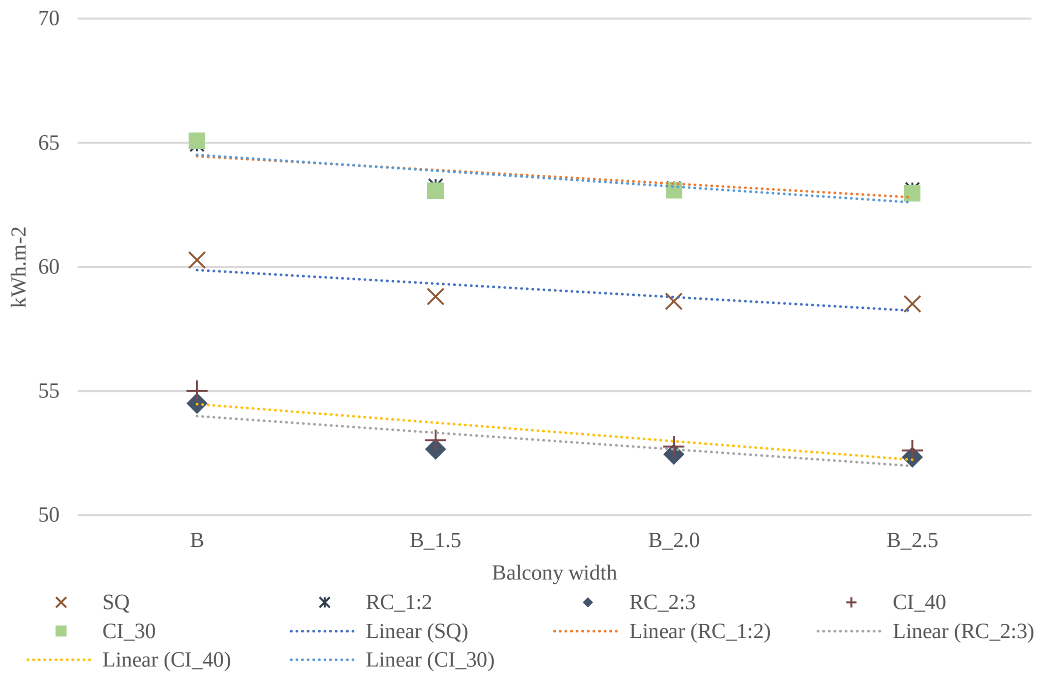



***Figure 84.*** Comparison of simulated annual energy demand (kWh.m2) of UGB morphologies for balconies' scenarios

### 5.1.2 WWR 75%

The following figures illustrate the correlation of annual consumption for cooling, heating and total, for five UGB morphologies, 4F scenario and four different balcony scenarios, studied for WWR 75%.

*Figure 85* illustrates the annual cooling demand for all typologies for 4F scenarios and balcony scenarios. Apparently, the wider the balcony, the better the energy performance shown by the morphologies is. CI_R30 morphology, performs poorer, competed to the other morphologies, since it has the smallest area of the courtyard and ground contact surface and is the most compact building. The best performance was obtained by SQ. **Figure 86** illustrates the annual heating demand for all typologies with different number of floors. Unlike the cooling case, apart for the CI_40 morphology, for heating the wider the balcony, the weaker the energy performance of the morphology is. RC_1:2 morphology, performs poorer competed to the other morphologies. The best performance was obtained by CI_R40.

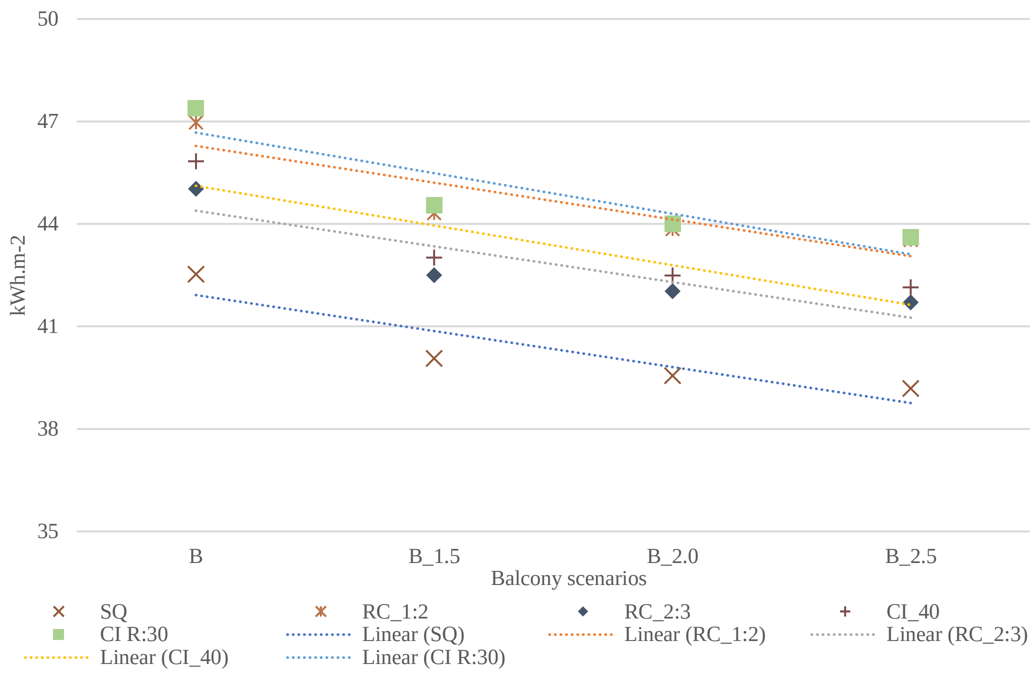



***Figure 85.***Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for balconies' scenarios

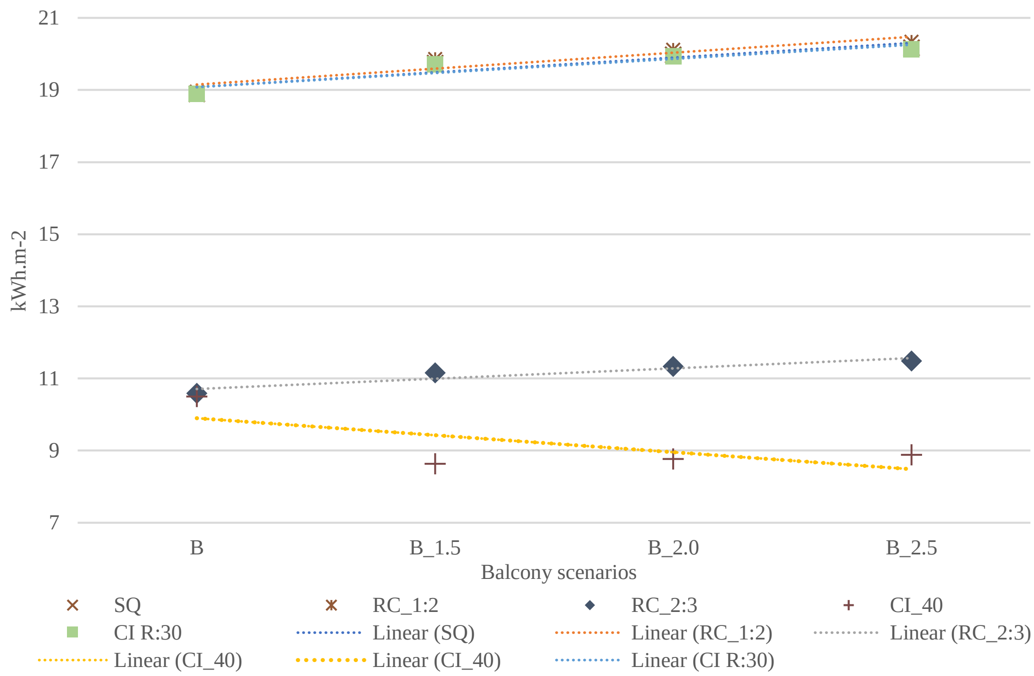



***Figure 86.***Comparison of simulated heating demand (kWh.m2) of UGB morphologies for balconies' scenarios

*Figure 87* illustrates the annual total of cooling and heating demand for all

typologies, for 4F and balconies scenario. Apparently, although with a very small difference, the wider the balcony, the better a morphology performs. In the total annual energy consumption, CI_R30 morphology performs poorer. The best total performance was obtained by CI_R40.

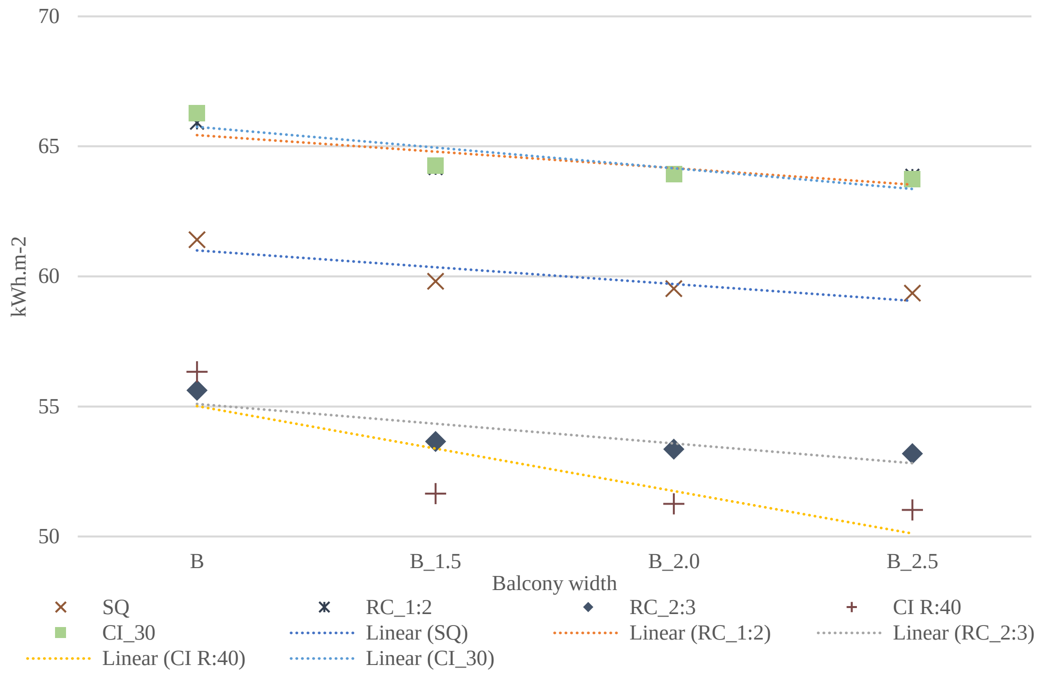



***Figure 87***. Comparison of simulated annual energy demand (kWh.m2) of UGB morphologies for balconies' scenarios

### 5.1.3 WWR 90%

The following figures illustrate the correlation of annual consumption for cooling, heating and total, for five UGB morphologies, 4F scenario and four different balcony scenarios, studied for WWR 90%.

*Figure 88* illustrates the annual cooling demand for all typologies for 4F scenarios and balcony scenarios. Apparently, the wider the balcony, the better the energy performance shown by the morphologies is. CI_R30 morphology, performs poorer, competed to the other morphologies, since it has the smallest area of the courtyard and ground contact surface and is the most compact building. The best performance was obtained by SQ. *Figure 89* illustrates the annual heating demand for all typologies with different number of floors. Unlike the cooling case, for heating the wider the balcony, the weaker the energy performance of the morphology is. RC_1:2 morphology, performs poorer competed to the other morphologies. The best performance was obtained by CI_R40 and RC_2:3.

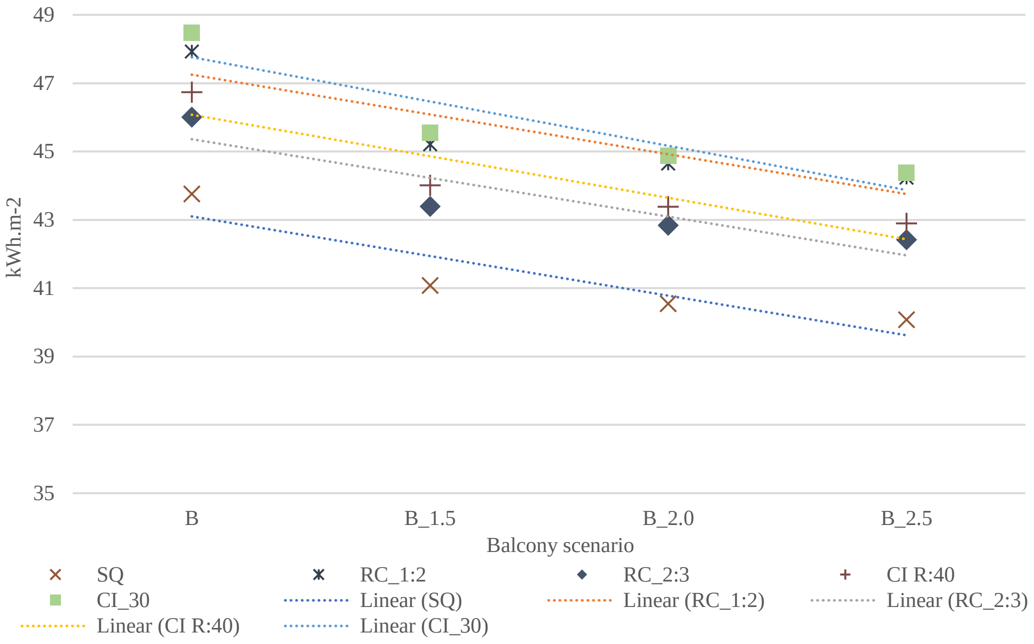



***Figure 88.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for balconies' scenarios

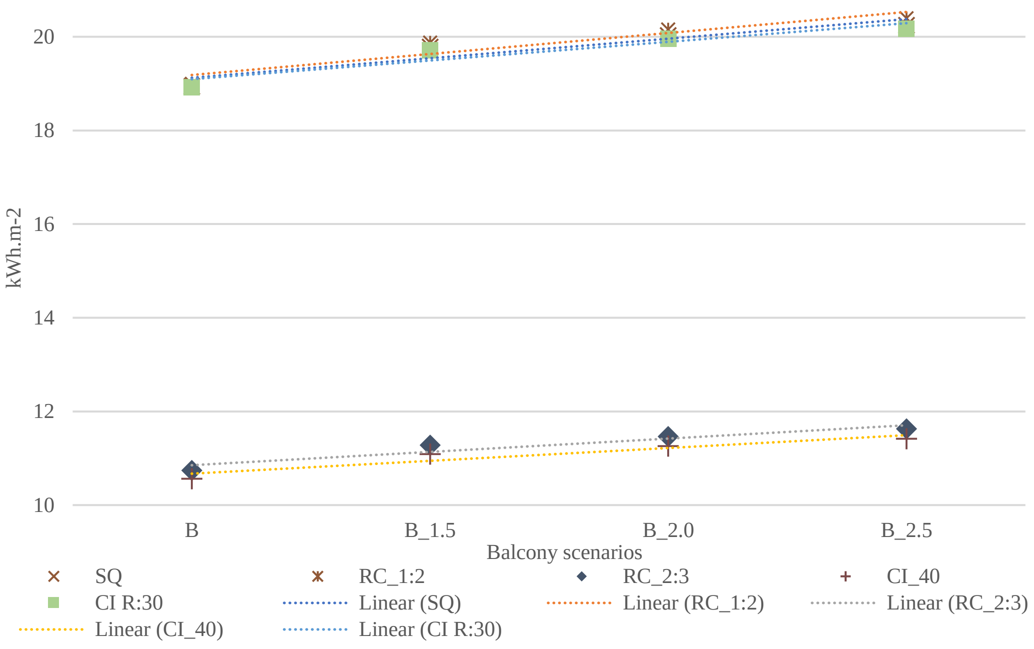


***Figure 89.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for balconies' scenarios

*Figure 90* illustrates the annual total of cooling and heating demand for all typologies, for 4F and balconies scenario. Apparently, although with a very small difference, the wider the balcony, the better a morphology performs. In the total annual energy consumption, CI_R30 morphology performs poorer. The best total performance was obtained by CI_R40.

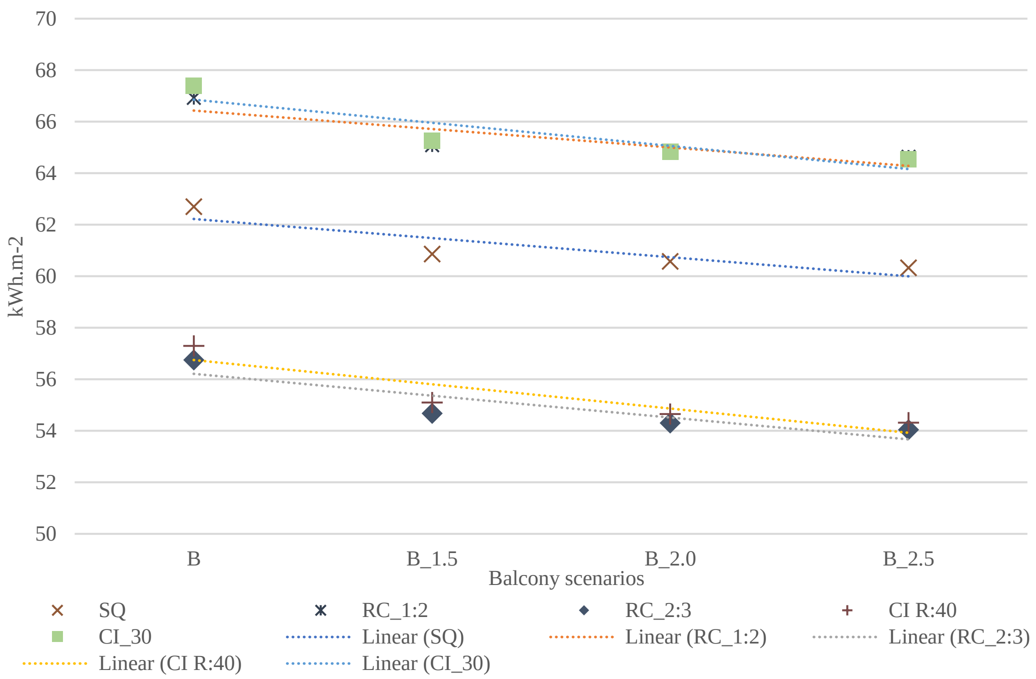



***Figure 90.*** Comparison of simulated annual energy demand (kWh.m2) of UGB morphologies for balconies' scenarios

### 5.1.4 Morphological comparison

In *Figure 91* the comparison of the total annual energy demand of the morphologies for the climate of New York is illustrated, in terms of no. of floors and the balcony scenarios, for a façade transparency of 60%. As it is shown, in the annual energy demand, the trend decreases as the width of the balcony increases. For typology CI_R40 energy consumption is subject to an increase of 29.74 $kWh.m^{-2}y^{-1}$, when it goes from four floors to ten underground floors, for WWR 60%. Small changes are observed with the increase of balconies' width, where for all morphologies, as the balcony width increases, we have an increase in energy consumption by 1.75-2.4 kWh.m$^{-2}$y$^{-1}$.

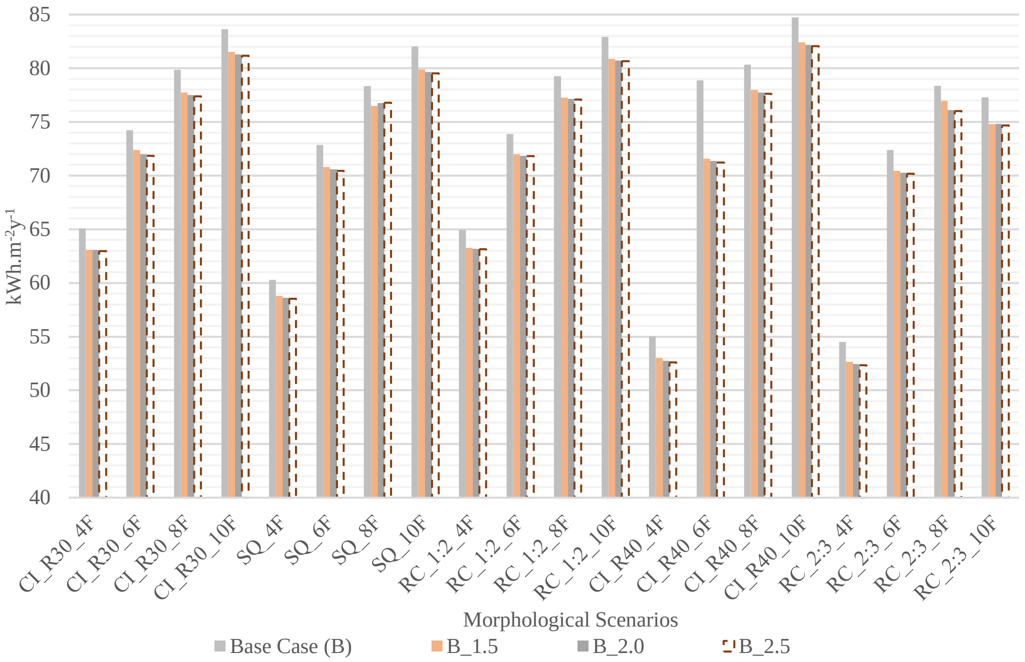



***Figure 91.*** Morphological comparation of annual energy demand (kWh.m-2y-1)

*Table 12* summarizes the simulation results obtained for all the scenarios in the climate of Berlin. A maximum of 19.2% of the total annual energy consumption can be reduced by choosing the right morphology for the selected climatic context. The morphology that performs the poorest is CI_R30, which for the B_1.5 scenario consumes 3.1% less energy and for the scenario B_2.5 consumes 3.3% less. The morphology that performs better is RC_2:3, which has an effectiveness of 16.3% for the base case and an effectiveness of 19.6% for B_2.5.

***Table 12.*** Comparison of morphologies' effectiveness for WWR_60%

| Scenarios | | B | B_1.5 | B_2.0 | B_2.5 |
|---|---|---|---|---|---|
| CI_R30 | 4F | - | 3.1 | 3.1 | 3.3 |
| | 6F | - | 2.5 | 3.0 | 3.2 |
| | 8F | - | 2.6 | 2.9 | 3.1 |
| | 10F | - | 2.6 | 2.8 | 3.0 |
| SQ | 4F | 7.4 | 9.7 | 9.9 | 10.1 |
| | 6F | 1.9 | 4.6 | 4.9 | 5.1 |
| | 8F | 1.9 | 4.2 | 3.9 | 3.8 |

| | | | | | |
|---|---|---|---|---|---|
| | 10F | 1.9 | 4.5 | 4.8 | 4.9 |
| RC_1:2 | 4F | 0.2 | 3.0 | 3.0 | 3.0 |
| | 6F | 0.5 | 3.1 | 3.2 | 3.3 |
| | 8F | 0.8 | 3.3 | 3.4 | 3.5 |
| | 10F | 0.9 | 3.4 | 3.5 | 3.6 |
| CI_R40 | 4F | 15.5 | 18.5 | 18.9 | 19.2 |
| | 6F | -6.3 | 3.6 | 3.9 | 4.0 |
| | 8F | -0.6 | 2.3 | 2.6 | 2.8 |
| | 10F | -1.3 | 1.5 | 1.8 | 1.9 |
| RC_2:3 | 4F | 16.3 | 19.1 | 19.4 | 19.6 |
| | 6F | 2.5 | 5.1 | 5.3 | 5.5 |
| | 8F | 1.9 | 3.6 | 4.7 | 4.8 |
| | 10F | 7.6 | 10.6 | 10.6 | 10.7 |

## 5.2 Athens

A comparison between annual cooling, annual heating and annual total energy consumption inside the apartments for four different balcony scenarios is illustrated in the figures below, to determine the impact of the hot-summer Mediterranean climate of Athens on the recommended morphologies.

### 5.2.1 WWR 60%

The following figures illustrate the correlation of annual consumption for cooling, heating and total, for five UGB morphologies, 4F scenario and four different balcony scenarios, studied for WWR 60%.

*Figure 92* illustrates the annual cooling demand for all typologies for 4F scenarios and balcony scenarios. Apparently, the wider the balcony, the better the energy performance shown by the morphologies is. CI_R30 morphology, performs poorer, competed to the other morphologies, since it has the smallest area of the courtyard and ground contact surface and is the most compact building. The best performance was obtained by RC_2:3. *Figure 95* illustrates the annual heating demand for all typologies with different number of floors. Unlike the cooling case, for heating, the wider the balcony, the weaker the energy performance of the morphology. RC_1:2 morphology, performs poorer competed to the other morphologies. The best performance was obtained by RC_2:3.

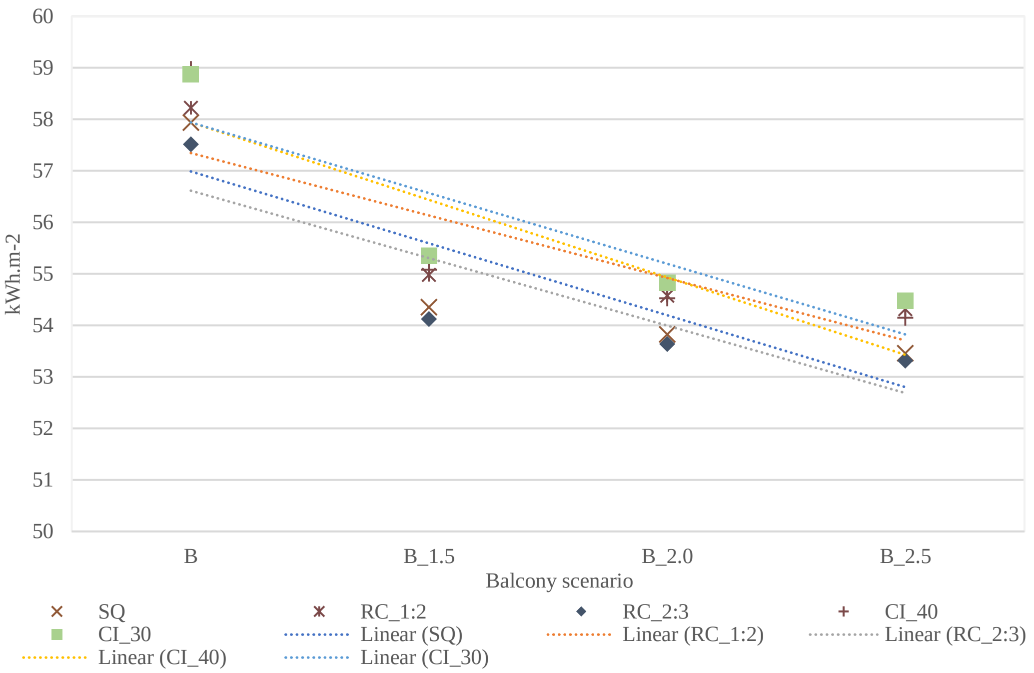



***Figure 92.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for balconies' scenarios

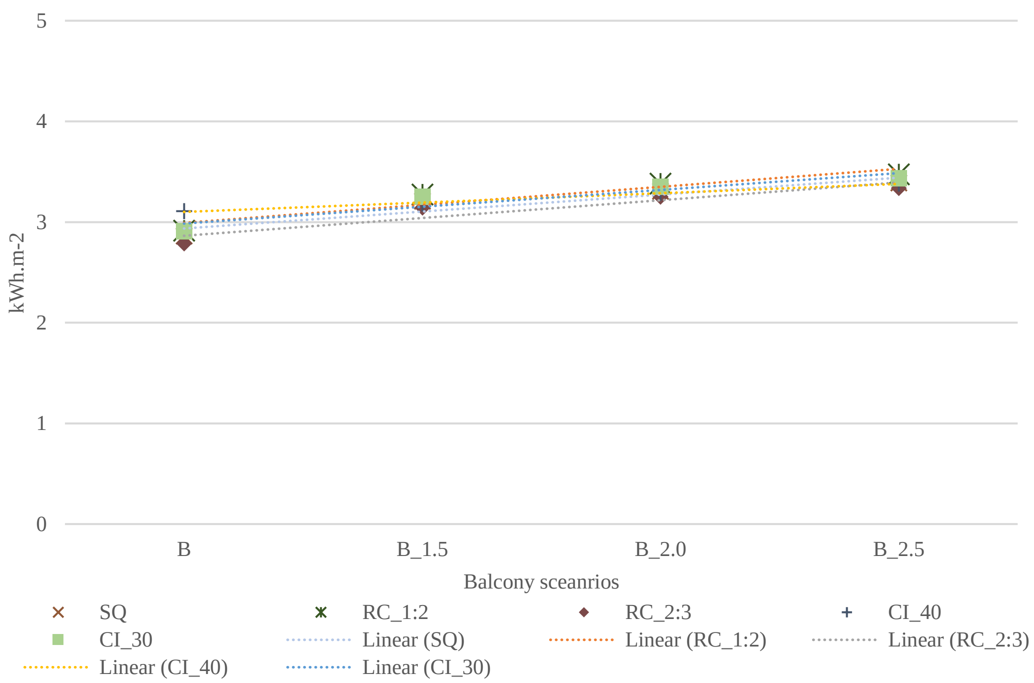



***Figure 93.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for balconies' scenarios

*Figure 94* illustrates the annual total of cooling and heating demand for all

typologies, for 4F and balconies scenario. Apparently, although with a very small difference, the wider the balcony, the better a morphology performs. In the total annual energy consumption, CI_R30 morphology performs poorer. The best total performance was obtained by RC_2:3.

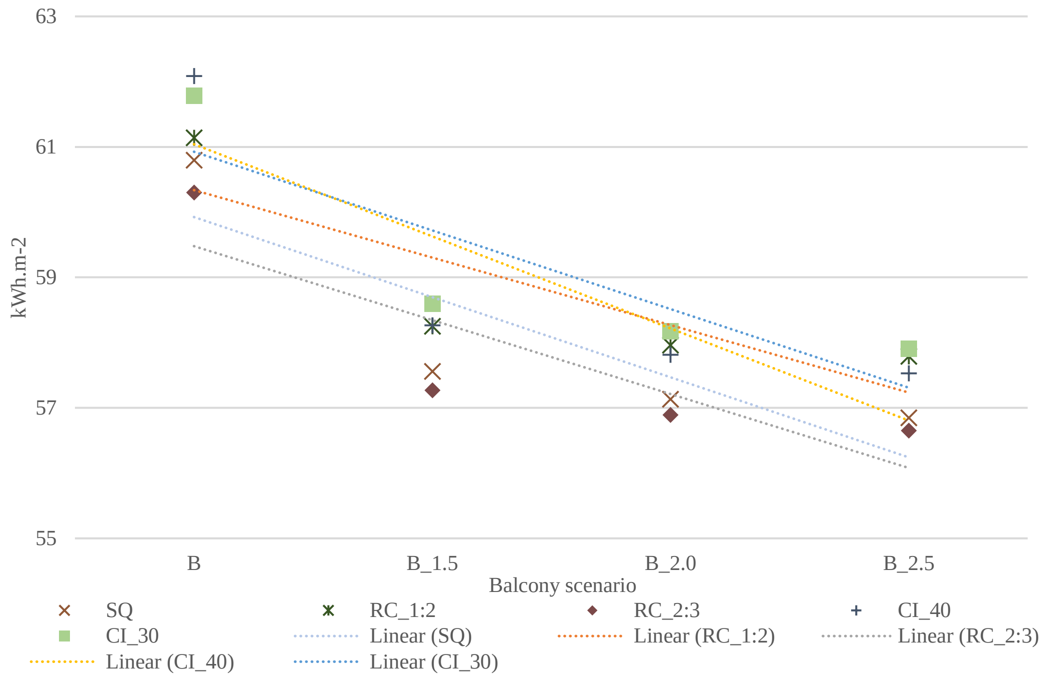



***Figure 94.*** Comparison of simulated annual energy demand (kWh.m2) of UGB morphologies for balconies' scenarios

### 5.2.2 WWR 75%

The following figures illustrate the correlation of annual consumption for cooling, heating and total, for five UGB morphologies, 4F scenario and four different balcony scenarios, studied for WWR 75%.

*Figure 95* illustrates the annual cooling demand for all typologies for 4F scenarios and balcony scenarios. Apparently, the wider the balcony, the better the energy performance shown by the morphologies is. CI_R30 morphology, performs poorer, competed to the other morphologies, since it has the smallest area of the courtyard and ground contact surface and is the most compact building. The best performance was obtained by SQ. *Figure 96* illustrates the annual heating demand for all typologies with different number of floors. Unlike the cooling case, for heating the wider the balcony, the weaker the energy performance of the morphology is. SQ morphology, performs poorer competed to the other morphologies. The best performance was obtained by CI_R40.

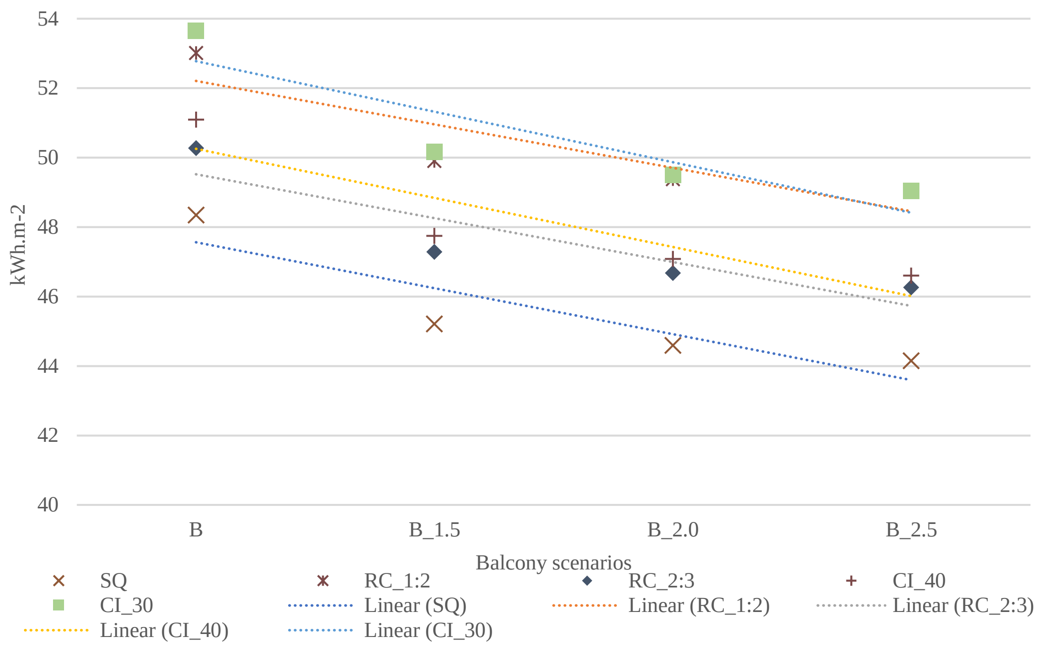



***Figure 95.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for balconies' scenarios

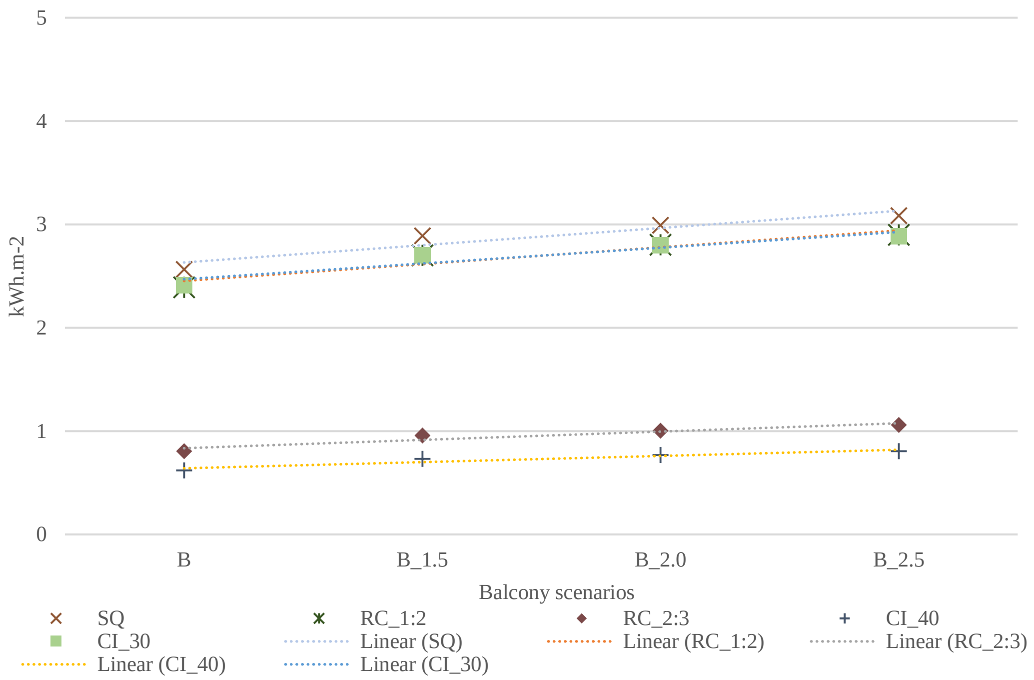



***Figure 96.*** Comparison of simulated heating demand (kWh.m2) of UGB

morphologies for balconies' scenarios

*Figure 97* illustrates the annual total of cooling and heating demand for all typologies, for 4F and balconies scenario. Apparently, although with a very small difference, the wider the balcony, the better a morphology performs. In the total annual energy consumption, CI_R30 morphology performs poorer. The best total performance was obtained by SQ and RC_2:3.

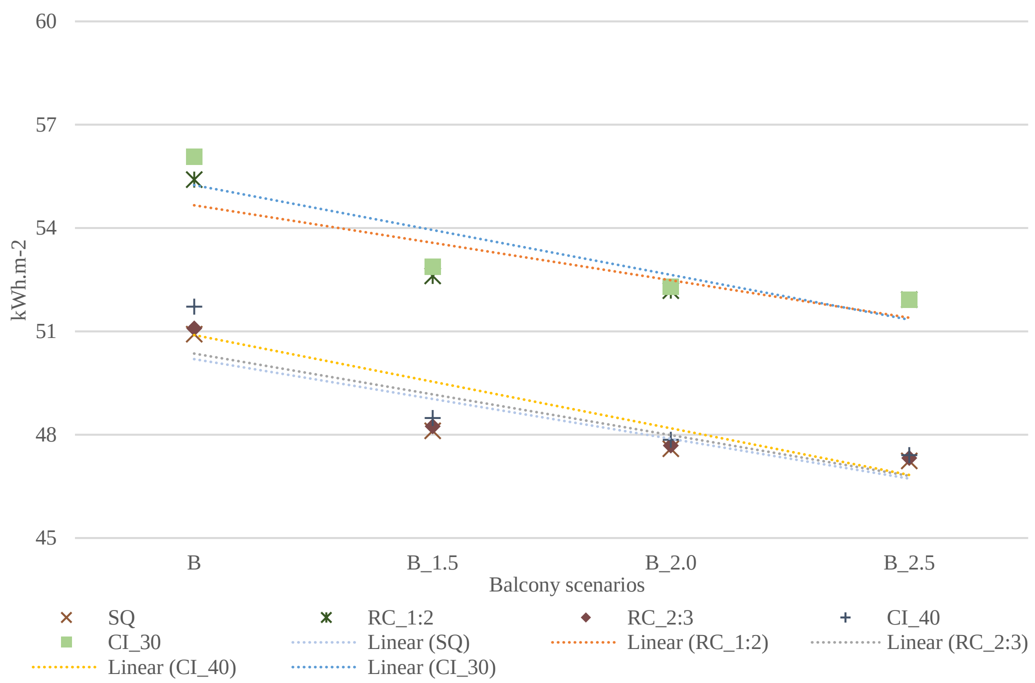



***Figure 97.*** Comparison of simulated annual energy demand (kWh.m2) of UGB morphologies for balconies' scenarios

### 5.2.3 WWR 90%

The following figures illustrate the correlation of annual consumption for cooling, heating and total, for five UGB morphologies, 4F scenario and four different balcony scenarios, studied for WWR 90%.

*Figure 98* illustrates the annual cooling demand for all typologies for 4F scenarios and balcony scenarios. Apparently, the wider the balcony, the better the energy performance shown by the morphologies is. CI_R30 morphology, performs poorer, competed to the other morphologies, since it has the smallest area of the courtyard and ground contact surface and is the most compact building. The best performance was obtained by SQ. *Figure 99* illustrates the annual heating demand for all typologies with different number of floors. Unlike the cooling case, for heating the wider the balcony, the weaker the energy performance of the morphology is. SQ morphology, performs poorer competed to the other morphologies. The best performance was obtained by CI_R40 and RC_2:3.

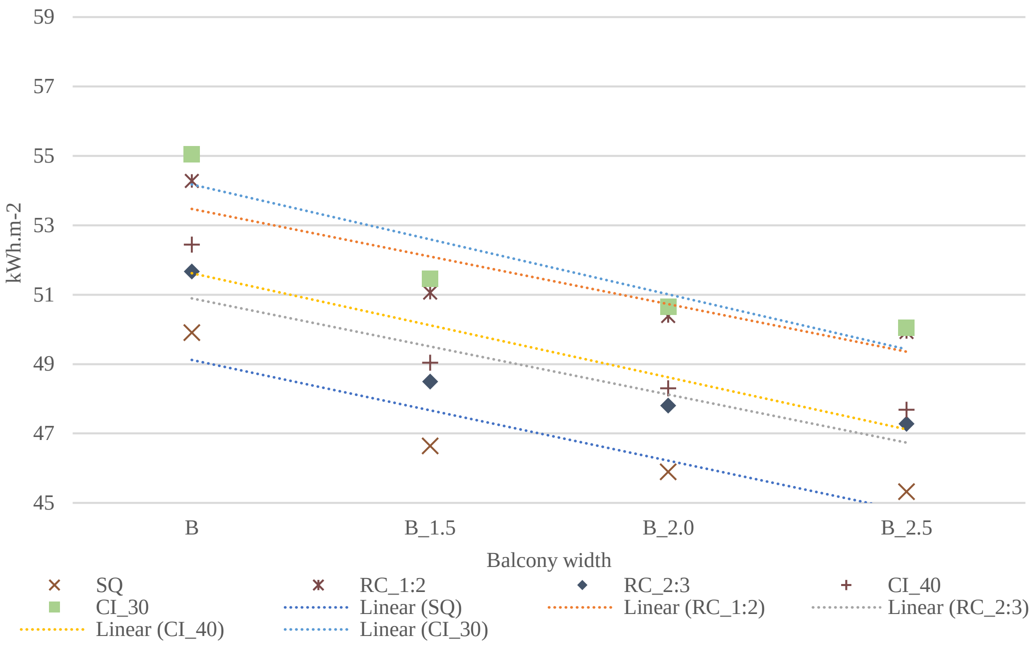



***Figure 98.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for balconies' scenarios

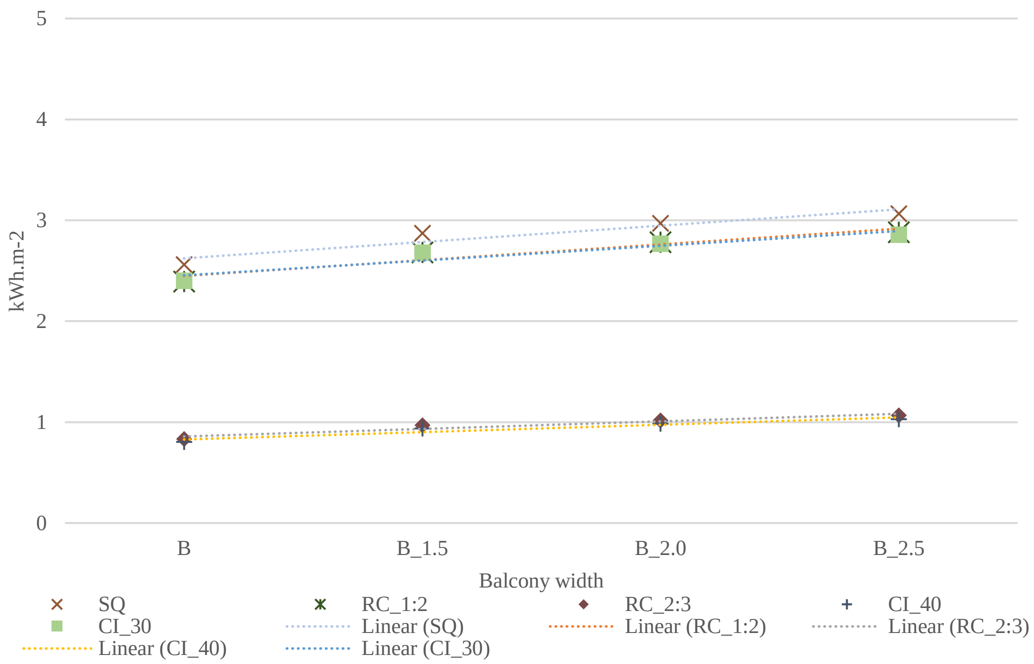


***Figure 99.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for balconies' scenarios

*Figure 100* illustrates the annual total of cooling and heating demand for all typologies, for 4F and balconies scenario. Apparently, although with a very small difference, the wider the balcony, the better a morphology performs. In the total annual energy consumption, CI_R30 morphology performs poorer. The best total performance was obtained by CI_R40.

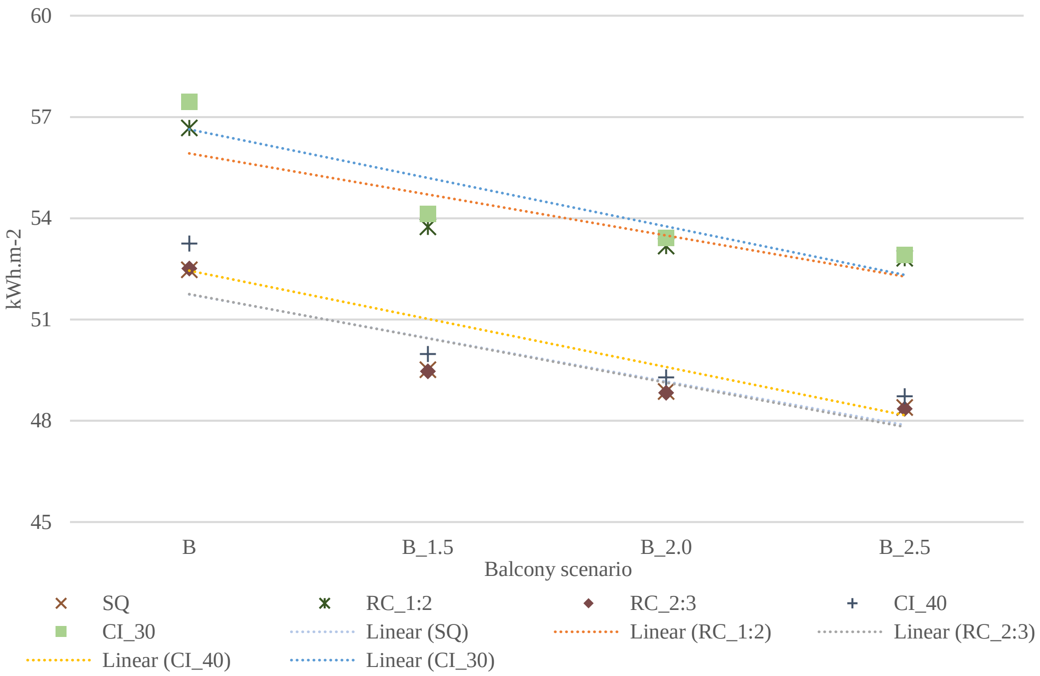



***Figure 100.*** Comparison of simulated annual energy demand (kWh.m2) of UGB morphologies for balconies' scenarios

### 5.2.4 Morphological comparison

In *Figure 101* the comparison of the total annual energy demand of the morphologies for the climate of Athens is illustrated, in terms of no. of floors and the balcony scenarios, for a façade transparency of 60%. As it is shown, in the annual energy demand, the trend decreases as the width of the balcony increases. For typology CI_R40 energy consumption is subject to an increase of 19.92 $kWh.m^{-2}y^{-1}$, when it goes from four floors to ten underground floors, for WWR 60%. Small changes are observed with the increase of balconies' width, where for all morphologies, as the balcony width increases, we have an increase in energy consumption by 3-3.73 kWh.m$^{-2}$y$^{-1}$.

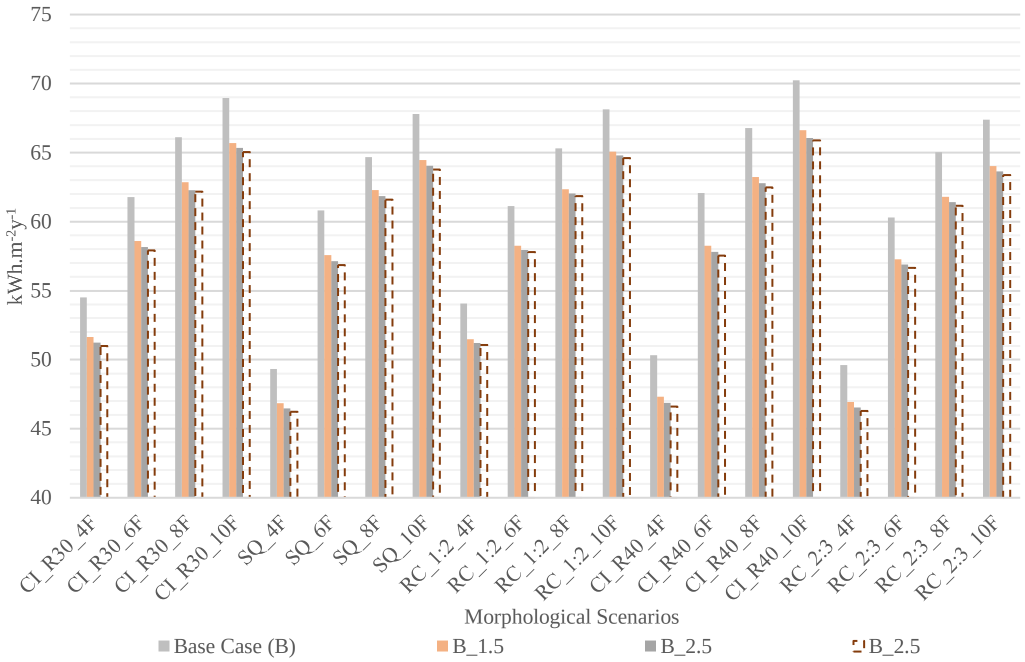



***Figure 101.*** Morphological comparation of annual energy demand (kWh.m-2y-1)

*Table 10* summarizes the simulation results obtained for all the scenarios in the climate of Berlin. A maximum of 15.1% of the total annual energy consumption can be reduced by choosing the right morphology for the selected climatic context. The morphology that performs the poorest is CI_R30, which consumes 5.3% less energy for B_1.5 scenario, and for the scenario B_2.5 consumes 6.5% less. The morphology that performs better is SQ, which has an effectiveness of 14.1% for the B_1.5 and an effectiveness of 15.2% for B_2.5.

***Table 13.*** Comparison of morphologies' effectiveness for WWR_60%

| Scenarios | | B | B_1.5 | B_2.0 | B_2.5 |
|---|---|---|---|---|---|
| CI_R30 | 4F | - | 5.3 | 6.0 | 6.5 |
| | 6F | - | 5.2 | 5.8 | 6.3 |
| | 8F | - | 5.0 | 5.8 | 6.0 |
| | 10F | - | 4.7 | 5.2 | 5.7 |
| SQ | 4F | 9.5 | 14.1 | 14.8 | 15.2 |
| | 6F | 1.6 | 6.8 | 7.5 | 8.0 |
| | 8F | 2.2 | 5.8 | 6.5 | 6.9 |
| | 10F | 1.7 | 6.5 | 7.1 | 7.5 |

| | | | | | |
|---|---|---|---|---|---|
| RC_1:2 | 4F | 0.8 | 5.6 | 6.0 | 6.3 |
| | 6F | 1.0 | 5.7 | 6.2 | 6.5 |
| | 8F | 1.3 | 5.7 | 6.2 | 6.4 |
| | 10F | 1.2 | 5.6 | 6.1 | 6.3 |
| CI_R40 | 4F | 7.7 | 13.2 | 14.0 | 14.5 |
| | 6F | -0.5 | 5.7 | 6.4 | 6.9 |
| | 8F | -1.0 | 4.4 | 5.1 | 5.5 |
| | 10F | -1.9 | 3.4 | 4.2 | 4.5 |
| RC_2:3 | 4F | 9.0 | 13.9 | 14.6 | 15.1 |
| | 6F | 2.4 | 7.3 | 7.9 | 8.3 |
| | 8F | 1.6 | 6.5 | 7.1 | 7.5 |
| | 10F | 2.3 | 7.1 | 7.7 | 8.1 |

## 5.3 Berlin

A comparison between annual cooling, annual heating and annual total energy consumption inside the apartments for four different balcony scenarios is illustrated in the figures below, to determine the impact of the oceanic climate of Berlin on the recommended morphologies.

### 5.3.1 WWR 60%

The following figures illustrate the correlation of annual consumption for cooling, heating and total, for five UGB morphologies, 4F scenario and four different balcony scenarios, studied for WWR 60%.

*Figure 102* illustrates the annual cooling demand for all typologies for 4F scenarios and balcony scenarios. Apparently, the wider the balcony, the better the energy performance shown by the morphologies is. CI_R40 morphology, performs poorer, competed to the other morphologies. The best performance was obtained by SQ morphology. *Figure 103* illustrates the annual heating demand for all typologies with different number of floors. Unlike the cooling case, for heating, the wider the balcony, the weaker the energy performance of the morphology. RC_1:2 morphology, performs poorer competed to the other morphologies. The best performance was obtained by CI_R40 and RC_2:3 morphologies.

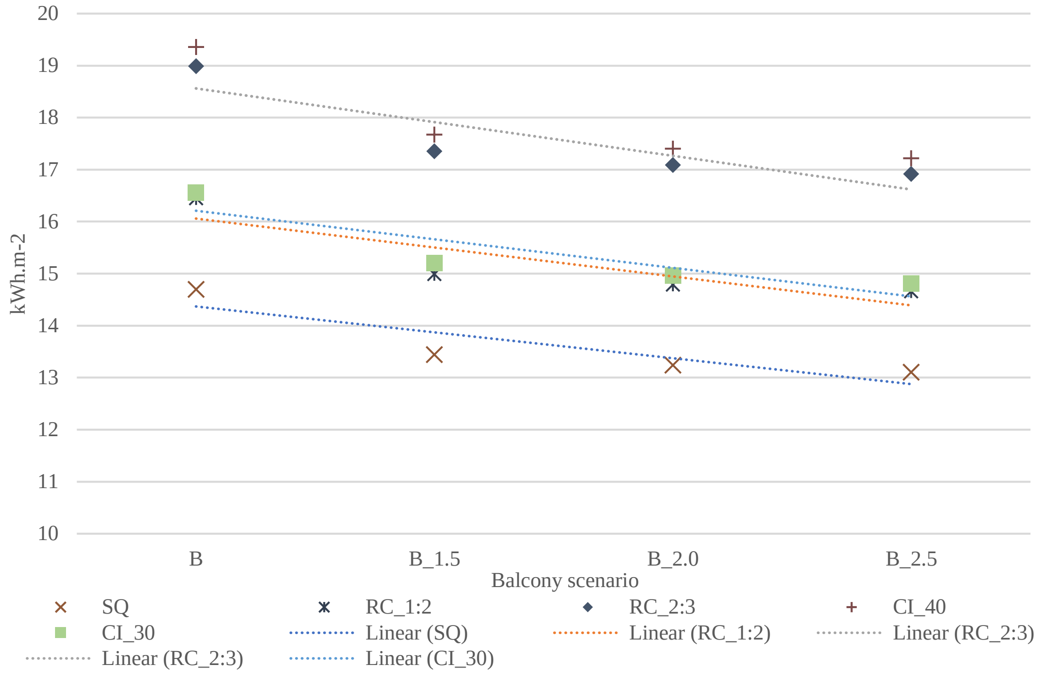



***Figure 102.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for balconies' scenarios

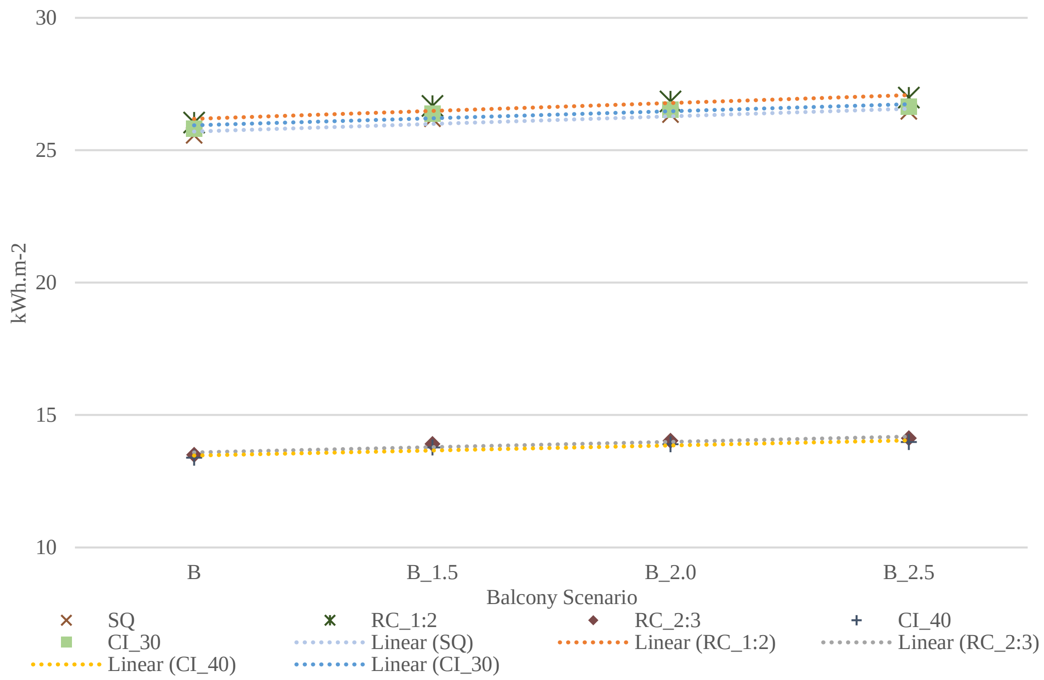



***Figure 103.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for balconies' scenarios

*Figure 104* illustrates the annual total of cooling and heating demand for all

typologies, for 4F and balconies scenario. Apparently, although with a very small difference, the wider the balcony, the better a morphology performs. In the total annual energy consumption, CI_R30 and RC_1:2 morphologies performs poorer. The best total performance was obtained by RC_2:3 morphology.

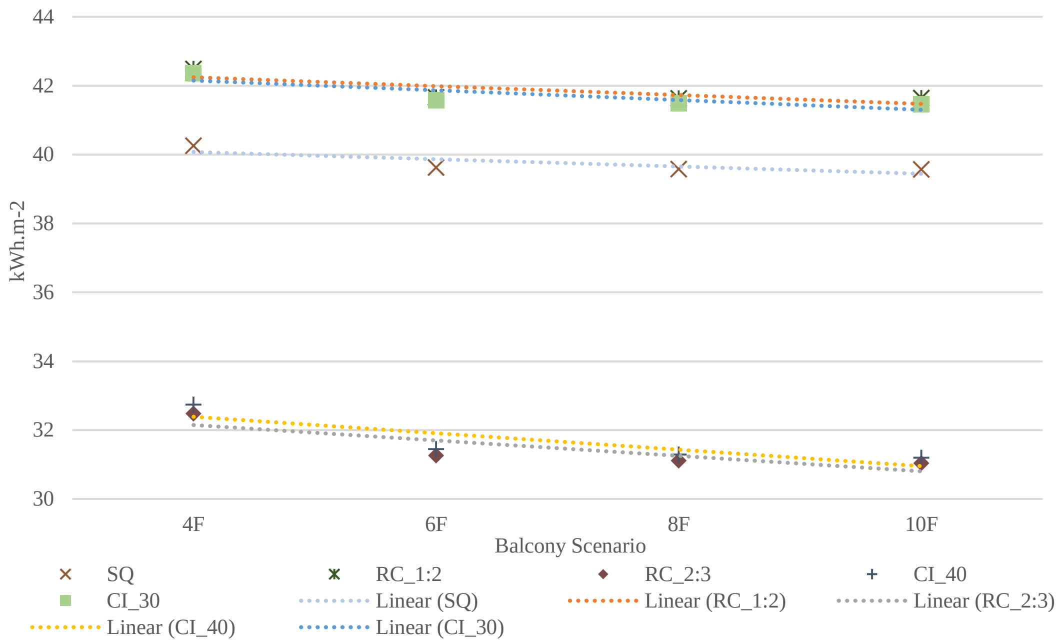



***Figure 104.*** Comparison of simulated annual energy demand (kWh.m2) of UGB morphologies for balconies' scenarios

### 5.3.2 WWR 75%

The following figures illustrate the correlation of annual consumption for cooling, heating and total, for five UGB morphologies, 4F scenario and four different balcony scenarios, studied for WWR 75%.

*Figure 105* illustrates the annual cooling demand for all typologies for 4F scenarios and balcony scenarios. Apparently, the wider the balcony, the better the energy performance shown by the morphologies is. CI_R40 morphology, performs poorer, competed to the other morphologies. The best performance was obtained by SQ. *Figure 106* illustrates the annual heating demand for all typologies with different number of floors. Unlike the cooling case, for heating the wider the balcony, the weaker the energy performance of the morphology is. RC_1:2 morphology, performs poorer competed to the other morphologies. The best performance was obtained by SQ.

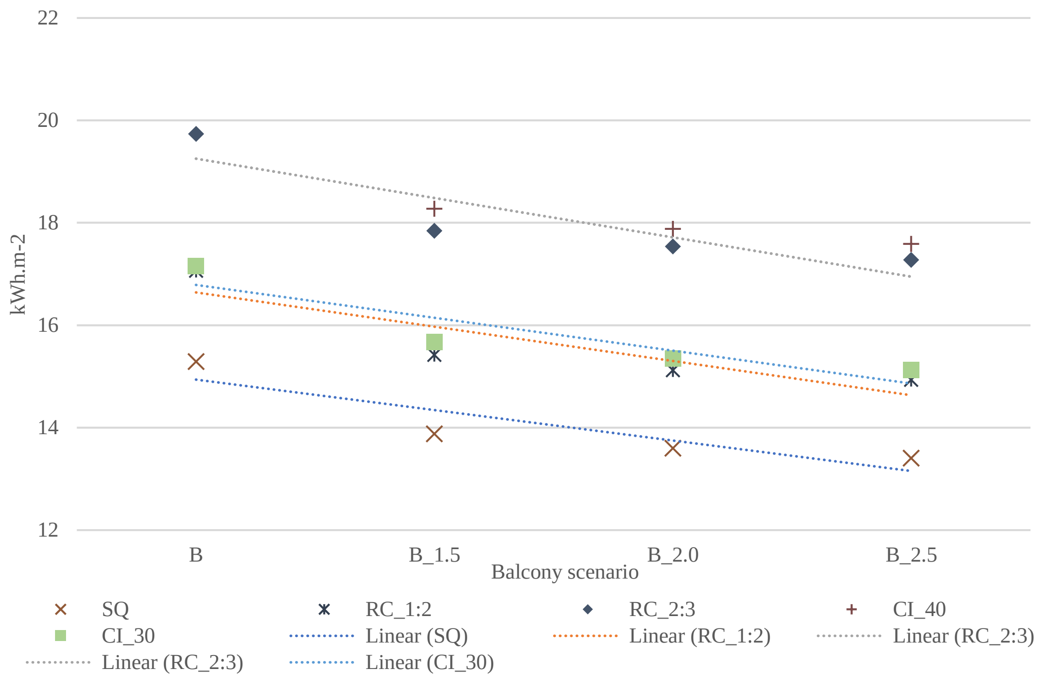



***Figure 105.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for balconies' scenarios

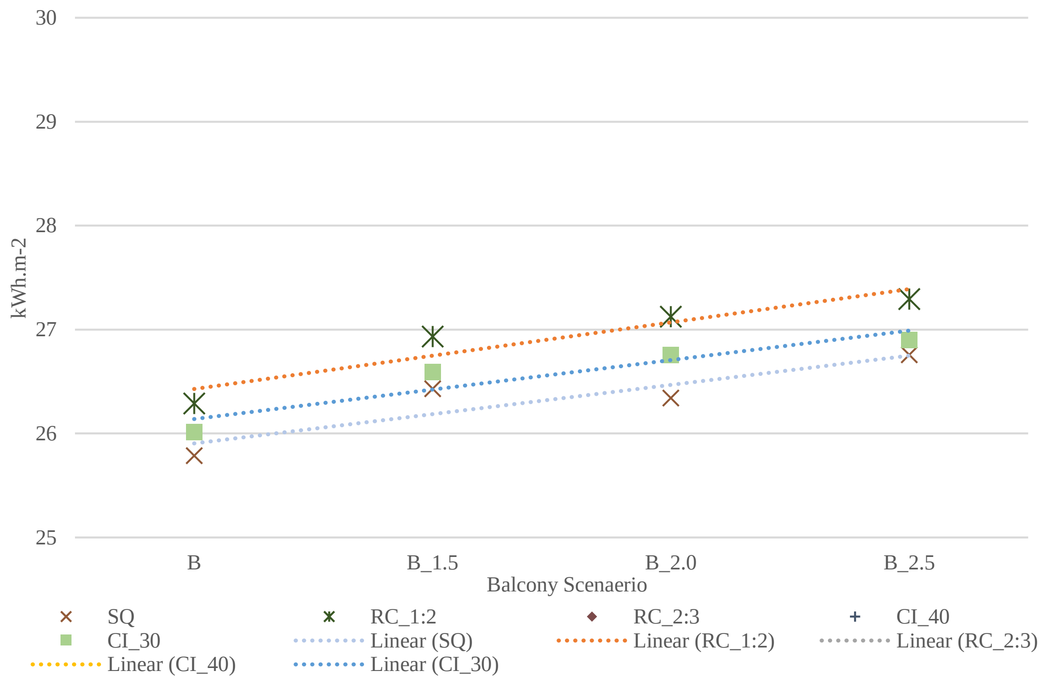



***Figure 106***. Comparison of simulated heating demand (kWh.m2) of UGB

morphologies for balconies' scenarios

*Figure 97* illustrates the annual total of cooling and heating demand for all typologies, for 4F and balconies scenario. Apparently, although with a very small difference, the wider the balcony, the better a morphology performs. In the total annual energy consumption, CI_R30 and RC_1:2 morphologies performs poorer. The best total performance was obtained by CI_R40 morphology.

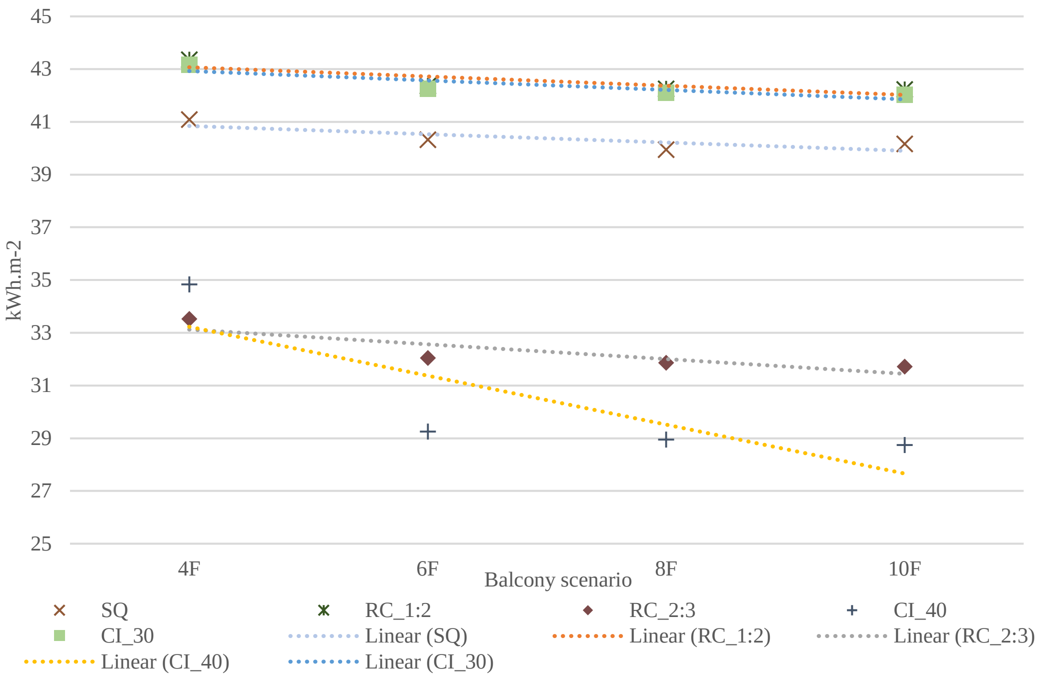



***Figure 107.*** Comparison of simulated annual energy demand (kWh.m2) of UGB morphologies for balconies' scenarios

### 5.3.3 WWR 90%

The following figures illustrate the correlation of annual consumption for cooling, heating and total, for five UGB morphologies, 4F scenario and four different balcony scenarios, studied for WWR 90%.

*Figure 108* illustrates the annual cooling demand for all typologies for 4F scenarios and balcony scenarios. Apparently, the wider the balcony, the better the energy performance shown by the morphologies is. CI_R40 morphology, performs poorer, competed to the other morphologies. The best performance was obtained by SQ. *Figure 109* illustrates the annual heating demand for all typologies with different number of floors. Unlike the cooling case, for heating the wider the balcony, the weaker the energy performance of the morphology is. RC_1:2 morphology, performs poorer competed to the other morphologies. The best performance was obtained by CI_R40 and RC_2:3.

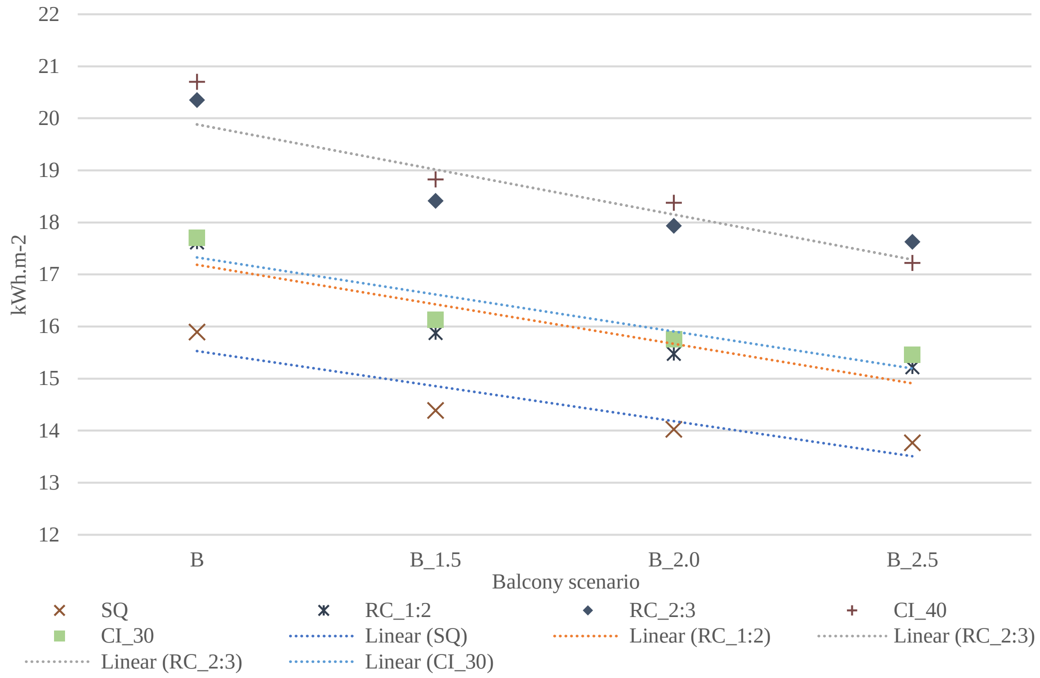



***Figure 108.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for balconies' scenarios

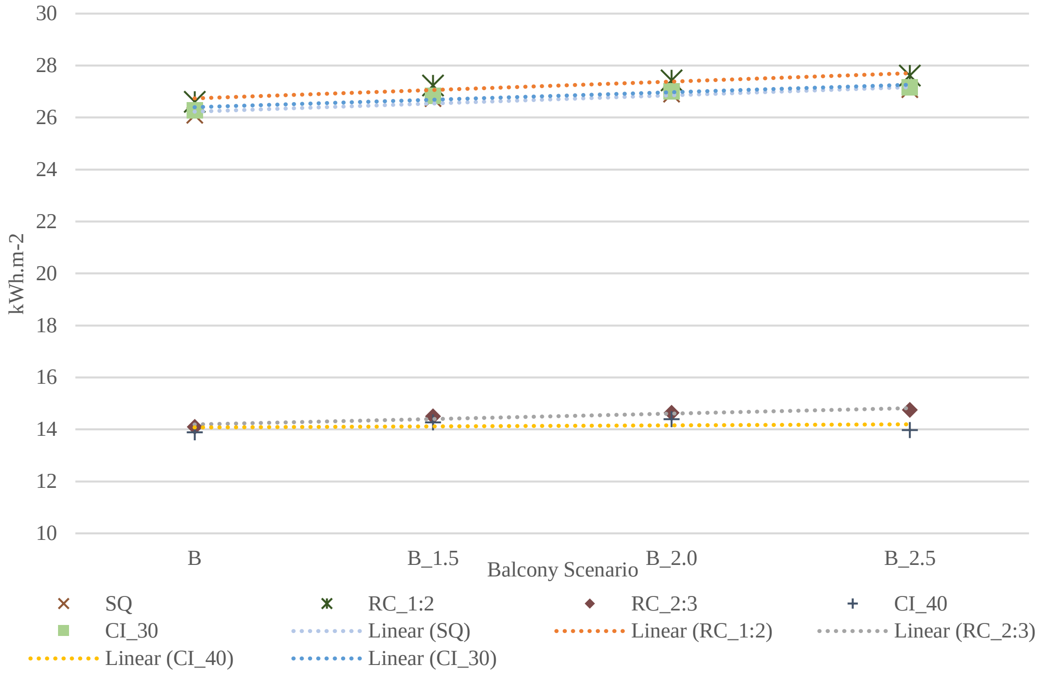



***Figure 109.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for balconies' scenarios

*Figure 110* illustrates the annual total of cooling and heating demand for all typologies, for 4F and balconies scenario. Apparently, although with a very small difference, the wider the balcony, the better a morphology performs. In the total annual energy consumption, CI_R30 morphology performs poorer. The best total performance was obtained by RC_2:3.

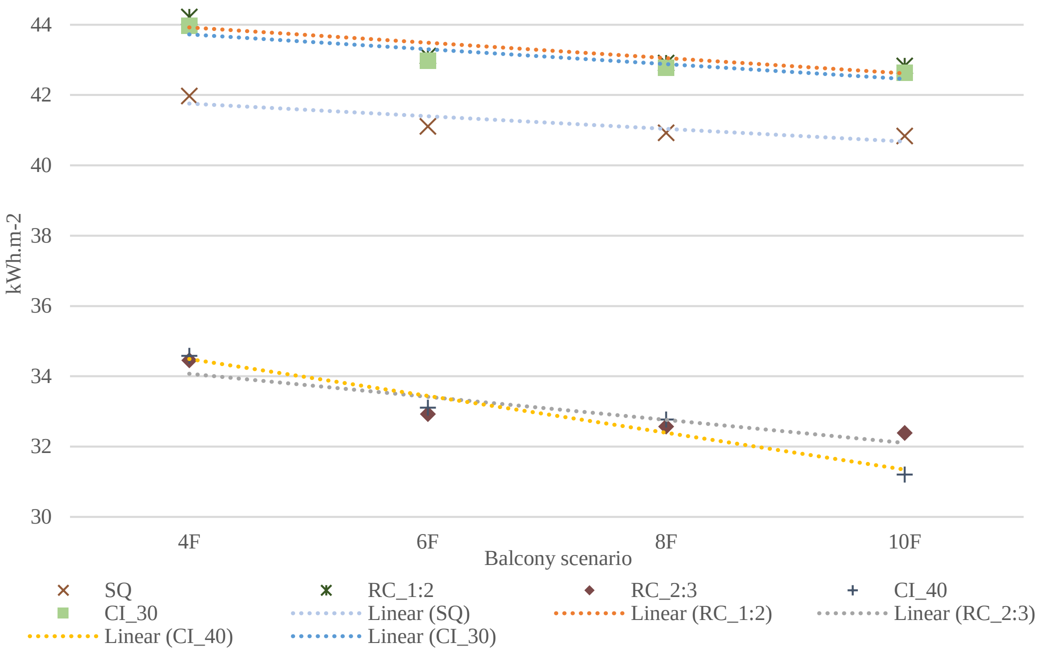



***Figure 110.*** Comparison of simulated annual energy demand (kWh.m2) of UGB morphologies for balconies' scenarios

### 5.3.4 Morphological comparison

In *Figure 111* the comparison of the total annual energy demand of the morphologies for the climate of Athens is illustrated, in terms of no. of floors and the balcony scenarios, for a façade transparency of 60%. As it is shown, in the annual energy demand, the trend decreases as the width of the balcony increases. For typology CI_R40 energy consumption is subject to an increase of 22.94 kWh.m$^{-2}$y$^{-1}$, when it goes from four floors to ten underground floors, for WWR 60%. Small changes are observed with the increase of balconies' width, where for all morphologies, as the balcony width increases, we have an increase in energy consumption by 0.69-1.54 kWh.m$^{-2}$y$^{-1}$.

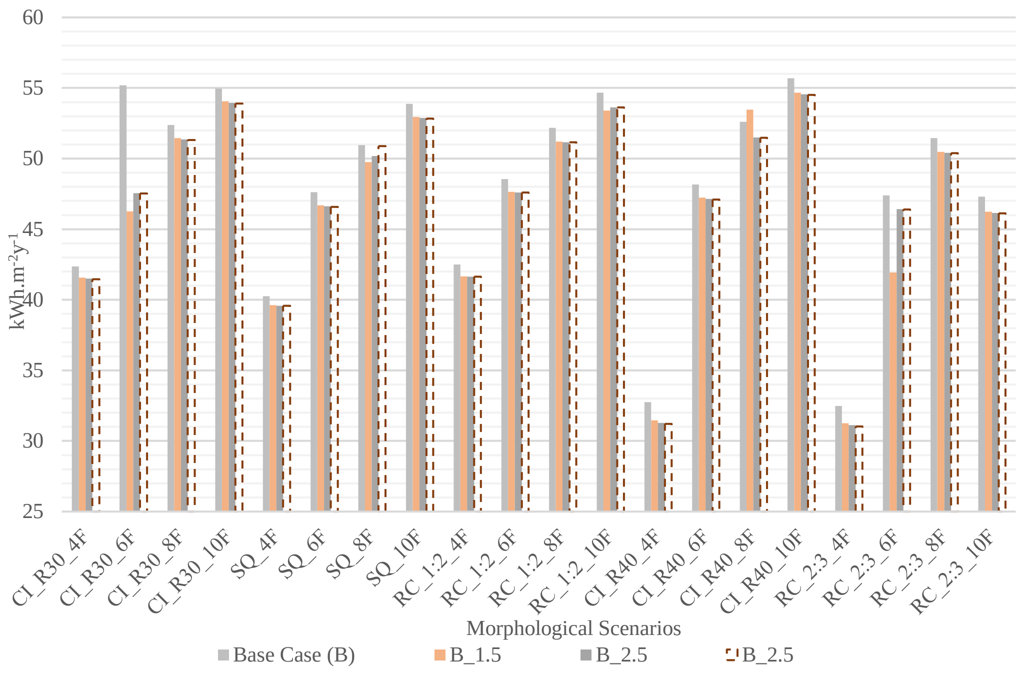



***Figure 111.*** Morphological comparation of annual energy demand (kWh.m-2y-1)

*Table 14* summarizes the simulation results obtained for all the scenarios in the climate of Berlin. A maximum of 23.3% of the total annual energy consumption can be reduced by choosing the right morphology for the selected climatic context. The morphology that performs the poorest is RC_1:2, which has a effectiveness of -0.3% for base case, and for the scenario B_2.5 it has an effectiveness of 1.7%. The morphology that performs better is RC_2:3, which has an effectiveness of 26.2% for the B_1.5 and an effectiveness of 26.7% for B_2.5.

***Table 14.*** Comparison of morphologies' effectiveness for WWR_60%

| Scenarios | | B | B_1.5 | B_2.0 | B_2.5 |
|---|---|---|---|---|---|
| CI_R30 | 4F | - | 1.9 | 2.1 | 2.2 |
| | 6F | - | 16.2 | 13.8 | 13.9 |
| | 8F | - | 1.8 | 1.9 | 2.0 |
| | 10F | - | 1.7 | 1.9 | 1.9 |
| SQ | 4F | 5.0 | 6.5 | 6.6 | 6.6 |
| | 6F | 13.7 | 15.4 | 15.5 | 2.2 |
| | 8F | 2.7 | 5.0 | 4.2 | 0.1 |
| | 10F | 2.0 | 3.7 | 3.8 | 1.9 |
| RC_1:2 | 4F | -0.3 | 1.7 | 1.7 | 1.7 |
| | 6F | 12.0 | 13.7 | 13.8 | 13.7 |
| | 8F | 0.4 | 2.2 | 2.3 | 2.3 |
| | 10F | 0.5 | 2.9 | 2.4 | 2.4 |

| | | | | | |
|---|---|---|---|---|---|
| CI_R40 | 4F | 22.7 | 25.8 | 26.2 | 26.4 |
| | 6F | 12.7 | 14.4 | 14.6 | 14.7 |
| | 8F | -0.4 | -2.1 | 1.7 | 1.7 |
| | 10F | -1.3 | 0.6 | 0.7 | 0.8 |
| RC_2:3 | 4F | 23.3 | 26.2 | 26.6 | 26.7 |
| | 6F | 14.1 | 24.0 | 15.9 | 15.9 |
| | 8F | 1.8 | 3.6 | 3.7 | 3.8 |
| | 10F | 13.9 | 15.9 | 16.0 | 16.1 |

# CHAPTER 6

# CONCLUSIONS

A new comprehensive framework is intended to complement an analytical and quantitative approach to the impact of energy performance of courtyard morphologies of residential underground buildings in three climatic contexts. The study is based on an analysis of the success performance, considering different design variables: shape, number of floors, transparency of the facade, width of the balconies. The main importance of this study is the optimization of the energy performance of different morphologies, thus contributing to the solution of the problems brought about by overpopulation and rapid urbanization of cities. This study aims for architects and urban planners in the future to take into consideration the benefits of the underground in the development of a new type of architecture. The proposed approach is an enhancement of methodologies proposed earlier and provides novel and worthy contributions compared to the mentioned studies as it reveals the following findings:

- The oceanic climate of Berlin displays the lowest energy demand, followed by the hot-summer Mediterranean climate of Athens, with an average difference of 7.6 $kWh.m^{-2}y^{-1}$. The climate which presents a greater demand for energy is the subtropical climate of New York, with a difference from the climate of Athens, of an average of 11.71 $kWh.m^{-2}y^{-1}$, and with a difference of 25.41 $kWh.m^{-2}y^{-1}$ from the climate of Berlin.
- For the climate of New York and Berlin, the morphology RC_2:3 displays the best performance compared to other climates. For the climate of Athens, the best performance results from the SQ morphology, followed by a difference of 0.3 $kWh.m^{-2}y^{-1}$ from the RC_2:3 morphology. The reasons why the RC_2:3 morphology has the best performance are: its larger contact surface with the ground, its larger courtyard surface and because it is the most compact building. For the hot climate of Athens, SQ performs better since the equal sides of the courtyard help to ventilate the spaces.

- For the climates of New York and Athens, the CI_R30 morphology has the worst energy performance, compared to other morphologies, with a performance respectively 28.3-28.5% worse for New York and 7.3-15.5% worse for Athens, in the 10F scenario. This comes as a result of the fact that CI_R30 has less contact surface with the ground, smaller courtyard area and is the most compact building. The morphology RC_1:2 displays the poorer energy performance for the oceanic climate of Berlin, with a performance of 15.5-16.0%, followed by the morphology CI_R30. The longitudinal extent of this morphology has a bad effect on the behavior of cold currents during the winter, thus negatively affecting energy.
- The comparison of annual simulated energy demand in terms of building compactness, shows that the least compact building, have the best energy performance, thus creating a correlation with a negative trend.
- The comparison of annual simulated energy demand in terms of facade transparency, shows that the higher the % of WWR, the weaker is the energy performance of the morphologies, thus creating a correlation with a negative trend.
- It turned out that the morphologies that perform better also have a big difference between the scenario when they are 4 floors and 10 floors, compared to the morphologies that perform poorly.
- The number of floors had a significant impact on the performance of the typologies, where the result is that the higher the number of underground floors are, the higher the energy requirements will be. For the climate of New York, the morphology with the weakest performance, CI_R30, for the depth of 10 floors underground, requires 38.2% more energy.
- For the balcony scenarios, it turned out that for each morphology, the wider the balcony, the more energy will be required for heating and less for cooling. For the climate of New York, is RC_2:3 has an

effectiveness of 9.6% for the base case and an effectiveness of 13.2% for B_2.5. Despite that, in the annual energy performance, deeper balconies help in better performance, although with a small difference of approximately 0.7-3.3 kWh.$m^{-2}y^{-1.}$

## 6.1 Recommendations for future research

Overall, the results highlight the promising energy benefits from subsurface morphological impact. However, the model development process and analysis are consistent with relevant peer-reviewed scientific studies and experiments considering the influence of climatic conditions, building properties, HVAC and indoor loads, providing optimal model performance. To further explore the research, experimental studies on building geometries should be conducted. Therefore, some priority areas for future research are suggested.

- Consideration of the depth that the building will reach
- The inclusion of shading elements in the results
- Further optimization of the dimensions of the courtyards
- Optimizing the transparences of the facades
- Optimizing the depth of balconies
- Further consideration of the properties of the land and the benefits that come from it in the energy performance of buildings.

However, in general, the developed study represents an effective and well-documented step towards an analytical approach to a delicate subject and emphasizes that the shape of the building and the consideration of the underground, if it is evaluated and developed in the best way by the architects, not only that I will reduce energy consumption in residential homes, but I will provide a solution to the big problem of urbanism that our society is facing today

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# APPENDIXES

## I. APPENDIX A (Balcony Scenarios)

### I.1 New York

#### I.1.1 WWR 60%

*Figure 109-117* show the cooling, heating and total annual energy demand of the morphologies, for the balcony scenarios, in the three types of floor numbers.

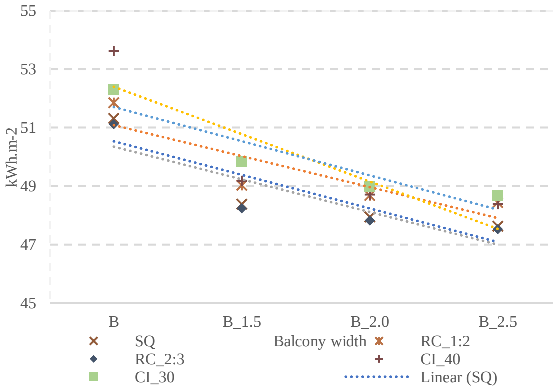



***Figure 112.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

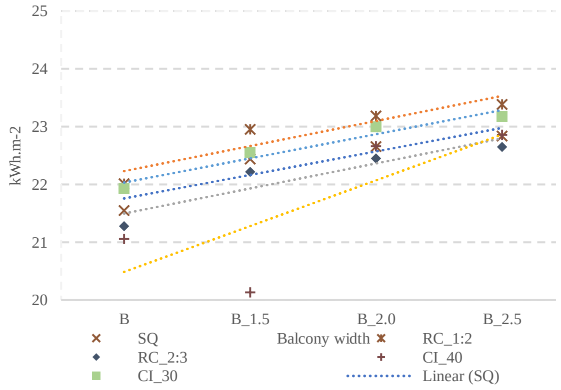



***Figure 113.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

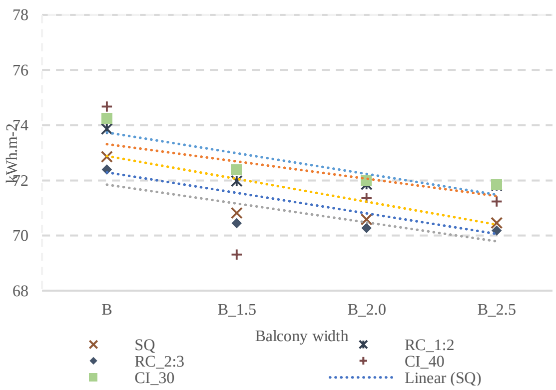



***Figure 114.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

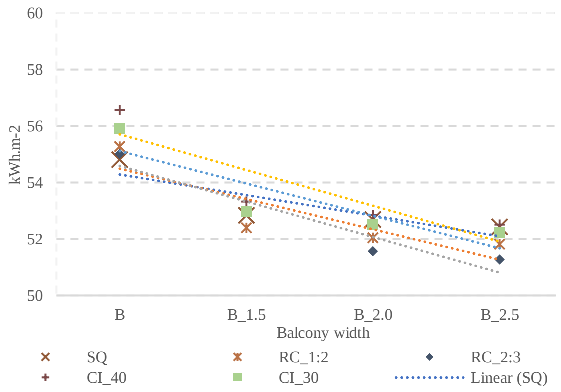



***Figure 115.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

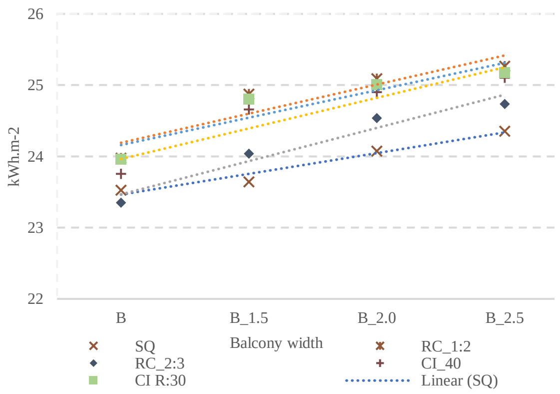



***Figure 116.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

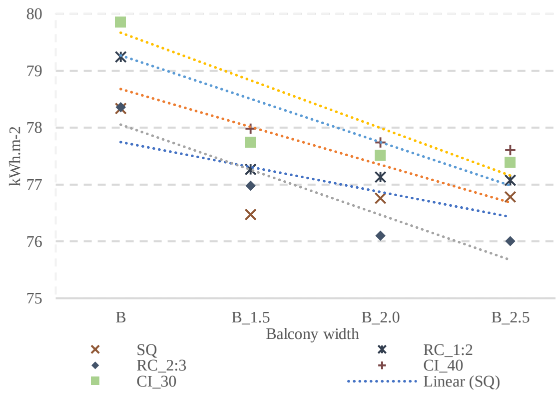



***Figure 117.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

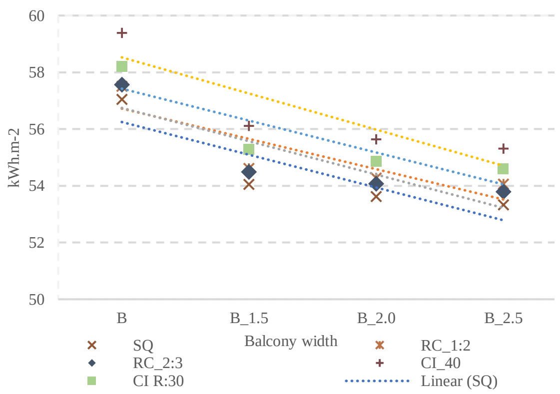



***Figure 118.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

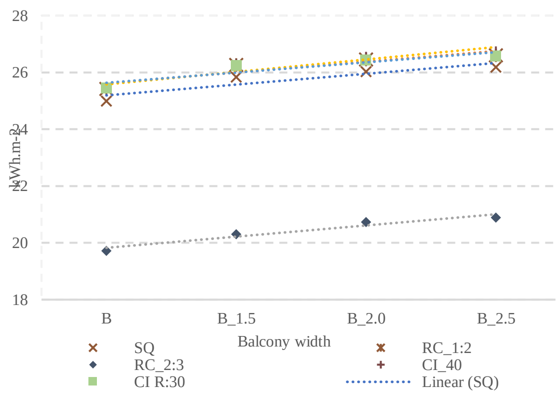



***Figure 119.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

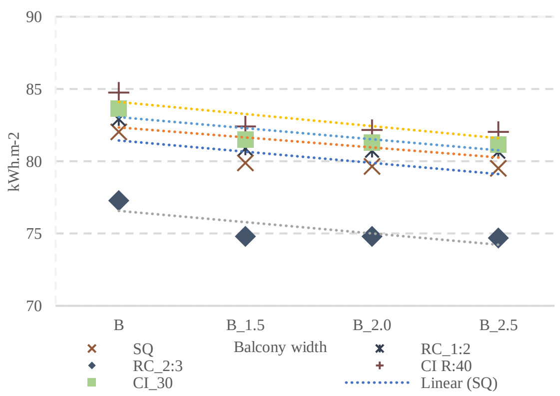



***Figure 120.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 10F and balconies'

scenarios

### I.1.2 WWR 75%

*Figure 118-126* show the cooling, heating and total annual energy demand of the morphologies, for the balcony scenarios, in the three types of floor numbers.

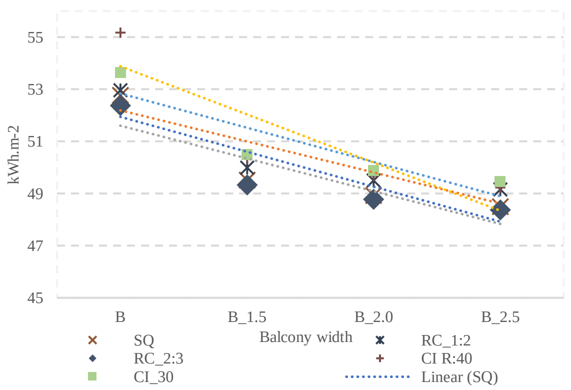



***Figure 121.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

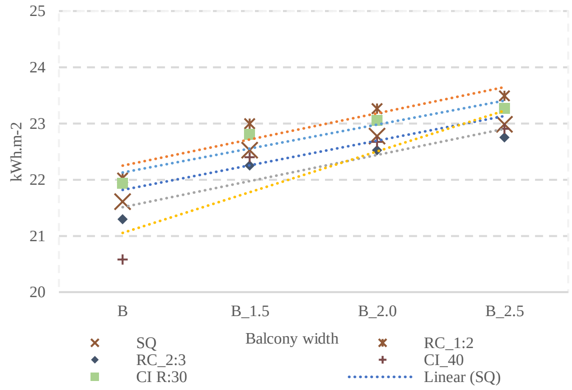



***Figure 122.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

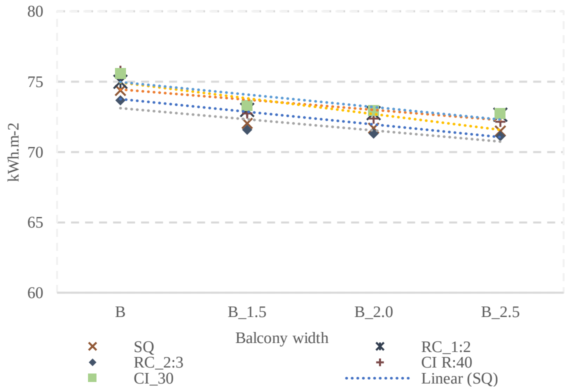



***Figure 123.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

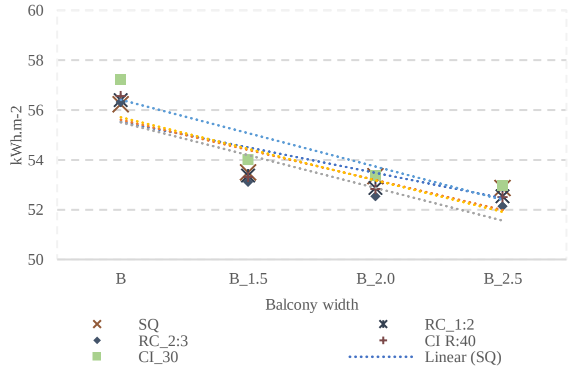



***Figure 124.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

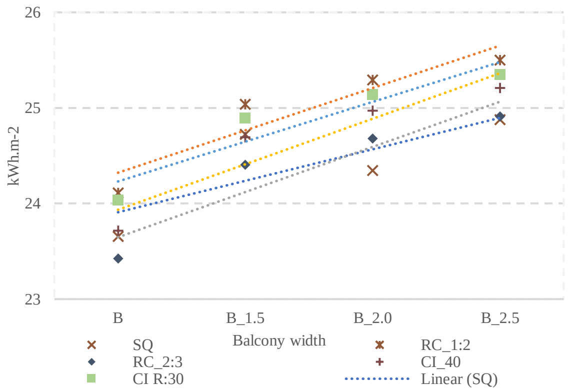



***Figure 125.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

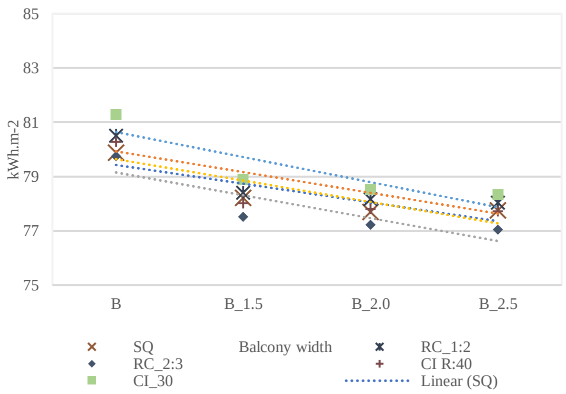



***Figure 126.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

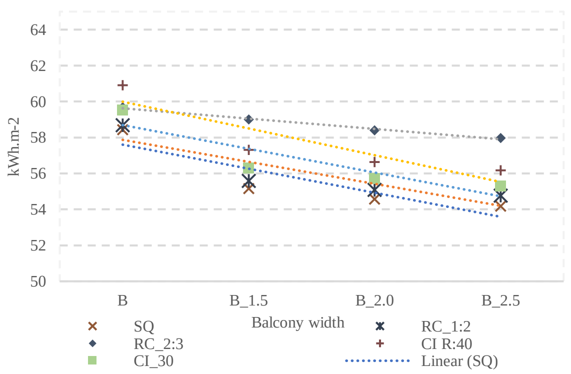



***Figure 127.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

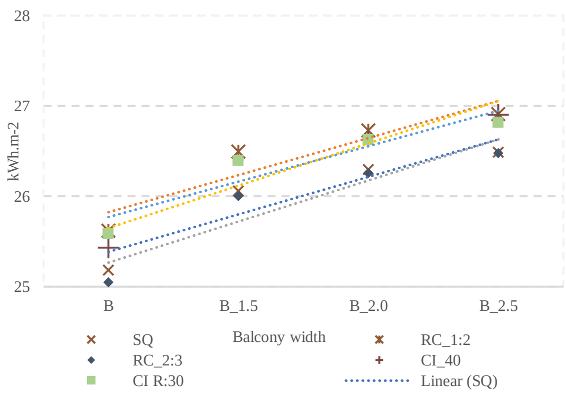



***Figure 128.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

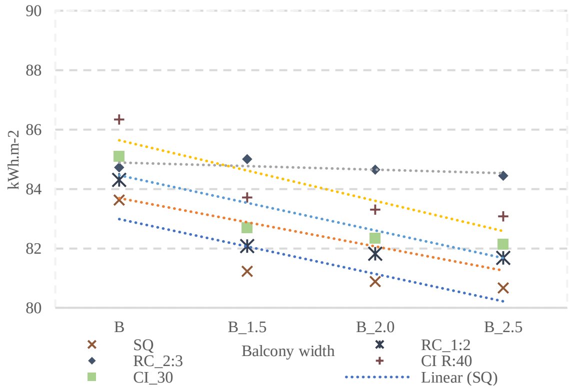



***Figure 129.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

### I.1.3 WWR 90%

***Figure 127-135*** shows the cooling, heating and total annual energy demand of the morphologies, for the balcony scenarios, in the three types of floor numbers.

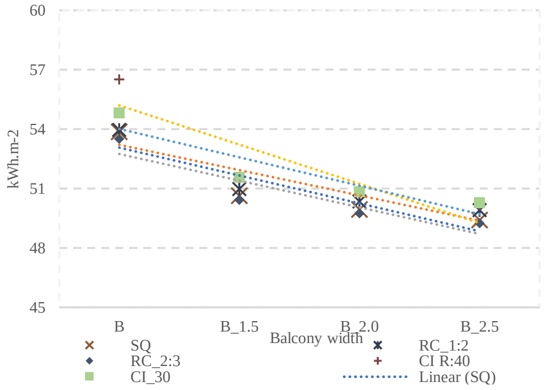



***Figure 130.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

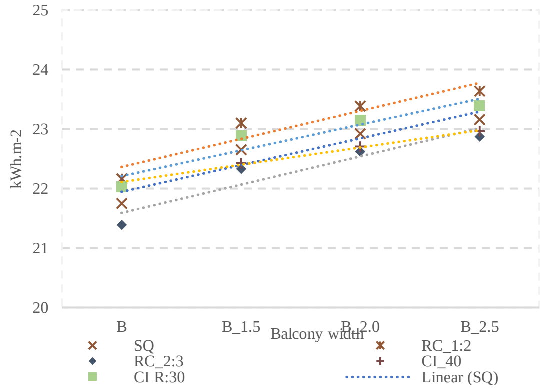



***Figure 131.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

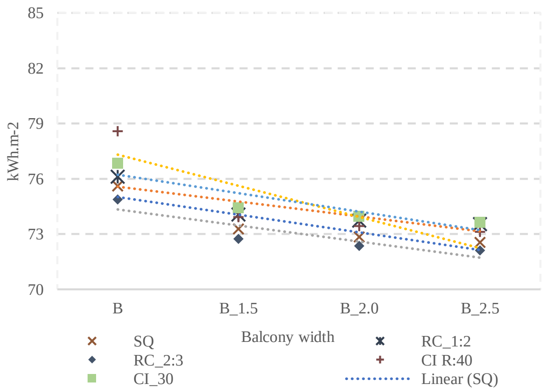



***Figure 132.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

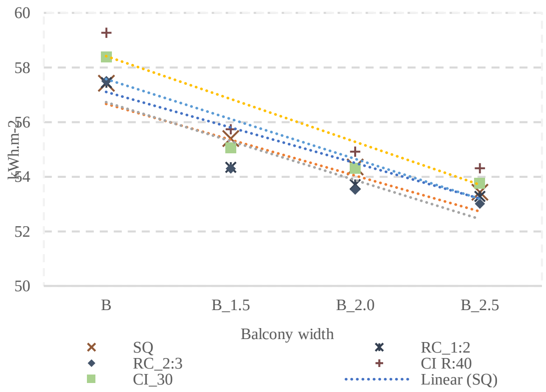



***Figure 133.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

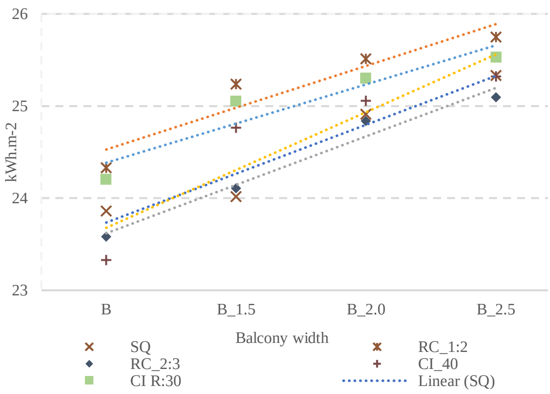



***Figure 134.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

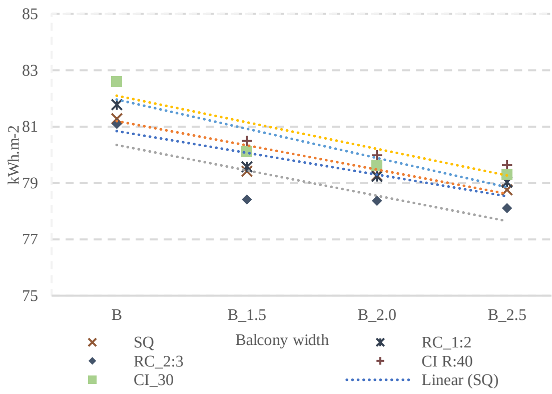



***Figure 135.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

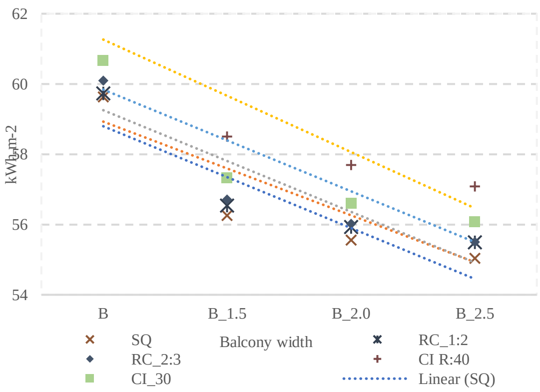



***Figure 136.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

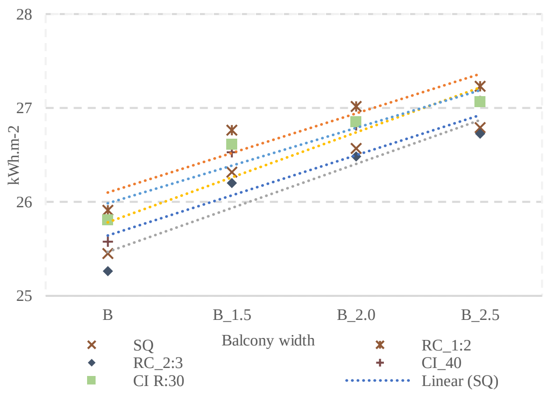



***Figure 137.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

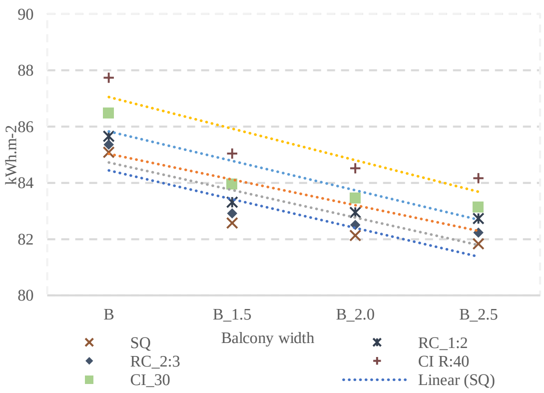



***Figure 138.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

## I. 2 Athens

### I. 2. 1 WWR 60%

*Figure 136-144* show the cooling, heating and total annual energy demand of the morphologies, for the balcony scenarios, in the three types of floor numbers.

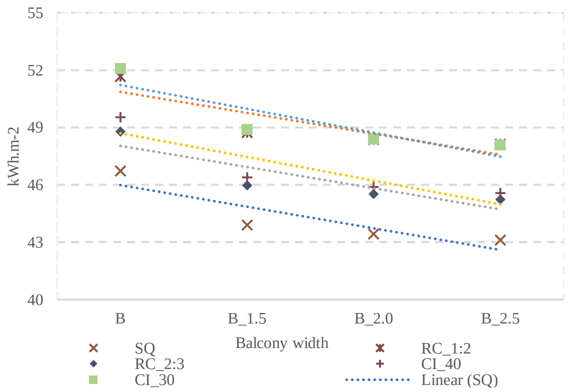



***Figure 139.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

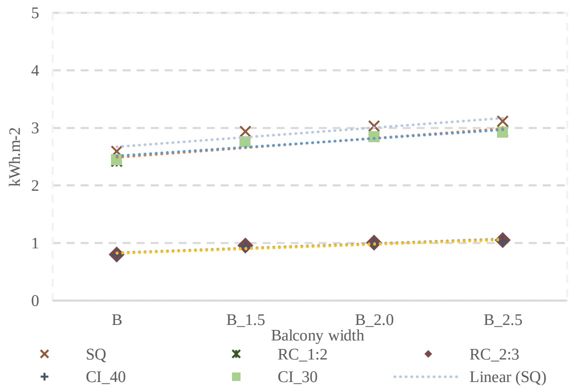



***Figure 140.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

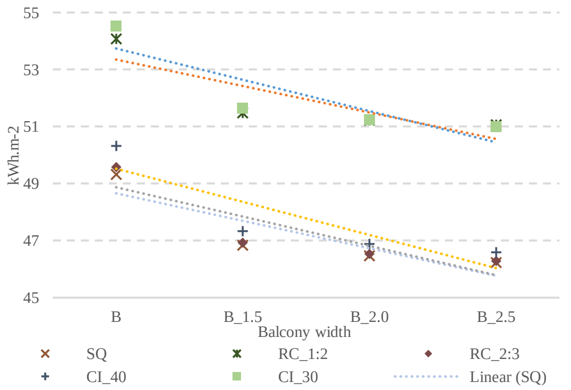



***Figure 141.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

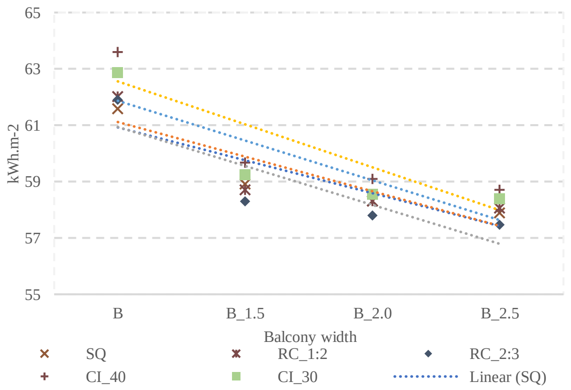



***Figure 142.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

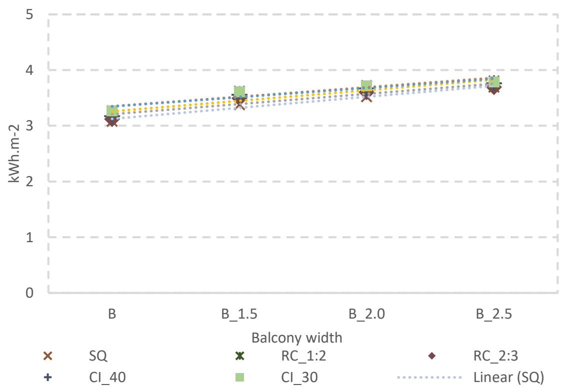



***Figure 143.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

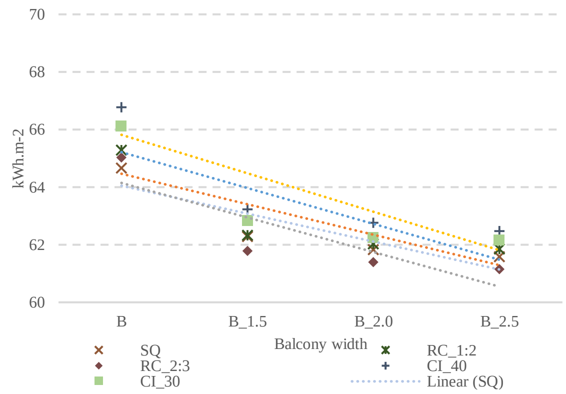



***Figure 144.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

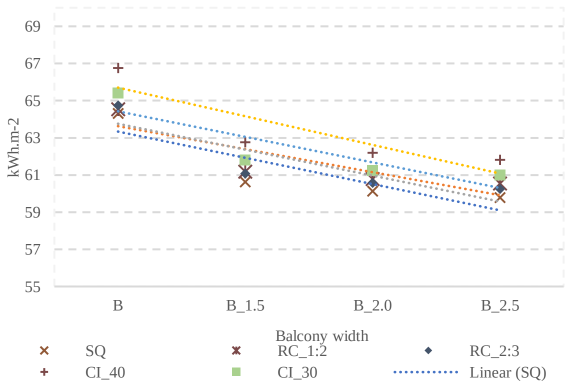



***Figure 145.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

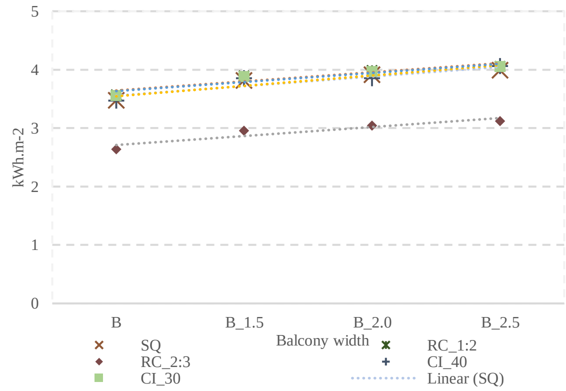



***Figure 146.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

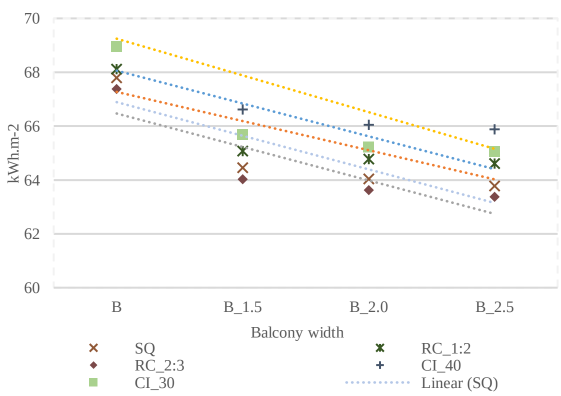



***Figure 147.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

### I. 2. 2 WWR 75%

*Figure 145-153* show the cooling, heating and total annual energy demand of the morphologies, for the balcony scenarios, in the three types of floor numbers.

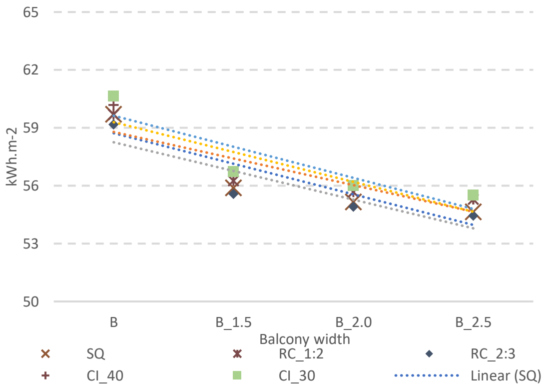



***Figure 148.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

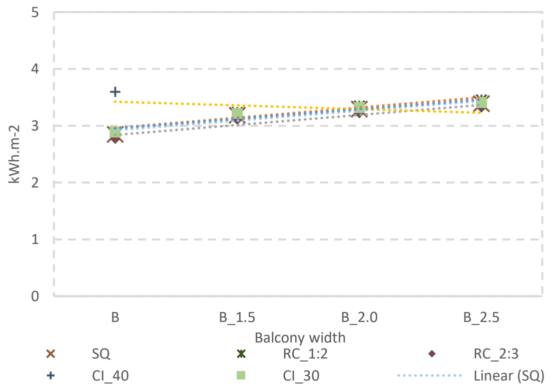



***Figure 149.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

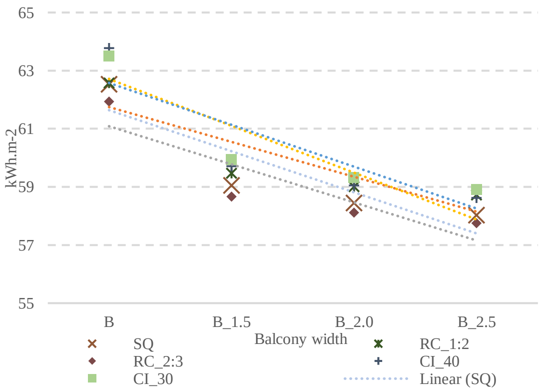



***Figure 150.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

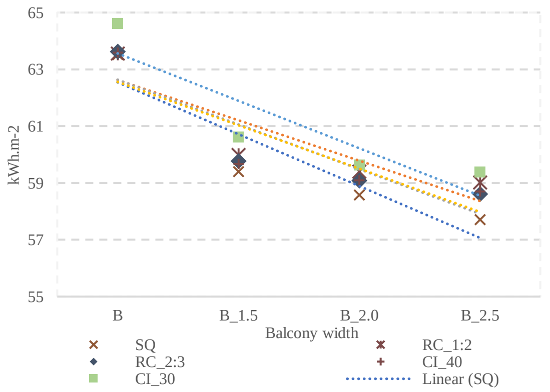
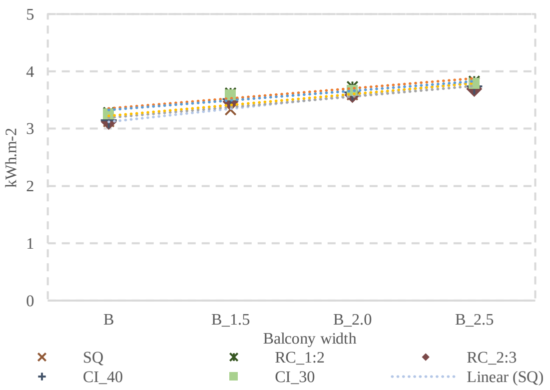



***Figure 151.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios



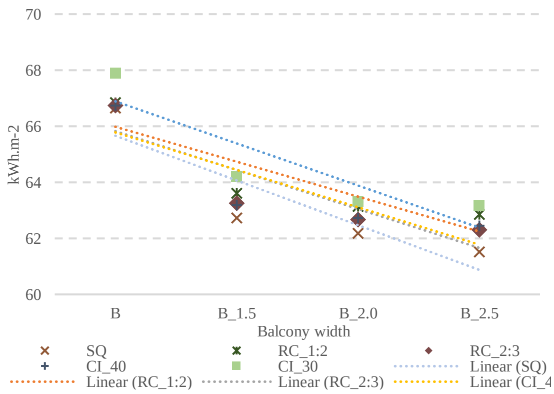
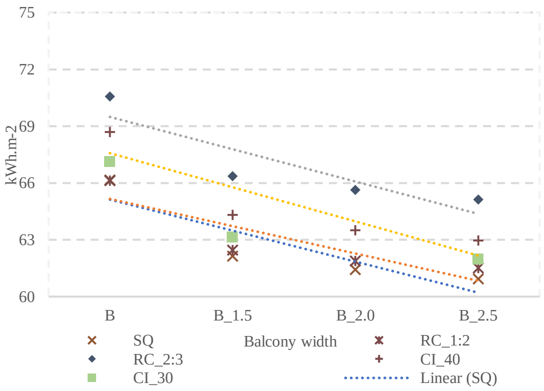



***Figure 152.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

***Figure 153.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios



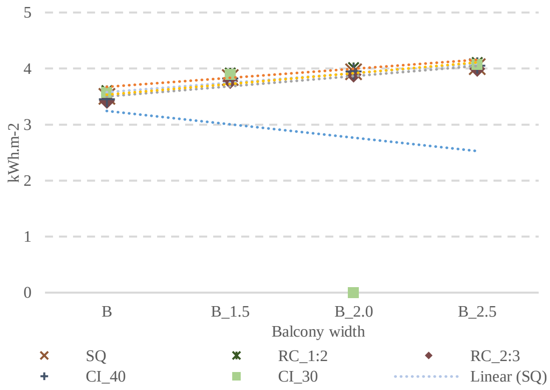




***Figure 154.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

***Figure 155.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

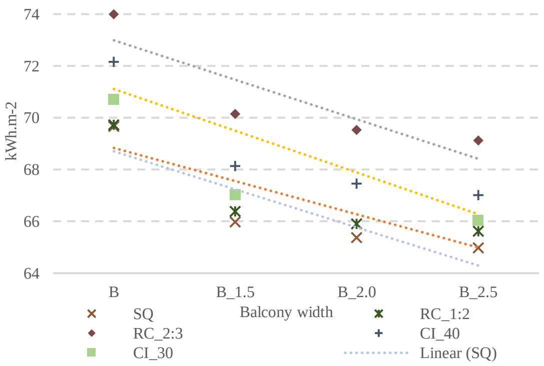
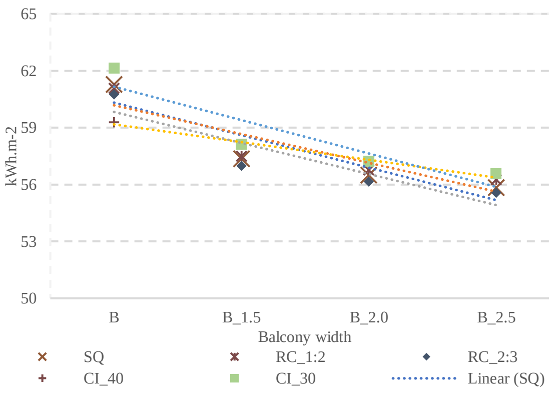



***Figure 156.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

### I. 2. 3 WWR 90%

*Figure 154-162* show the cooling, heating and total annual energy demand of the morphologies, for the balcony scenarios, in the three types of floor numbers.



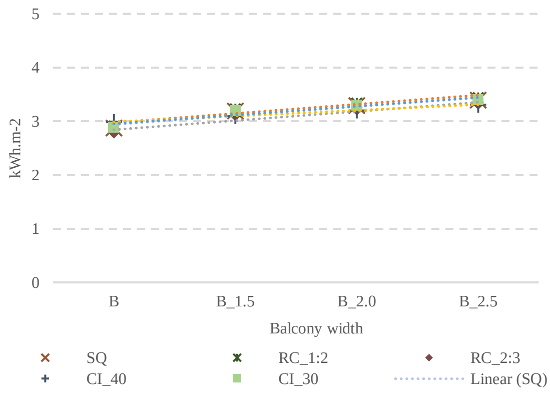
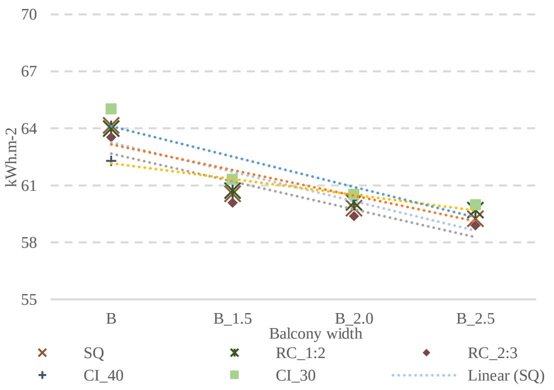




***Figure 157.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

***Figure 158.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios



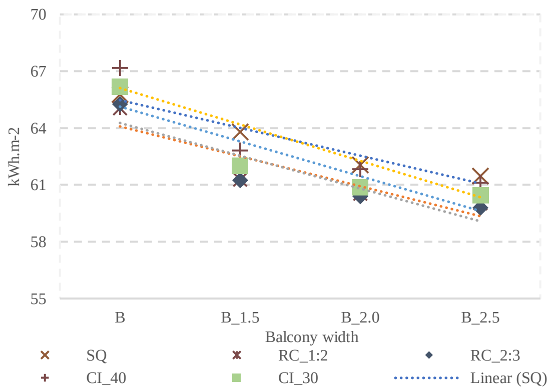




***Figure 159.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

***Figure 160.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

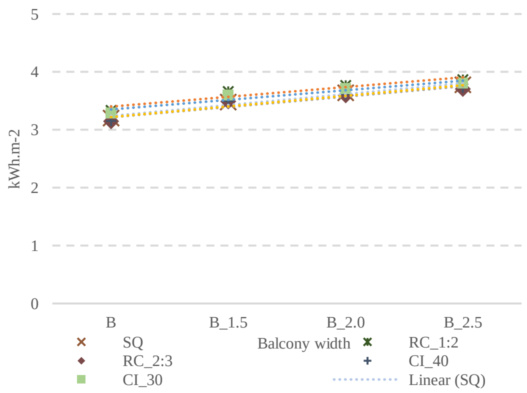



***Figure 161.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

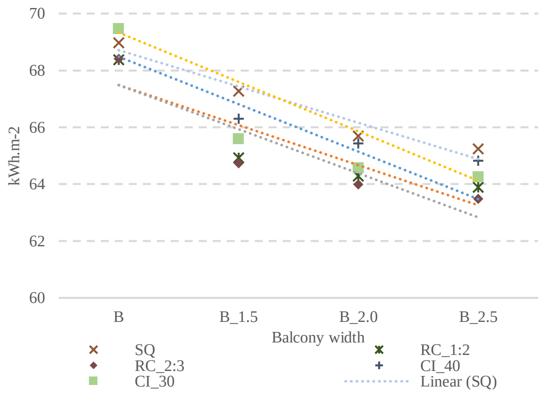



***Figure 162.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

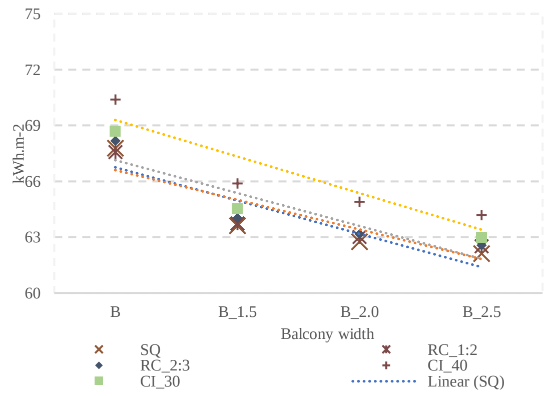



***Figure 163.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

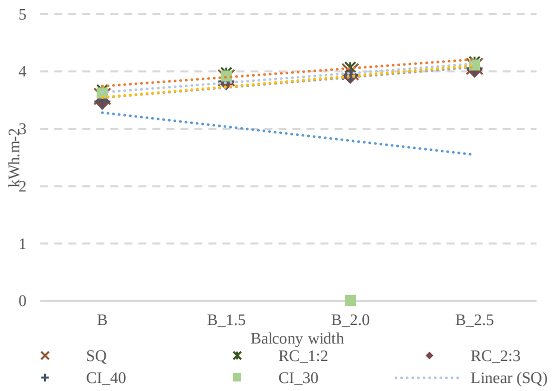



***Figure 164.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

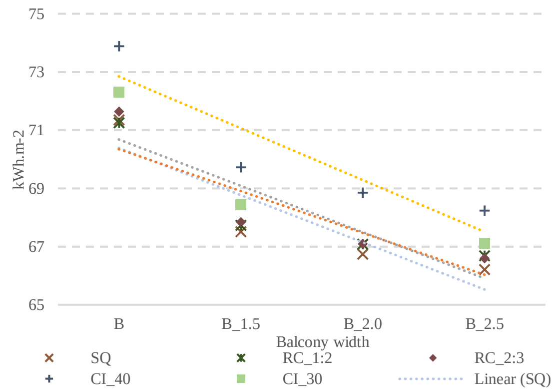



***Figure 165.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

## I. 3 Berlin

### I. 3. 1 WWR 60%

*Figure 163-171* show the cooling, heating and total annual energy demand of the morphologies, for the balcony scenarios, in the three types of floor numbers.

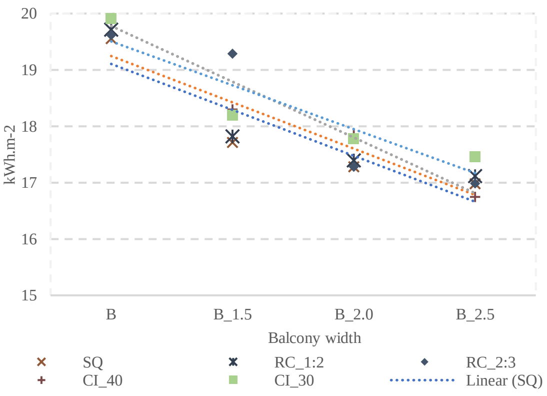



***Figure 166.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

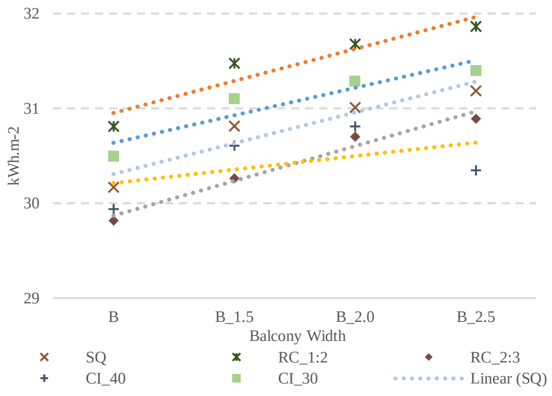



***Figure 167.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

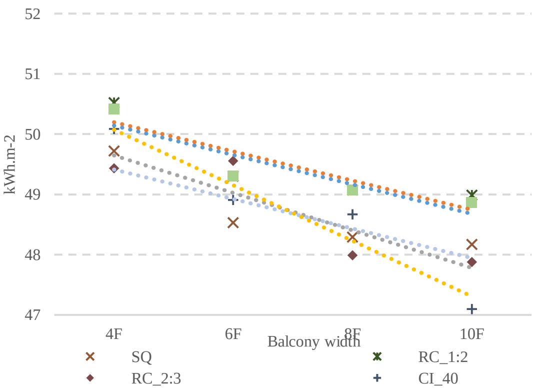



***Figure 168***. Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

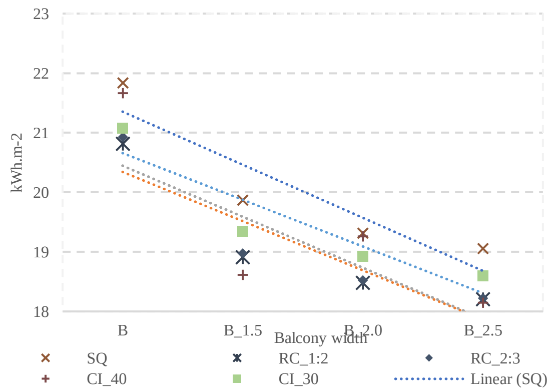



***Figure 169.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

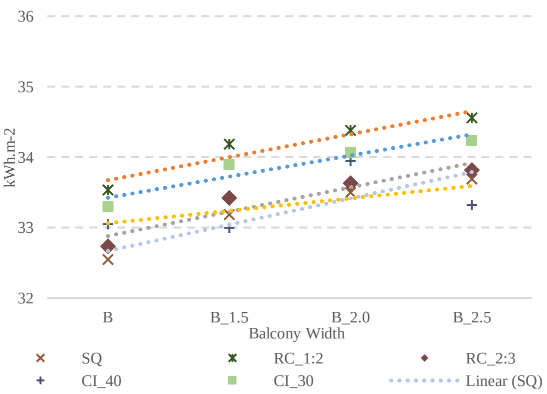



***Figure 170.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 8F and balconies'

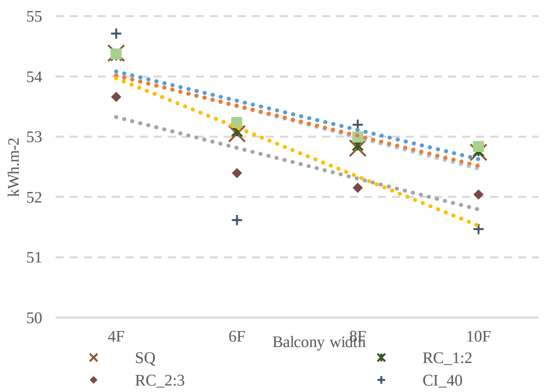



***Figure 171.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 8F and

scenarios

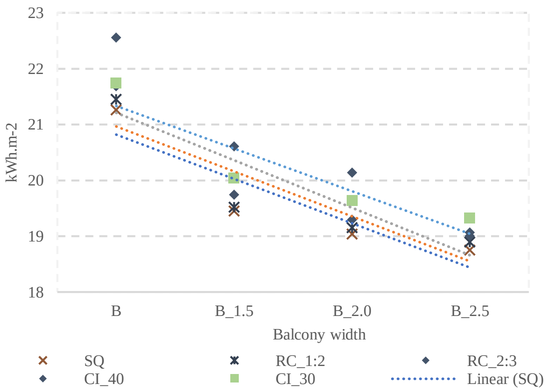



*Figure 172.* Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

balconies' scenarios

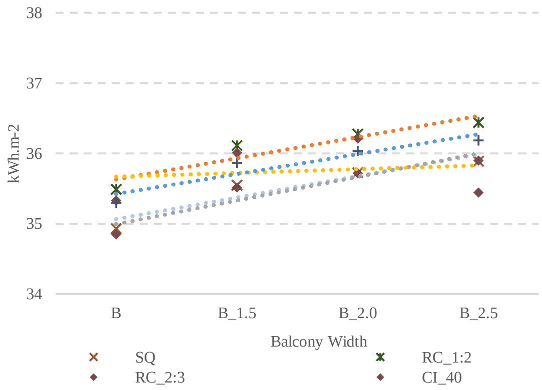



*Figure 173.* Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 10F and balconies' scenario

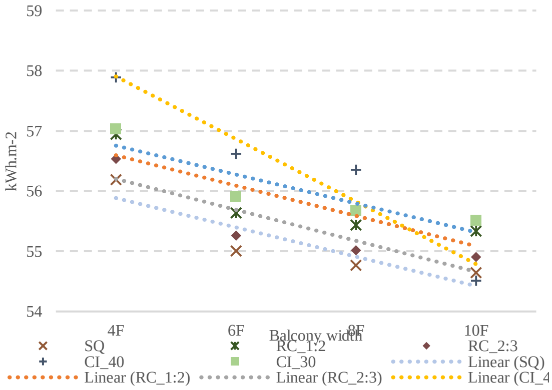



*Figure 174.* Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

### I. 3. 2 WWR 75%

*Figure 172-180* show the cooling, heating and total annual energy demand of the morphologies, for the balcony scenarios, in the three types of floor numbers.

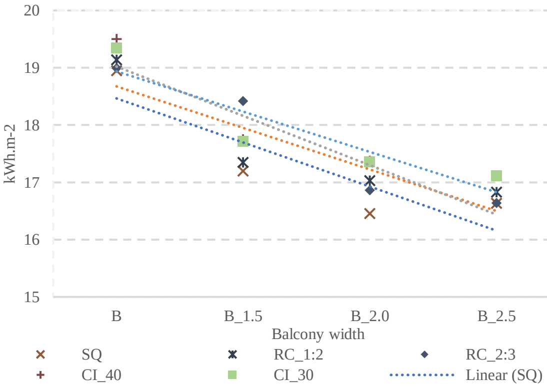



***Figure 175.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

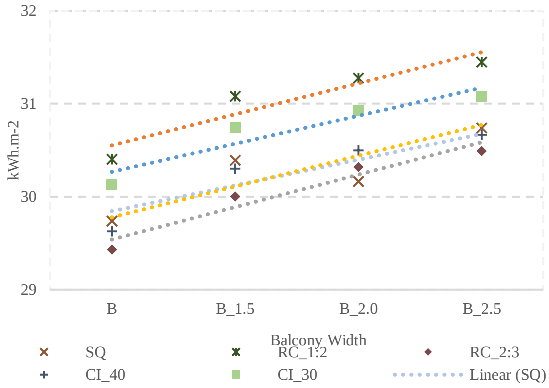



***Figure 176.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

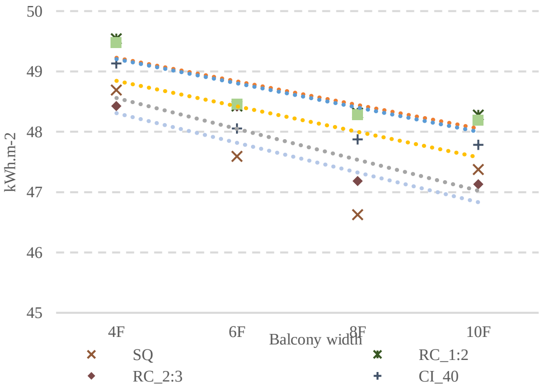



***Figure 177.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

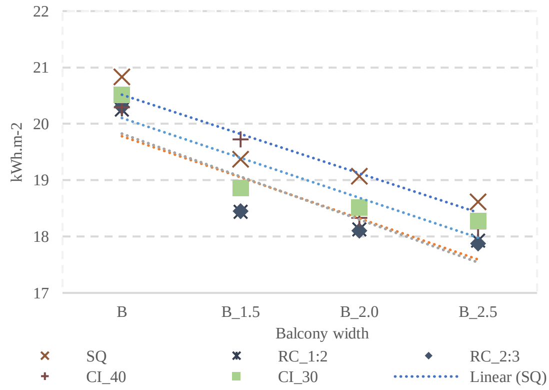



***Figure 178.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

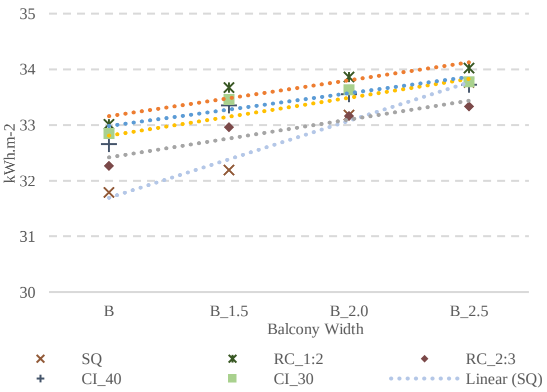



***Figure 179.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

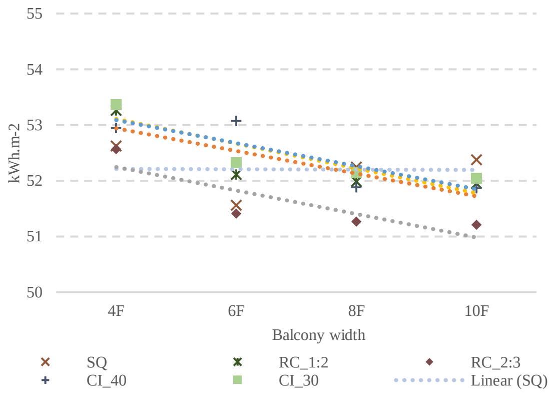



***Figure 180.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

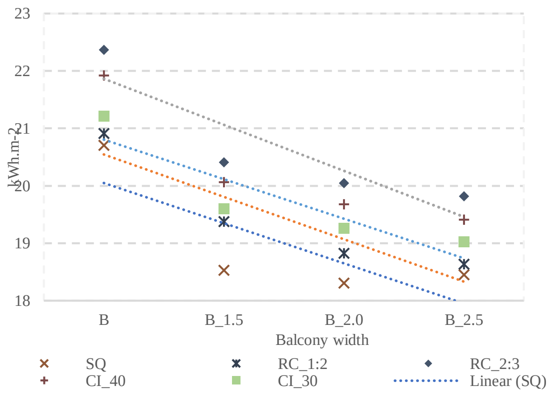



***Figure 181.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

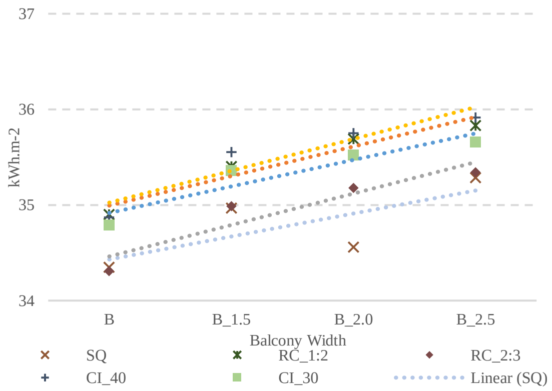



***Figure 182.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

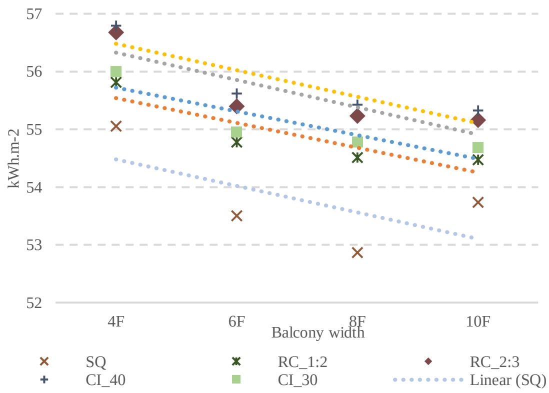



***Figure 183.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

### I. 3. 3 WWR 90%

*Figure 181-189* show the cooling, heating and total annual energy demand of the morphologies, for the balcony scenarios, in the three types of floor numbers.

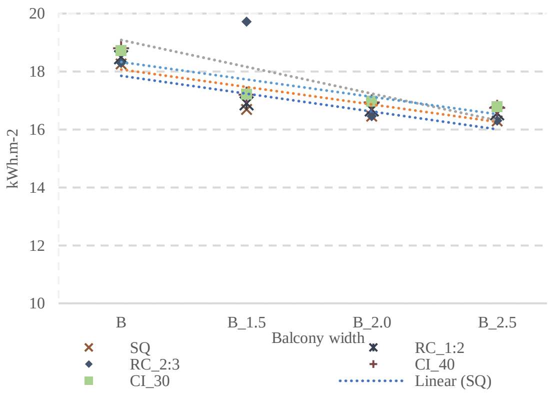



***Figure 184.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

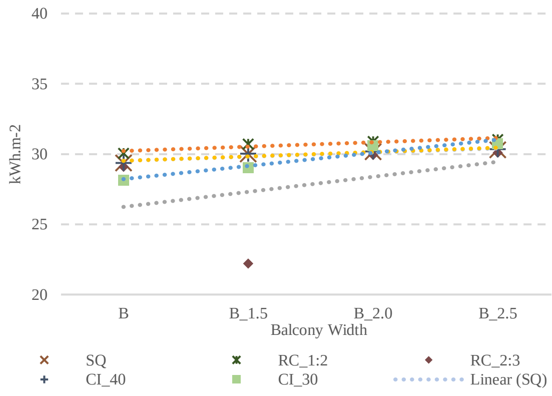



***Figure 185.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

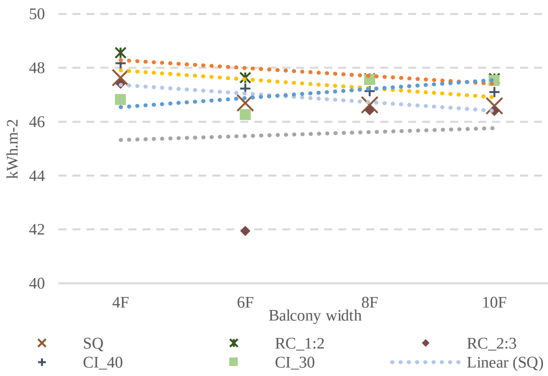



***Figure 186.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 6F and balconies' scenarios

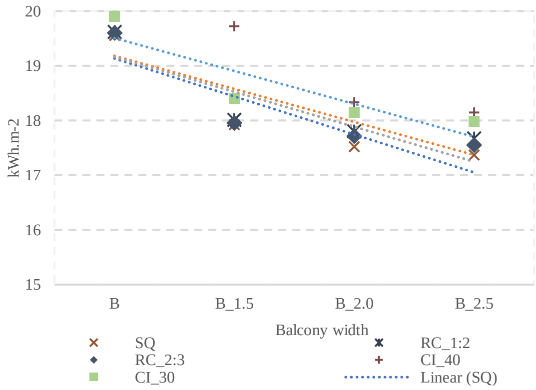



***Figure 187.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

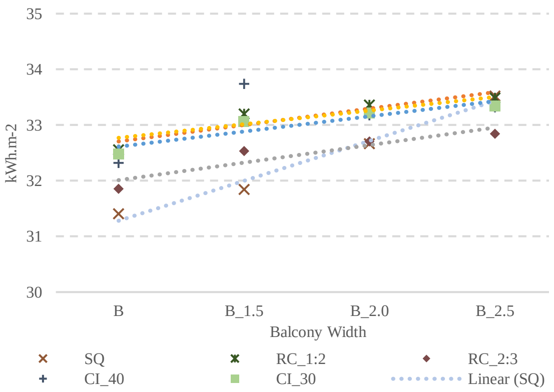



***Figure 188.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

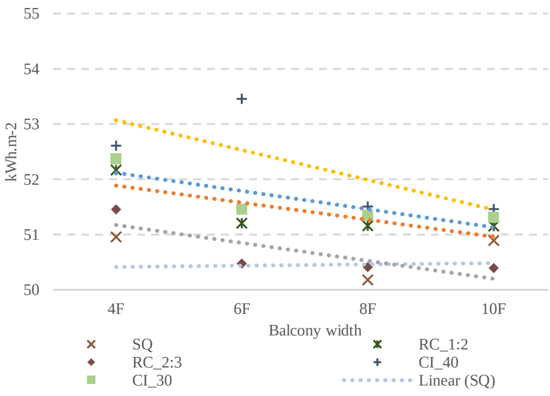



***Figure 189.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for 8F and balconies' scenarios

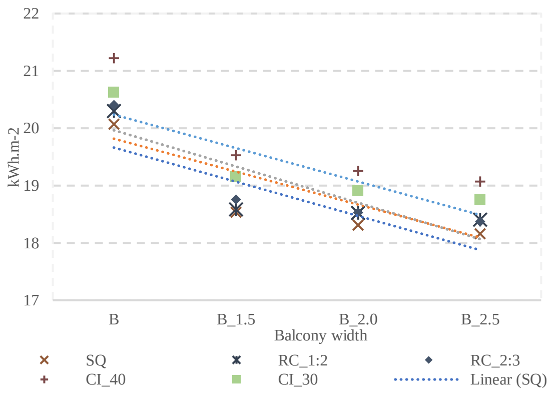



***Figure 190.*** Comparison of simulated cooling demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

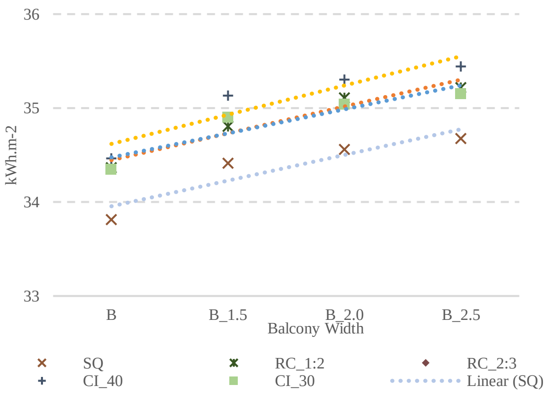



***Figure 191.*** Comparison of simulated heating demand (kWh.m2) of UGB morphologies for 10F and balconies' scenarios

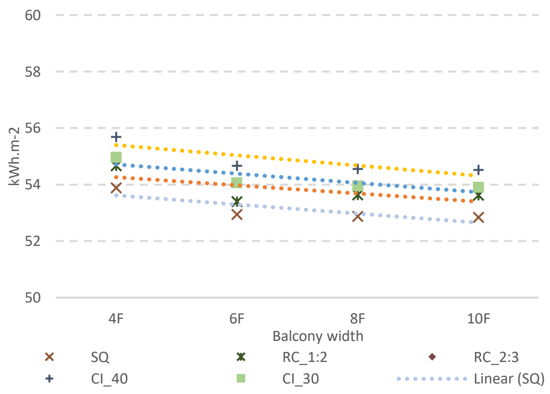



***Figure 192.*** Comparison of simulated total energy demand (kWh.m2) of UGB morphologies for F and balconies' scenarios