Systematic Literature Review of Bioclimatic Design Elements:

Theories, Methodologies and Cases in the South-eastern Mediterranean Climate

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Abstract

This paper presents a systematic review of the extant literature on bio-climatic design systems with the aim of conserving global energy resources. The present study explores the ways in which specific passive-cooling design strategies can be tailor-made to their locality, and residential buildings can be purpose-built and modified to optimise occupant thermal comfort and acclimatise indoor-air environments. A range of state-of-the-art vernacular passive-cooling designs that address the sustainability of a given proposal in relation to their respective locations and climate characteristics are presented; the extensive interpretations of these passive-cooling design strategies are in sharp contrast to the highly expensive, technical and exclusive environmental solutions that are so often universally applied in different locations, regardless of the physical, cultural and socio-economic contexts of each. The aim of this research is to investigate the efficiency of passive design systems in light of the thermal performance of prototype vernacular buildings to demonstrate the applicability and feasibility of installing vernacular passive-cooling design strategies onto building envelopes.

One of the prominent conceptual frameworks utilised in this paper is intended to address concerns related to the use of technologies that promote energy efficiency and ecological sustainability, most of which rely upon complex technological devices and a one-size-fits-all approach that only wealthy corporations and institutions are able to afford. Alternately, an increasing number of architects, theorists and politicians—albeit not yet enough—are investigating affordable technologies that are better able to be embedded in cultural practices. These manifestos are main determinant factors for a thorough review of the extant literature on passive-cooling design strategies and undertaking building energy simulations on base-case prototype vernacular buildings to demonstrate the energy effectiveness of implementing existing construction strategies onto current building envelopes.

The study findings suggest that contemporary design methods lack sustainable designs on a purely technical basis on which it is typically discussed and demonstrates that significantly more needs to be done to conform to locally identifiable requirements and practices. It was determined that while many of vernacular passive-cooling design strategies are still effective, others are disappearing due to changes in construction technology. This systematic review outlines an alternative, hybrid approach to sustainability that is proudly inherent in vernacular environmental design principles. The study conclusions offer an alternative perspective on sustainable design and brings to the forefront a broader systematic analysis of current literature that focusses on environmental technologies in the south-eastern Mediterranean area and the Middle East, where the weather is subtropical (*Csa*) and partly semi-arid (*Bsh*). The present study further demonstrates that for environmental design to be sustainable, a fundamental reorientation needs to emerge and move away from current construction practices with purely understanding of the domestic built environment, which fails to address the societal values of a particular place and people; and the findings underscore the necessity of recalling invisible technologies that are embedded in socio-cultural practices to effectively ventilate our dwellings and optimise occupant levels of thermal comfort throughout the year.

Keywords: Bioclimatic design; Building energy simulation; Passive cooling; Solar energy; Sustainability; Vernacular architecture; South-eastern Mediterranean

Nomenclature	
A	Area (m^2)
°C	Degrees Celsius
E	Energy (kWh/m^2)
f_c	Correction factor of thermal mass
m	Mass (kg)
M	Thermal conductivity coefficient (kJ/m^2K)
R	Heat absorptivity coefficient (m^2K/W)
T	Temperature (°C)
W_s	Monthly average wind speed (m/s)
Abbreviations	
A/C	Air conditioning
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEM	Building-energy simulation
BES	Building-energy simulation
CIBSE	Chartered Institution of Building Services Engineers
CO_2	Carbon dioxide
DTS	Dynamic thermal simulation
EU	European Union
IES	Integrated Environmental Solutions
MET	Meteorological Office
PMV	Predicted mean vote
PPD	Predicted people discomfort
RH	Relative humidity
RHI	Relative humidity index
TRY	Test reference year (weather file)
VPC	Vernacular passive cooling

1. Introduction

In the South-eastern Mediterranean Europe and Middle East countries where the weather is subtropical (*Csa*) and partly semi-arid (*Bsh*), most modern residential buildings without mechanical air conditioning systems are unsuitable for current and future climate-change projections, especially in densely built urban areas [1]. Most of these structures are designed to keep natural phenomena in high-rise residential buildings and to separate space-conditioned indoor environments from the outdoors to the greatest possible extent in order to harness effective natural ventilation for each occupied space [2]. Many scholarly articles have discussed the fact that modern residential buildings are predominately reliant on mechanical air-conditioning systems and lead to high electricity demands to provide thermally comfortable indoor air temperatures, especially when the weather conditions are hot and humid [3-5]. For this reason, in hot and warm climate zones, such as south-eastern Mediterranean countries—and specifically, the eastern Mediterranean island of Cyprus—households have significant expenditures in the summer months due to a dependence on the use of domestic cooling appliances on weekdays and weekends [5].

Recent studies have emphasised that the use of wall-mounted air conditioning units during the summer periods has led to increased cooling loads and electricity consumption and peak cooling loads and electricity demands [6]. This is partially due to high outdoor air temperatures recorded at the case-study locations, and it also significantly correlates with deficient building envelopes. In line with these findings, other researchers have extensively investigated the thermal performance of buildings under heatwave scenarios in 2030, 2050 and 2080; and additional studies have highlighted the significance of climate-change projections and the impact thereof on domestic energy use [7, 8]

One of the most recent empirical studies was undertaken by Ozarisoy and Altan [5], who claimed that due to the consequences of various of environmental parameters in Cyprus, building thermal properties and occupant socio-demographic characteristics, two-thirds of all households have experienced problems regularly paying their energy bills. These findings highlighted those long stretches of at-home occupancy and issues in the production of electricity, such as reductions and cutbacks in electric power, have most frequently been observed during the summer [5, 9, 10]. From this empirical pilot study, it was determined that as a consequence of global warming, households predominantly rely on the use of air-conditioning systems, and that they would be unable to keep thermally comfortable indoor air temperatures if the electricity fails, particularly during the day [11, 12].

In order to provide comfortable indoor environments in purpose built high density residential estates, this research focussed on reviewing a critical analysis of sustainable construction materials and the revival and applicability of passive-cooling strategies by exploring the potential efficiency of adopting vernacular construction materials and elements reveal in the form of dwellings as a complex cultural value needs influences and how they, where influenced by the climatic conditions of their locality. For this reason, vernacular architecture that was developed over several generations necessarily has elements or characteristics that ensure comfortable micro-climate indoor environmental conditions by efficiently using natural ventilation and solar energy [13]. However, these elements or characteristics should be evaluated and modified to be consistent or compatible with modern requirements prior to adopting new materials or techniques, such as energy-efficient building materials and systems, in retrofitting interventions [14]. Figure 1 illustrates the methodological workflow of the analysis of systematic literature review and development stages of building energy simulations.

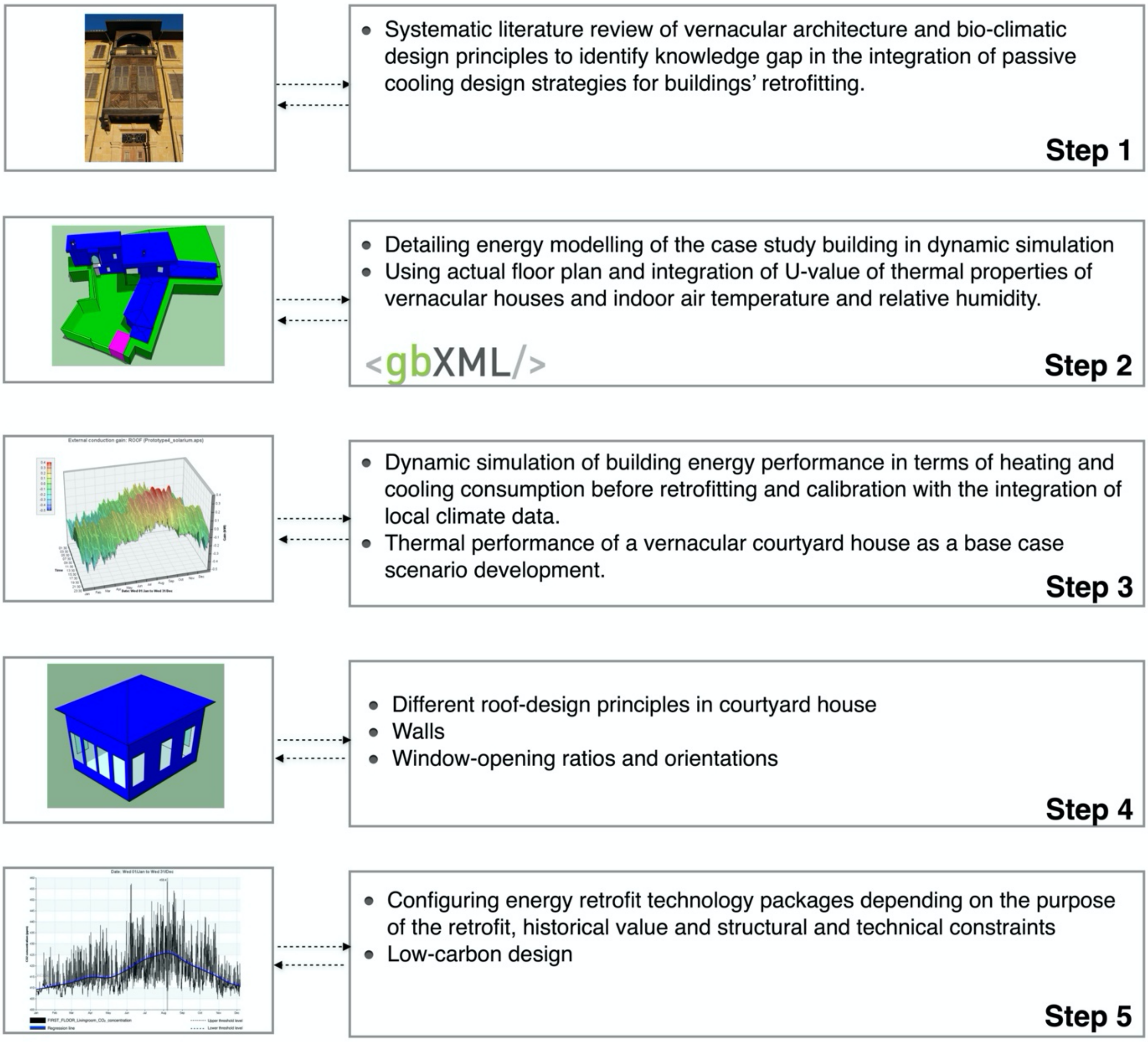


Fig.1. The methodological workflow developed to reclaim revival applicability of bioclimatic design elements.

The initial aim of this study was to investigate the indoor thermal qualities of vernacular buildings in the South-eastern Mediterranean climate of Cyprus to determine if any lessons on ventilation, shading and construction methods can be learned and how these might be applied when retrofitting existing residential building stock. Precedent strategies and exemplar vernacular buildings were examined, and construction materials and elements of vernacular buildings were examined. A thorough investigation was undertaken in conjunction with attempts to corroborate appropriate choices related to orientation, building materials and the use of natural energy resources in order to achieve comfort conditions for occupants without the need for mechanical cooling systems. An analysis was independently conducted on various combinations of shading and ventilation profiles to highlight the effectiveness of vernacular passive-cooling design strategies and possible interferences thereof on modern building applications. To fulfil the research aim and objectives, this paper attempted to review and understand whether passive-cooling design strategies that use vernacular architectural elements and construction materials can provide comfortable conditions within residential buildings in hot, humid climates.

1.1 Novelty of this research

The novelty of this study is a critical examination of the validity of a universalist mode of thinking based on a purely technological approach in relation to environmentally sustainable designs, which are often referred to as 'green architecture'. Instead, this topic is re-interpreted in terms of its relationship to the cultural practices surrounding the development of the aforementioned conceptual framework and a re-examination of the particular situation versus the universal dilemma is proposed (see **Graphical Abstract**). The objective of the present study is to develop and test energy-efficient state-of-the-art, cooling design systems aimed at optimising the thermal comfort of occupants while reducing their cooling-energy demands in existing and newly built housing stock in the Mediterranean basin.

The range of existing vernacular passive-cooling techniques suggested in this study can be applied at the early decision-making stage of building retrofitting schemes. One of the primary reasons that this housing typology in this particular Mediterranean context were chosen was to construct affordable, sustainable housing for the public and private sectors that is designed to be climate resilient and state-of-the-art with techno-cultural tools that were developed to implement passive-cooling design strategies in the residential sector. The present study elaborates on an energy-performance analysis of modern housing developments in Europe, which clearly shows that various proposed energy-efficient cooling systems should be considered because of significant energy savings and the resulting optimised thermal comfort of the occupants therein. As such, this study adds significant value and data to building energy simulation studies that have attempted to demonstrate energy savings by re-defining passive design elements into current and future house retrofitting strategies; this is an exemplar study for similar building typologies that were built during similar construction eras across south-eastern Mediterranean Europe.

The literature review highlights critical insights that are useful for defining energy-efficient retrofitting policies in Section 2. The methodology adopted and developed to characterise the building energy simulation models applied in Cyprus is discussed in Section 3. The interpretations of the extant literature review of adopting building energy simulations to perform detailed dynamic thermal simulations on archetype buildings across the globe are presented in Section 4. Finally, a set of detailed parameters is provided, which define the reference buildings and can be adopted for similar contexts in southern Europe in Section 5.

2. Theories

2.1 Importance of Reviewing Vernacular Passive-Cooling Strategies

This research constitutes a systematic review to understand the energy efficiency of locally available materials and the implications of developing guidelines for sustainable design principles in building retrofitting efforts. Through a critical investigation and analysis of vernacular buildings across four different climatic regions in Cyprus, it was found that porous ceramic is the most commonly used building material to construct thermally efficient external wall insulation in regions where the climate is hot and dry in the summer [15]. Many scholarly articles have mentioned that porous ceramic was made on the building site by local tradespeople from locally available resources and commodities [16, 17]; it was inexpensive and easy to create, and it was easily transported to the building site because it was lightweight [18, 19].

Notably, the use of this locally produced material by many civilisations in the construction of buildings spanned several centuries, from the 11^{th} century BCE to the 19^{th} century CE [20]. It is assumed that in addition to local availability and easy access to the construction site, this material was used because of the thermal properties and the ability to provide the functions of sustainability assessment criteria to various forms of buildings [21]. Specifically, this material was able to absorb and store heat, while simultaneously providing adequate ventilation and cooling down indoor air temperatures [21, 22]. It is also important to highlight that the lightweight features allowed it to be applied to structural retrofitting of historical buildings [23]. Perhaps one of the most important aspects of this substance is the lifespan and durability thereof, even after many centuries [23, 24]. However, the use of porous ceramic was abandoned after the 19^{th} century and has since been replaced with different types of construction materials, primarily heavy concrete, which is not environmentally responsible and is energy inefficient [25].

One of the most well-known studies on this topic, which was entitled 'Natural energy and vernacular architecture—Principles and examples with reference to hot and arid climate', was conducted by Fathy in 1986 [26]. This work explored the determinant factors that have allowed vernacular buildings in hot climate regions to be able to adapt better to the climate according to bioclimatic design principles evolved over many generations, compared to a majority of modern residential buildings [27]. Fathy suggested that ancient builders created harmony between dwellings, dwellers and the physical environment to construct thermally efficient houses and considerable solar control in the summer [28].

Many exploratory case-study projects have reviewed vernacular dwellings and identified different bioclimatic architectural strategies that were aggregated by ancient builders, who were known to adapt houses according to the physical properties of context, environment and climate [29, 30]. In order to adapt household thermal comfort to changing environmental conditions throughout the year, these dwellings were equipped with high, thick walls; wind-catcher systems; central courtyards; water elements; and arcaded solariums [31]. These vernacular passive-cooling strategies (VPCs) allowed for modifications due to the impact of high outdoor temperatures during the summer and also maintained optimum heating conditions in the winter [32]. One other important note is that, because these passive-cooling systems were made of locally available materials, they employed different bioclimatic design principles, mostly used renewable energy sources in domestic use and adopted historic construction practices that recycled available materials and showed respect for nature [33].

There has been a plethora of reviews to assess the significant impact of the thermal properties of vernacular buildings on occupant thermal comfort, but little research has been conducted to understand the potential energy efficiency of implementing these passive-cooling design strategies into modernised buildings [34-36]. A pilot study by Serghides in 2007 and 2010 highlighted that the implementation of VPCs in residential building retrofitting interventions led to as much as 60% less energy needed for heating and cooling [37]. In these analysis of the thermal performance of vernacular buildings, the building scientist explained that these strategies represent a resource that has considerable potential to aid in the understanding of principles of bioclimatic architectural strategies in sustainable design and construction [38, 39]; one of the main reasons is that corroborating within the values and needs of occupants, as well as considering to the adoption to the built environment, these bioclimatic elements could be culturally and physically energy efficient for domestic use [40]. At the same time, many scholarly articles have found that vernacular construction materials and systems are primarily relevant to local needs and are based on minimal, local use of energy and resources in line with the natural and social environments [41, 42]. It has been asserted by Golzari in 2014 that vernacular buildings should be a matter of concern in sustainability by means of implementation of bioclimatic architectural strategies in the decision-making and construction phases of holistic retrofitting projects that are currently under consideration [5]; as this is the case, many lessons can be learned from vernacular technology and VPCs, as demonstrated by the houses in Cyprus.

To improve the energy efficiency of thermally inefficient modern buildings, an overheating risk has been most frequently observed in vulnerable social housing development estates due to climate change and the detrimental impact thereof on occupant thermal comfort [43, 44]. This indicates that modern buildings require high cooling demand to create thermally comfortable indoor environments [45]. It has been argued by Serghides in 2010 that there is currently a sizeable accumulation of technical information, and yet present-day houses tend to be less comfortable than traditional structures [46]. It is important to consider interactions between buildings, systems and occupants in order to provide thermally comfortable conditions in homes [47]. In a study by Serghides in 2010 [48] on the energy use in self-built modern houses, determinant factors that cause or explain environmentally disruptive actions, which help to illustrate the overall thermal performance of buildings in a hot and humid climate, were delineated. The author asserted that a retrospective evaluation of vernacular architecture was needed to determine how our predecessors addressed thermal-design problems with the tools and techniques available to them. The study also suggested that it is important to understand the differences between present-day approaches and strategies to contend with the climate and those of indigenous builders [49]. Figure 2 delineates the schematic illustration of systematic literature review undertaken to provide background information on investigating passive cooling design elements in the south-eastern Mediterranean climate of Cyprus.

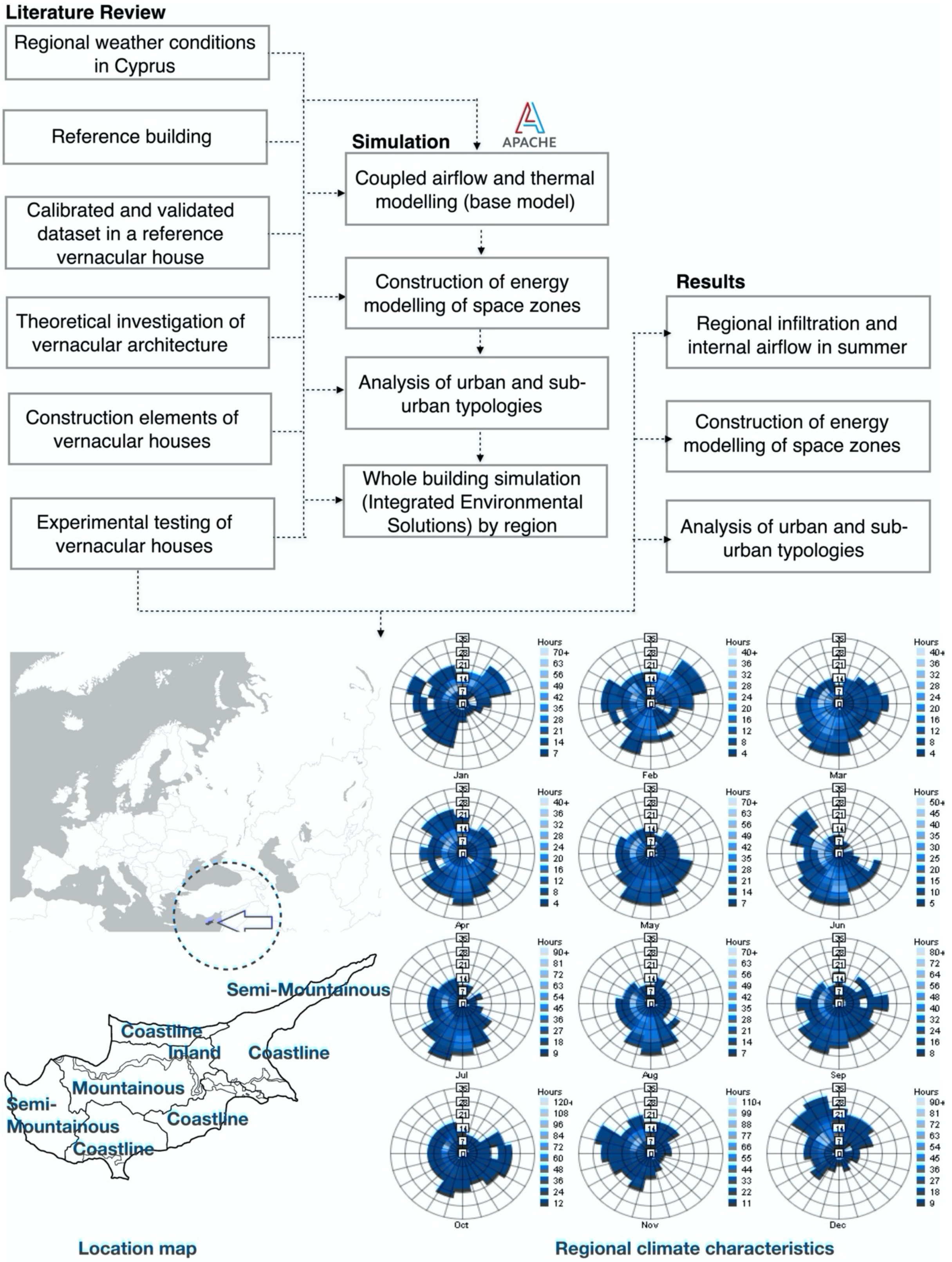


Fig.2. The importance of geographical characteristics and local climate conditions to develop evidence-based passive cooling design strategies for buildings' retrofitting.

It has been asserted by Michael and his research consortium in 2017 that an evaluation of vernacular architecture could reveal complex cultural values and how the structures were influenced by local climatic conditions [50]. Moreover, it has been implied by Dincyurek in 2003 that 'vernacular architecture' in Cyprus is difficult to define; like the land from which it springs or grows, these structures reflect the varied lifestyles of occupants and the availability of the resources of each region [51]. However, it has also been suggested that the variety of terrain on the island (i.e., inland, mountainous, semi-mountainous and coastal) spawned a variety of needs, building materials and building forms [52]. Additionally, the experience of local builders and their devotion to tradition, and integration with the ability to receive and assimilate foreign cultural preferences are reflected in the variety of habitats that have been created on the island [53, 54].

It is also important to understand the differences between the present-day approach and passive-cooling design strategies to upgrade the thermal performance of modern buildings while also taking occupant thermal comfort into consideration. This study will focus on passive-cooling design strategies that enhance the thermal performance of residential buildings during the summer period, avoid overheating and improve both indoor climatic conditions and micro-climates around the buildings, specifically shading, the thermal capacity of building construction materials and other passive-cooling techniques in order to provide a meaningful and accessible approach that could be adopted by policymakers [55, 56].

2.2 Significance of Considering Vernacular Architecture and Bioclimatic Design Elements in Building Retrofitting Interventions

Many scholarly articles have appreciatively described architectural styles and traditional construction methods for naturally ventilated residential buildings on the Mediterranean island of Cyprus. However, little research has been conducted on the thermal performances thereof in order to upgrade the energy performances of these structures [57, 58]. Most of these investigations acknowledged the internal thermal quality of vernacular houses and criticised inefficiencies in the building envelopes of concrete-built contemporary residential buildings.

Two additional scholarly journal articles were published by Serghides in 2010 and 2015 [48, 59]. The earlier paper investigated the energy performance of a new vernacular hybrid residential-building and found that a typical low-income multi-family social housing unit spent between 29% and 51% of the overall income to cool indoor environments in summer; the study also concluded that implementing insulation material onto the building envelope led to a significant decrease in heating-energy consumption [48].

In the later study, a dynamic-thermal simulation method was implemented to evaluate the thermal behaviour of a base-case representative multi-family apartment unit in Cyprus [59]; this study concluded that uninsulated concrete walls led to higher rates of heat loss, compared to traditional vernacular wall typologies. The study also examined other passive-cooling design strategies, such as the implementation of top-window openings and appropriate shading systems on building envelopes in different residential-building typologies [59]. Nevertheless, therefore, the vernacular environmental design elements, which was evolved and developed over many generations must have an efficient cooling strategy that optimise occupant thermal comfort under the risk of a building envelope overheating in the summer [60]. However, these low-energy passive-cooling design strategies should be evaluated and adapted to be consistent and compatible with modern building systems requirements, including taking the implied regulations and measures of the energy performance of buildings directives to upgrade the energy efficiency of existing residential-building stock into account [5, 61]. Figure 3 demonstrates the black-box analytical energy modelling strategy developed to test energy effectiveness of vernacular houses in the south-eastern Mediterranean climate.

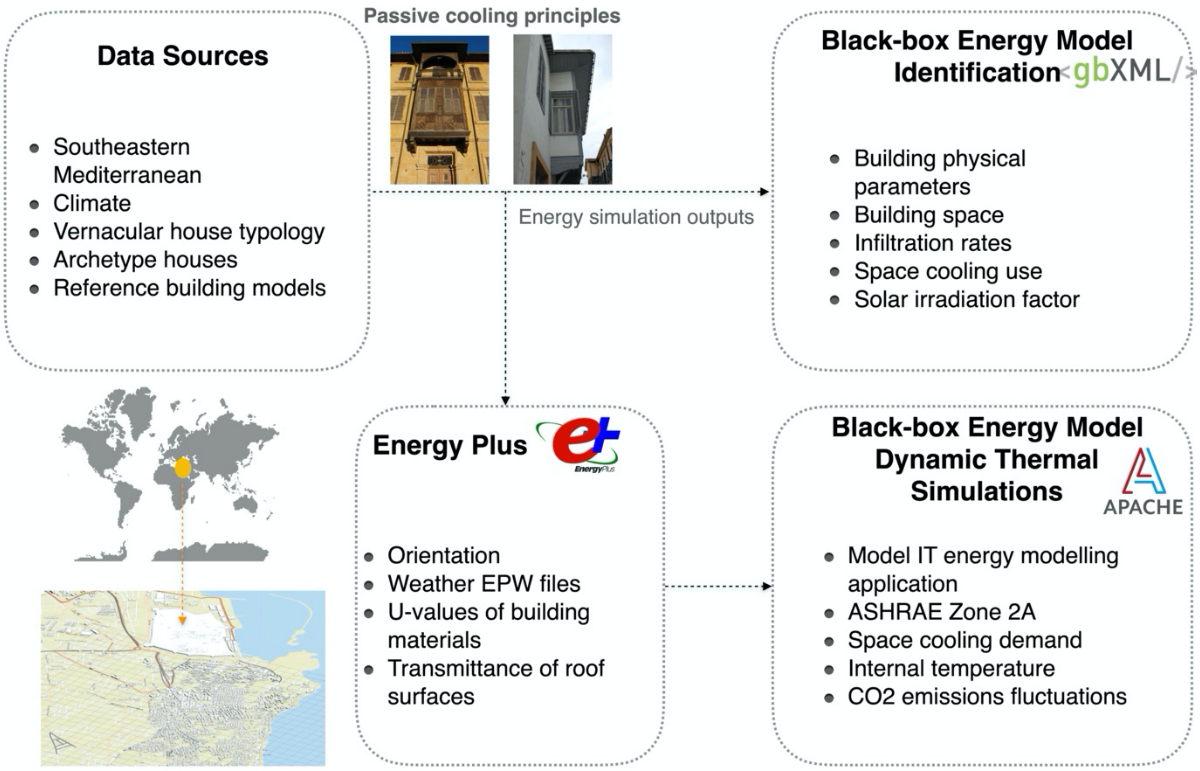


Fig.3. The workflow of dynamic thermal simulations to test thermal performance of vernacular houses.

Historically, research investigating the efficiency of implementing VPCs associated with contemporary residential buildings has focused on longstanding bioclimatic design principles that are essential for optimising indoor air temperatures in hot, dry climates [62]. Even though these strategies have been ignored or surpassed by architects in recent decades, it has been asserted by that the generalisability of much of the published research on this issue is problematic [63, 64]. Because of this, one study by Oktay in 2002 argued that vernacular building elements and the potentialities thereof in most southern European countries have been neglected and replaced by methods that are inappropriate to local conditions and physical, economic, social, cultural and aesthetic requirements [65]. Similarly, a study by Michael et al. [66] found that traditional architectural methods and strategies, especially those of the hot, humid Cypriot climate, are undervalued and unused in contemporary buildings. There seems to be little awareness of the impact of government efforts to upgrade the energy efficiency of existing building stock [67].

Notably, other studies have emphasised that in order to understand the solar-thermal performance of vernacular buildings in a specific time and context, it is necessary to understand the climate and thermal behaviour of locally available building materials [67, 68]. Ozarisoy and Altan [5] also argued that many vernacular technologies no longer function properly due to cultural and ecological changes throughout the centuries. This in turn affected the efficiency of implementing VPCs when undertaking a holistic retrofitting in the residential sector [5, 67, 68]. Moreover, it has also been suggested that because the values and knowledge embedded in vernacular buildings are able to be systematically identified, studies that consider the decision-making processes for retrofitting interventions will significantly lower the cost and increase the value of these interventions [69].

One of the main reasons of devising this study in accordance with reviewing bioclimatic design systems of vernacular buildings and undertaking building energy simulations is that previously published exemplar studies only considered assessing energy performance and occupants' thermal comfort in the tropical climate and there is a little research conducted to investigate the revival applicability of bioclimatic architecture for the retrofitting of buildings in the South-eastern Mediterranean climate of Cyprus. Therefore, in this study, the findings highlight that the selection of energy simulation tools are important in the decision making process of retrofit interventions in the residential sector which are presented in Section 4. For that reason, this study explicitly discusses different simulation parameters that could bring significant empirical analysis on assessing overheating risk and providing subsequent information for delivery of effective retrofit interventions in the Mediterranean basin.

3. Methods

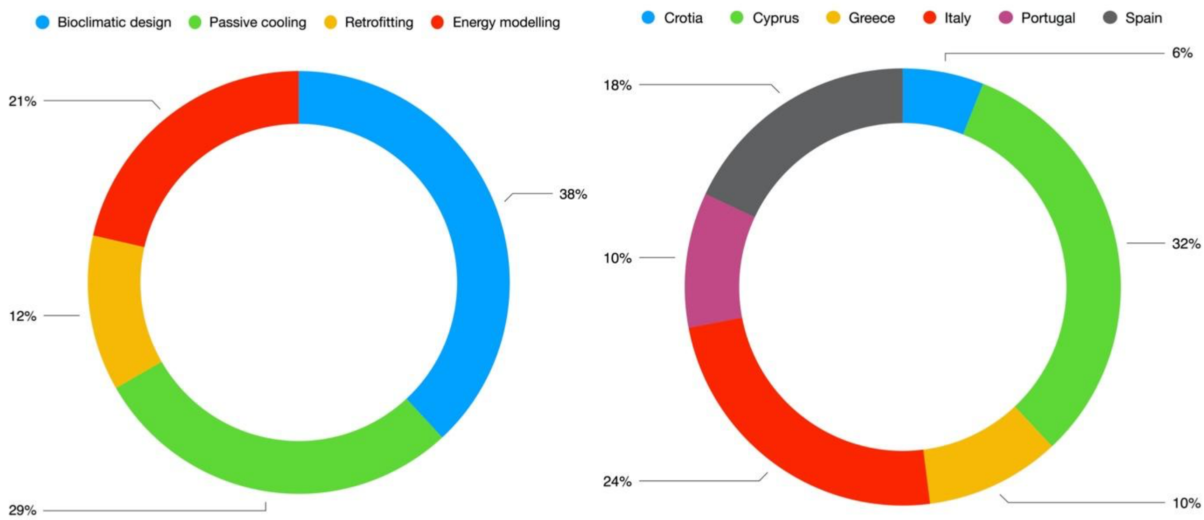
3.1 Systematic Literature Review

This study sought to identify the thermal properties of vernacular buildings and reviewed the reasons that previous builders and craftsmen selected particular locations and orientations for their constructions; how these indigenous builders solved climatic, topographical and environmental constraints; and why and how they used particular building materials and construction solutions to design climate-responsive structures. The aim of this section is to provide an up-to-date systematic review of bioclimatic design systems, passive cooling, retrofitting and building energy modelling. To retrieve articles for the topic 'Building Energy Simulation', three title (TI) record files were created, as listed in Table 1.

Table 1: Search data for existing studies

Concepts	**Keyword-Search Selection Criteria**	**Review Articles**	**Original Research Papers**	**Conference Proceedings**
Bioclimatic design	TI = (‘bioclimate*’ OR ‘thermal performance’)	8	25	2
Passive cooling	TI = ((‘passive evaporative cooling*’ OR ‘thermal comfort’ OR ‘natural ventilation’) AND ((‘passive design*’ OR ‘fenestration strategies’)))	12	32	3
Retrofitting	TI = ((‘building performance*’ OR ‘energy use’ OR ‘thermal comfort’) AND ((‘energy use*’ OR ‘passive design’)))	7	12	7
Energy modelling	TI = ((‘building performance*’ OR ‘energy use’ OR ‘overheating’) AND ((‘passive design*’)))	9	42	8

Table 1 demonstrates a summary of the search data for articles on BESs conducted in the Web of Science Core Collection database. The set results of the advanced searches were combined using the ‘OR’ Boolean operator to obtain 200 articles. To fill the research gap and outline the contribution to the knowledge, this study investigated ongoing studies and potential solutions to resolve the identified issues. The methodology involves a detailed literature review to provide an overview of existing studies of vernacular passive cooling and a systematic selection and study of review articles, original research papers and conference proceedings to investigate the benefits and challenges of assessing building overheating risks and occupant thermal comfort. Figures 4 (a) and (b) present an overview of the search results.



(a) (b)

Fig.4. (a) Keywords and percentage distribution related to appearance; **(b)** countries of pilot studies examined in accordance with keyword selection criteria.

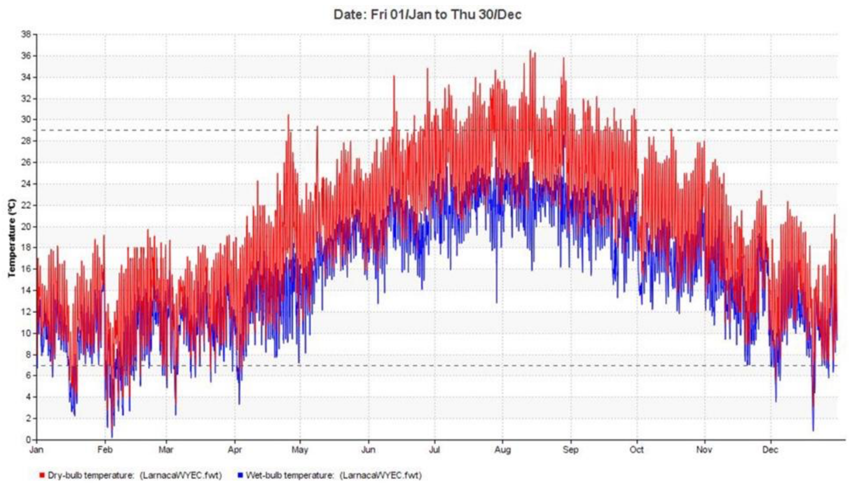
The review articles were filtered from a list of journal articles and conference proceedings that were published between 2000 and March of 2021. The source of the systematic selection of articles used for the analysis was the 'Web of Science Core Collection', which is maintained by Clarivate Analytics. The main procedure involves creating a design for a search of the articles. Abstracts of the documents were reviewed using the meta-analysis method.

3.2 Field Study: On-site observations

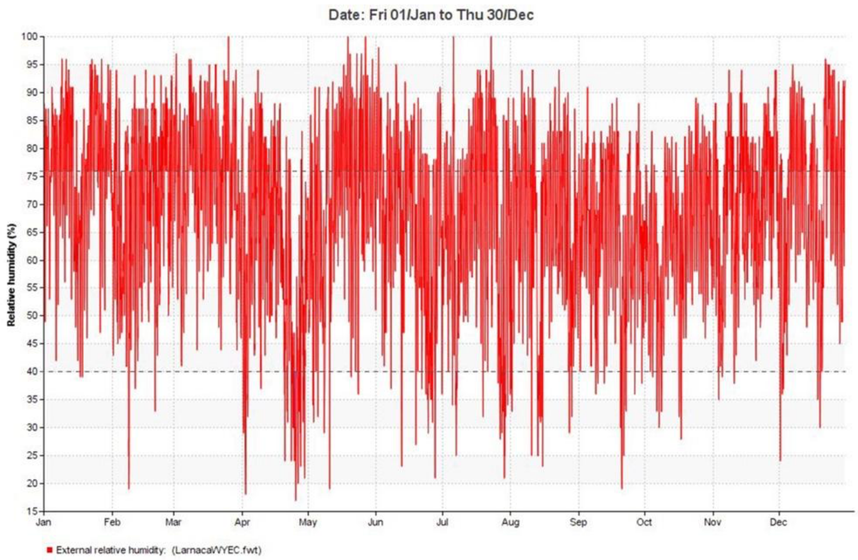
The objective of this study is to evaluate and regenerate the applicability of bioclimatic design principles in current retrofitting efforts for residential buildings. In this study, three exemplar historic buildings were reviewed, based on archival documents that utilised available resources from drawings, maps, illustrations and narratives from selected books and diaries compiled by explorers and travellers, in addition to on-site photographic observations (see **Video A**). To accomplish this, the gathered data was analysed to discern the applicability of these ancient construction systems for present-day residential building designs. The study included six different study cases in which three different solar design systems were used in the construction process with the primary purpose of the building to be an energy-efficient structure that was cool in the summer and warm in winter, while at the same time providing natural ventilation throughout the building (see **Video B**). These prototype base-case vernacular buildings were built during the time frame that spanned from the 11th century BCE to 19th century CE; the case studies were selected because they represented the most dominant vernacular housing typologies, and the sustainable design elements that are associated with each were used in different types of building construction systems.

3.3 Case Study: Location and Climate

An extensive literature review and building energy simulations were carried out in an area that was geographically located approximately on a latitude of 35°N and a longitude of 33°E [70]. According to the Köppen–Geiger climate classification scheme, the climatic characteristics of the study context were identified as being typically sub-Mediterranean [70]. The average yearly temperatures were a maximum of 20°C and a minimum of 13.7°C, as shown in Figure 5 (a). The average relative humidity was between 84% at 05.30 hours and 78% at 11.30 hours, as shown in Figure 5 (b). Additionally, the average rainfall was 417mm and the amount of sunshine was between 3,000 and 3,100 hours per year, as shown in Figure 5 (c). The hottest month was August with average monthly temperatures that were a maximum of 28.7°C and a minimum of 19.7°C, and absolute temperatures that were a maximum of 37.5°C and a minimum of 21.7°C [71].



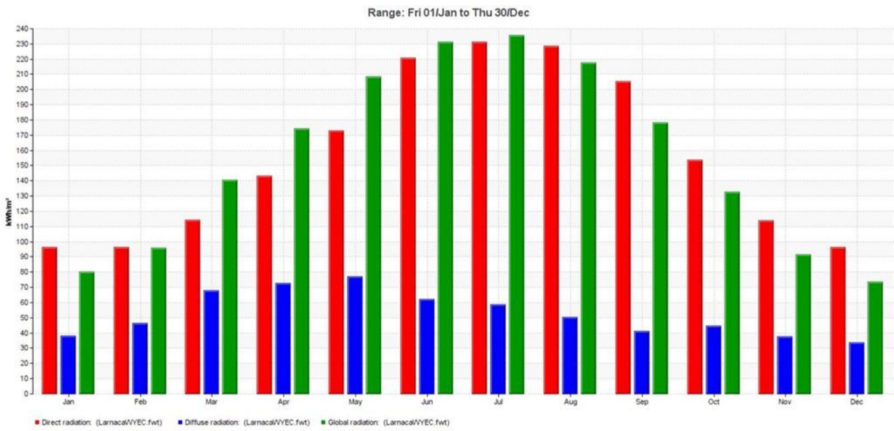
(a)



(b)

Fig. 5. (a) Illustration of the minimum and maximum temperatures, minimum mean and maximum mean air temperatures and the mean air temperature; **(b)** relative humidity levels.

As shown in Figure 5 (a), the average relative humidity was 89% at 05.30 hours and 81% at 11.30 hours. Conversely, the coolest month was January with average monthly temperatures that were a maximum of 17.7°C and a minimum of 5.5°C, and absolute temperatures that were a maximum of 19.8°C and a minimum of 4.7°C. The average relative humidity was 82% at 05.30 hours and 78% at 11.30 hours [72]. The bioclimatic characteristics and the geographic location of the area represented some of the most important influences that influenced the traditional vernacular architecture in Cyprus. Furthermore, the evolution of vernacular architecture has been found to be directly correlated to the climate of this specific study context; the sun and wind are likely other predominant factors that affected the manner in which traditional builders chose the orientation and location of vernacular courtyard houses in remote regions across the island [73].



(c)

Fig. 5 (c) Environmental conditions of case-study location; solar radiation, solar irradiance and sunshine hours.

As shown in Figure 5 (c), solar-radiation statistics reveal that most regions of the island have 75% average bright sunshine hours during the period when the sun is above the horizon [74]. Notably a horizontal surface over Cyprus at the top of the atmosphere typically receives 112 kWh/m^2 per day in December and 220 kWh/m^2 per day in June. Due to the island's geographical location, the data demonstrate that during the cloudiest months of December and January, the average duration of sunshine is 5.5 hours, while this figure reaches an average of 12 hours a day in the summer. In this study, it was deduced that adaptation to climate depends on multiple factors within different environmental conditions, all of which were explored at the base-case vernacular buildings. Because of this, solar height was a significant factor as it relates to daylight exposure and thermal conditions.

3.4 Archetype buildings selection criteria

The selection criteria of case-study buildings were premised on the thermal properties, spatial floor-plan configurations, solar-shading design principles, location (i.e., urban or rural regions) and orientation of the buildings and the topographical characteristics of the study areas, as shown in Figure 6. The study was designed to be conducted in three distinct investigative stages—theoretical, analytical and experimental—in order to demonstrate the energy efficiency of passive-cooling design strategies in the decision-making processes of holistic retrofitting in the residential sector. As such, the objectives are threefold: First, to demonstrate the relevance and potential of vernacular architecture to optimise indoor air temperatures in modern residential buildings in the present context of the built environment. Second, to analyse the design principles of vernacular buildings in order to provide subsequent information for the basis of retrofitting interventions. Third, to correlate the outcomes of a review of vernacular design elements and the implications thereof on occupant thermal comfort with human-based data when building energy simulations for calibrating energy end-use efficiencies of those buildings under investigation. Overall, this study aimed to devise energy-efficient retrofitting solutions by taking the implementation of locally available building materials and passive-cooling design strategies into consideration.

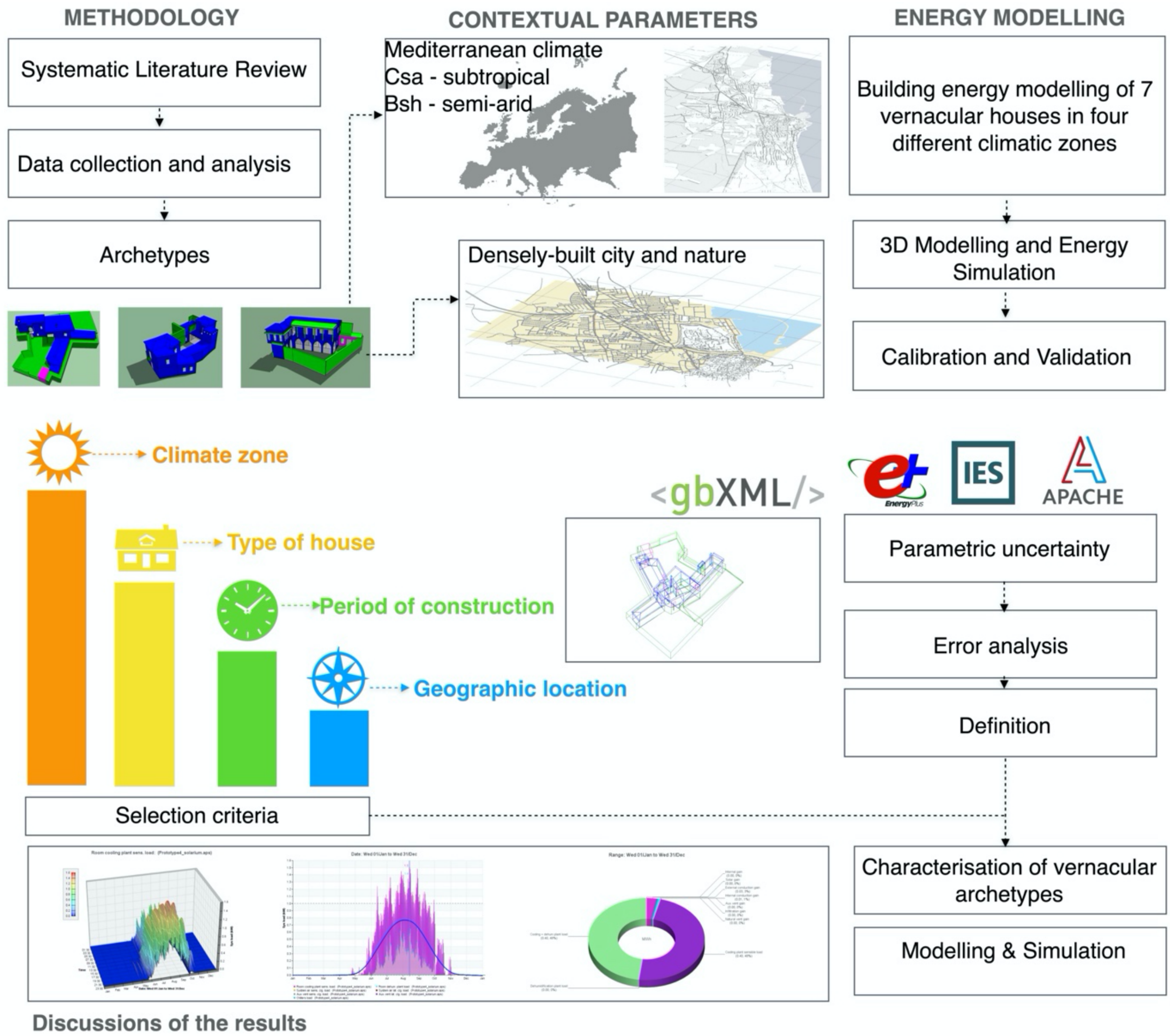


Fig.6. The selection criteria of archetype vernacular houses for the study.

3.5 Building Energy Modelling and Simulation

This study also aimed to validate the extensive literature review undertaken on vernacular buildings and the bioclimatic design principles thereof by employing building-energy simulations. It sought to consider different vernacular buildings that were selected for the purpose of base-case scenario development. To fulfil the research aim and objectives, case-study buildings were selected from both rural and urban vernacular building typologies. In order to demonstrate the significance of the investigated bioclimatic design principles, the Integrated Environmental Solutions (IES) software suite Version IES 2020.1.0.0 was used throughout the study [74]. The scope of the simulations was based on indoor air temperatures in relation to thermally comfortable temperatures for each selected occupied space in the representative vernacular buildings. Figure 7 delineates the set-up of the building energy model with taking into consideration location, climate and thermal comfort parameters.

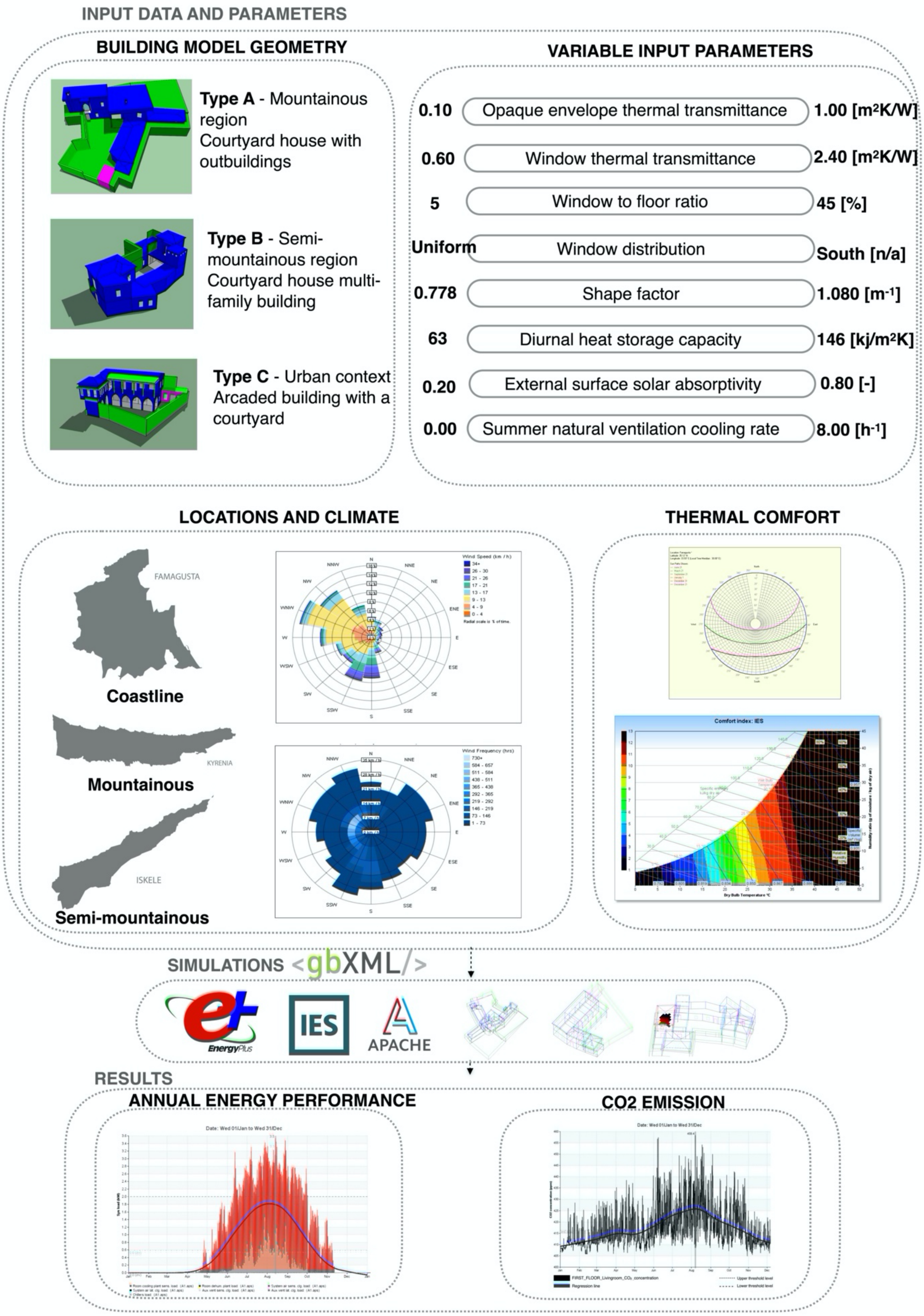


Fig.7. The step-by-step development of building energy simulation set in put parameters for the study.

The IES simulation tool was selected as the building-modelling simulation software because of sufficient validity when calculating the thermal analysis and indoor air environment in spaces, and because it could accurately perform in nearly all hours that were analysed in the thermal simulation; specifically, the Thermal Comfort software interface of the IES suite was an application that measured the 'adaptive comfort' of the representative base-case residential tower blocks. When this interface was considered in combination with the Dynamic Thermal Simulation components of the IES tool, it was possible to concurrently assess the energy performance of material changes. The expected energy performance of the prototype vernacular buildings and the significant retrofitting potential of implementing locally available materials were simulated between May and September of 2020 in order to test worst-case scenarios for bringing evidenced-based retrofitting interventions to uptake.

The objective of this portion of the research aimed to investigate the energy efficiency of different types of vernacular buildings in the study area; specifically, the building fabric thermal performance and the effect of bioclimatic design systems to energy use modelled and tested. To accomplish this, the most representative vernacular courtyard houses were investigated to provide evidence-based research for retrofitting interventions. Additionally, the average air temperatures and relative humidity levels for the summer and the winter were calculated in order to present an overall view of each case study and to ensure a more accurate analytical comparison of the case-study buildings under investigation.

4. Analysis and Discussions

4.1. Reviewing of Bioclimatic Design Systems

4.1.1. Solar–Thermal Design Specifications of Traditional Cypriot Houses

There are many studies on the implementation of passive-cooling strategies in subtropical hot and dry climates in the existing literature [75, 76]. An extensive literature review was presented by Serghides et al. [48] in which the authors highlighted the importance of considering basic building geometry to retain heat in the winter and provide an appropriate solar-shading system to protect households from excessive summer sun. They concluded that the orientation and shape of a vernacular building should reflect the location and climate; a compact form with verandas is the most appropriate for hot, humid climates, because one of the most important heat gains is conduction gains from high temperatures and/or solar radiation through the building envelope [77].

The most commonly devised shading systems should consider the orientation of buildings and the topographical characteristics of the geographic context. The study concluded that western and southern building façades are ideal orientations for the implementation of solar access controls, such as shading devices in the form of arcaded terraces, verandas or overhanging balcony projections [78]. These shading strategies have been developed and evolved over the course of centuries by local builders who considered the climate, the environment and socio-cultural values [79]. Hence, a study by Michael and his research consortium in 2017 determined that red brick and concrete blocks with a ventilated clay-tile façade of 4cm on the outer face demonstrated an efficient energy performance and was appropriate for the Cypriot context [79]. It was asserted by Pagliano and Zangheri in 2010 that in the refurbishment of 25 dwellings, adding a 2.5cm insulation layer of expanded polystyrene on the roof was the most economic retrofitting solution used under a retrofitting scheme of low-income housing in Cyprus [80].

From the pilot case-study project on a multi-criteria group decision-making method for the thermal renovation of masonry buildings, it can be understood that the *u*-values and the thermal transmittance of building materials play a crucial role in improving the energy efficiency of existing residential buildings [81]. For this reason, this study examined the thermal efficiency of vernacular buildings and investigated the formal characteristics, construction methods and building materials used by builders in the past in order to properly measure how the structures perform according to local environmental and climatic conditions. The studies on effects of vernacular climatic strategies on energy consumption suggested it is crucial to develop effective interventions by fully understanding the importance of bioclimatic design principles [81, 82]. Table 2 gives overview descriptions of construction properties of four different climate zones in Cyprus.

Table 2. The list of technical parameters relative to local materials

Building Properties	**Zone 1 Famagusta**	**Zone 2 Larnaca**	**Zone 3 Nicosia**	**Zone 4 Paphos**
U-value W/m^{2}K	Zone 2A (Hot and Dry)	Zone 2A (Hot and Dry)	Zone 3B (Warm and Dry)	Zone 3A (Warm and Humid)
Vertical opaque walls	3.36	3.4	3.34	3.48
Roofs	2.32	2.38	2.3	2.38
Floors towards unheated rooms	0.36	0.42	0.33	0.49
Elements towards other units	1.8	1.8	1.8	1.8
Windows	2.4	2.6	2.2	3
Glasses	1.9	2.1	1.7	2.7

Accordingly, the work of Serghides [48] also highlighted the limitations of purely disciplinary methods to conceptualise housing energy requirements; this study explicitly discussed the thermal performance of vernacular buildings in Cyprus and had a significant impact on the adoption of passive-cooling design strategies in contemporary buildings. The author primarily investigated traditional Cypriot houses, which were constructed to provide shelter from climate extremes and a variety of determinant factors related to energy use that took the efficiency of natural ventilation and solar energy in base-case representative residential buildings into consideration [83,84]. Moreover, this study posited that passive-cooling strategies on a hot summer afternoon never failed to impress contemporary occupants and other locals, who wonder how the vernacular buildings were able to offer such a comfortable indoor air environment without the benefit of advanced scientific knowledge.

At the same time, there has been a considerable amount of extant literature in the area of the potential energy efficiency of either incorporating locally available building materials onto building envelopes or adopting passive-cooling design strategies in building retrofitting efforts [85, 86]. One of the key studies by Philokyprou et al in 2013 and 2017 explained that the most typical vernacular housing typology in Cyprus was built with one or two storeys and a central courtyard, as shown in Figures 8 (a) and (b).

(a) (b)

Fig. 8. (a) The solarium; **(b)** courtyard constitute fundamental traditional building structures that provide thermal comfort in rural regions.

Different studies have, however, highlighted the potential of the housing sector to significantly contribute to the reduction of domestic energy use by implementing several methods from sustainable building materials implemented in vernacular architecture [87, 88]. As such, some of these studies indicated that vernacular structures primarily relied on the presence of a courtyard, which provided appropriate natural ventilation and solar penetration throughout liveable spaces [84]. These studies also indicated that the single-storey, central-courtyard house was the most common type of structure in historic urban settlements; these types of vernacular houses contained a symmetrical or partially inorganic layout design of private open spaces in the form of a courtyard [88, 89]. This means that typical vernacular buildings always faced inward and had thick, high surrounding walls due to the privacy concerns of occupants; this design etymology also addressed the problem of high solar radiation and acclimatised indoor air environments. It is important to note that some of the recent pilot projects adopted various techniques in modern residential buildings in Cyprus that improved occupant thermal comfort without relying on air conditioning systems [90, 91]. The results show that there was significant reduction in occupant energy use due to the efficiency of thick-wall construction systems combined with appropriate fenestration designs.

While earlier research demonstrated the potential benefits of implementing passive-cooling design strategies to cool down indoor air environments in inefficiently built residential buildings, further evidence-based research is needed to improve the energy efficiency of residential buildings while considering bioclimatic design principle (see **Supplementary Material A**) [92]. The research findings on key performance indicators approach in building renovation for the sustainability of the built environment support the idea that in addition to the thermal efficiency of central courtyard configurations in vernacular buildings, it is also important to discuss the spatial floor-plan layout designs of rooms and spaces oriented to the south when considering the efficacy of solar radiation in the winter and rooms and spaces oriented to the north when considering the coolness of the indoor environment in the summer [93]; it was argued that these rooms primarily opened out onto a central courtyard and had wind-catcher systems for cooling purposes.

In 2003, Dincyurek et al. [51] published a paper in which they described many vernacular buildings that had thick walls and roofs made of sun-dried bricks from locally available materials; they further suggested that rooms were designed to have direct access to courtyard, and windows on the peripheral walls were normally lacking and were of minimal size and above eye level to provide privacy in the home. Allocating small top-window openings on external walls also helped to keep hot winds and dust out of the indoor occupied spaces. Research has shown, however, that the rooftops of vernacular houses were mostly overhanging and oriented toward the street in order to harness the prevailing wind direction [94]; occupant privacy on the balcony projection was ensured by a perforated shading element that was higher than standing eye level, which surrounded the edges of the space in respect of cultural norms of the research context in the 19th century; the island of Cyprus was administered by the Ottomans between 1561 and 1878 CE [47, 51]. Similarly, the parapet provided shade and allowed indoor spaces to remain relatively cool and assisted with cooling efforts at night [75]. This layout also provided appropriate shading for pedestrians and also for indoor occupied spaces, as shown in Figures 9 (a) and (b).

(a) (b)

Fig. 9. (a) Overhanging balcony projection design incorporated on a south-facing building envelope to provide solar protection throughout the year; **(b)** extended large balcony projection oriented toward the street with two side-window openings to harness natural ventilation in urban regions.

A study by Serghides et al., 2019 has also found that arcaded semi-open spaces (i.e., verandas) were used in vernacular buildings in hot, humid regions [47, 48]. An evaluation of different arcaded space configurations has been the subject of several research studies, which claimed that these structures had a significant impact on the thermal performance of indoor occupied spaces [95]. These studies asserted that the semi-open spaces had a significant effect on the indoor air temperature of each occupied space in a single-storey, central-courtyard design that was the typical vernacular building style in urban and rural regions [47, 48, 86]. It is important to note that when these arcaded semi-open spaces were constructed in vernacular buildings in Cyprus, the rooftops were usually constructed with timber and covered with locally available palm leaves as an insulation material against solar protection [75].

4.1.2. Implications of Vernacular Architecture on Occupant Thermal Comfort

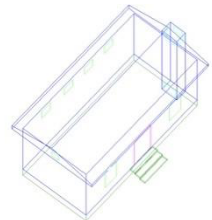
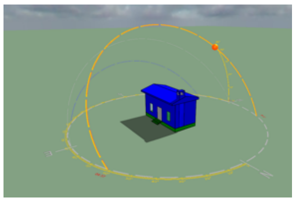
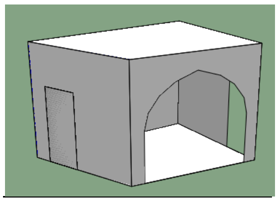
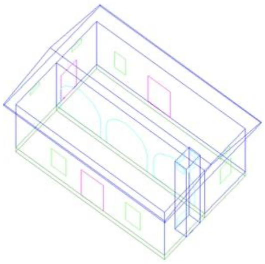
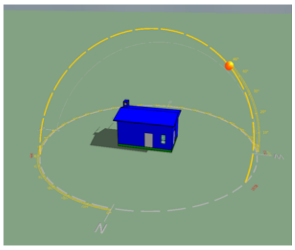
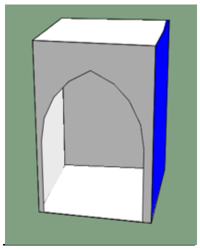
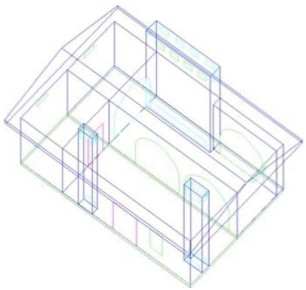
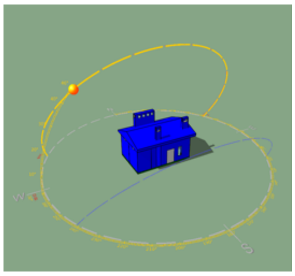
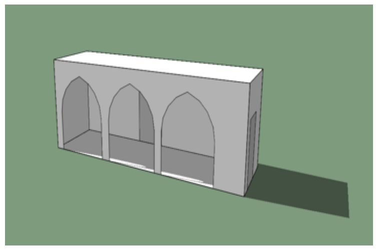
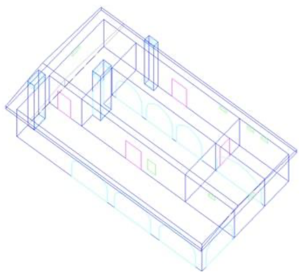
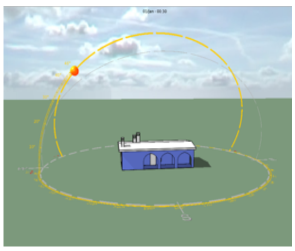
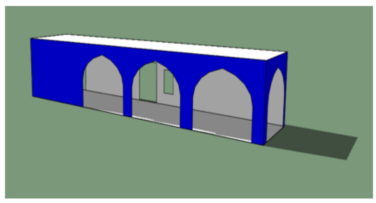
It seems obvious that vernacular architecture is linked to traditional architecture, but typical bioclimatic design principles were chosen as a conceptual framework of this study in order to demonstrate the energy efficiency of locally available materials and the design strategies that were developed by early builders [96, 97]. For the purpose of this study, which was conducted in a south-eastern Mediterranean climate, the single-story, central-courtyard house was the most common type of vernacular building that considered different aspects of solar-energy design principles to optimise occupant thermal comfort throughout the year [76]. There have been limited attempts to investigate the energy efficiency of VPCs in Cyprus and even fewer efforts to analyse or explain the forms, advantages and disadvantages thereof or to evaluate structural performance in the summer according to occupant thermal comfort expectations [48]. To fulfil the research aim and objectives, this section primarily discusses the built-form and spatial floor-plan layout design evolution of this vernacular housing typology to understand the main environmental design principles that have been inherited from local builders or craftsmen throughout the centuries (see **Supplementary Material B**).

The significance of vernacular architecture has frequently been described and emphasised by academics [89]. Much of the current literature on the design elements of vernacular architecture focuses on understanding the efficiency of VPCs and the effect thereof on indoor thermal environments, particularly in hot, humid climates [98, 99]. To address the issue of high solar radiation in the summer, one of the empirical studies by Santamouris et al. in 2007 describes those vernacular buildings represent hundreds of years of accumulated experience of many generations of experience and knowledge on building construction.

At the same time, different theories have been put forth in the literature regarding the vernacular technologies that have evolved over the past decade. In 1989, Rapoport [100] published a paper in which he explicitly described vernacular architectural design as an accumulation of the experience, successes and failures of ancient builders and the way that built environments interact with nature and locally available materials at the context. Previous research findings support the assertion that vernacular construction elements and materials are directly correlated to the thermal performance of buildings [95]. Thus, it has been argued by Santamouris and Kolokotsa in 2013 that the concept of adapting vernacular building architectural elements and theories and practices associated with energy use is of utmost importance to fully understand the passive-cooling strategies in historic buildings [96].

The early stages of this study will therefore investigate the evolution of the spatial floor-plan layout design of vernacular buildings in order to understand how previous builders dealt with the climate and the inherent ecological features of the building site [51]. This could be explained by the Cypriots isolated and confined structure on adaptive human comfort to an island's climatic conditions within implementing locally available resources into building's retrofitting concurrently with solar shading systems [76]. Table 3 illustrates the taxonomy of bioclimatic design systems by exploring effective fenestration design principles and shading element features are available in vernacular buildings in urban and rural regions of Cyprus.

Table 3. Taxonomy of bioclimatic design principles

Floor-Plan Layout	Ventilation Openings	Shading Features
 **Type A: Single room**	 Chimney and side openings	 Internal single arcade opening
 **Type B: Double room**	 Chimney and top-window openings	 Internal single-arcade opening
 **Type C: Triple room**	 Chimney, wind-catcher tower systems and vertical side openings	 Internal triple-arcade opening with vertical side openings
 **Type D: Quadruple room**	 Chimney and well-integrated underground wind tower systems	 External triple-arcade sun-terrace openings

Note: Type A – Single room (see Dataset A); Type B – Double room (see Dataset B); Type C – Triple room (see Dataset C); Type D: Quadruple room (see Dataset D)

As previously stated, Serghides [48] published an exploratory case study in 2010 that explicitly described the evolutionary stages of a long room in four different types of spatial floor-plan layouts. One of the primary reasons for this was because the plan layouts in vernacular buildings in Cyprus demonstrated variations according to four different climatic characteristics: mountainous, semi-mountainous, inland and coastal [52].

As is shown in Table 3, these spatial floor-plan layout designs were formed by considering different bioclimatic aspects in order to provide thermally comfortable indoor air environments; wind-catcher systems for natural ventilation and arcaded semi-open terraces for shading were devised to address the hot, humid climate of Cyprus [101]. However, several architects and builders have recently acquired a peculiarly narrow understanding and practice of energy, however, particularly upgrading the thermal performance of existing stock by retrofitting [5]. Problems sometimes arise depending on how architects engage with natural energy in decision-making process [102]. In this century, a non-modern architect would need to learn how to capture, channel, intercept, store, accelerate and modulate the total energetic dissipation of buildings through energy-efficient designs before participating in retrofitting interventions [103].

The main claim of this research is that no other concept has disturbed and disfigured the understanding on the energy efficiency of VPCs in the Cypriot climate; nevertheless, no material and energy practice in architecture has more completely instilled and reinforced the adaptability of bioclimatic architectural strategies. The core of the problem is this: When architects began to systematically engage in understanding building thermal performance in early modernity, the pedagogies and practices of modern architecture paradoxically became epistemically divided from the architectural and urban vitality of thermodynamics due to the prevalence of isolation as a concept, rather than principally adapting VPCs.

4.2. Building Energy Simulations

4.2.1. Precedent of Longitudinal Field Studies to Analyse Energy Calibration

Many field studies have been conducted in various climates across the world, which demonstrated that household energy consumption and occupant thermal comfort are closely linked to the local climate [104-107]. A previous study by a scholar, for example, conducted longitudinal surveys with vulnerable Danish households highlighted that the heat coefficient factor of building envelopes are the main causes for high levels of thermal discomfort. Therefore, this survey was being conducted to one case study building only. It is deemed to indicate that the findings which were intended to demonstrate the nationally representativeness of Danish housing stock cannot be generalised for the whole region due to the respondent limitation which can generate result bias. Tables 4 (a) and (b) illustrate the integration of a BES into the development of an STS approach for policymakers

Table 4 (a): Previously developed BES frameworks.

References	A. Study Location	B. Primary Aim of Model	C. Methodology	D. Selected Software
[108]	Stockholm, Sweden	To develop a novel approach to use rich datasets to improve the energy efficiency of different building archetypes based on specific urban energy challenges	Urban BEM workflow developed to estimate energy savings for 5,532 buildings; aggregated energy models developed for building retrofitting and electric heating	- *RStudio IDE* - *gridExtra* Metrics - *Tidyverse* - *UpSetR* and *VennDiagram* - *Energy Plus* - *Design Builder*
[109]	Florida, U.S.	To develop an experimental validation of an early-design 3D dynamic thermal model	Exploratory case-study approach at Off-Grid Zero Emissions Building at Florida State University; mathematical equations utilised; BES conducted	- Early-design stage 3D dynamic thermal simulation tool - *vemBUILDING* - Mathematical modelling tool - *Fortan*
[110]	European Union	To develop a methodological approach that combines bottom-up energy modelling, DTS and life-cycle cost assessments to formulate a performance evaluation of residential EU building stocks	672 buildings selected as archetypes of residential EU building stocks built before 2010; BES conducted	- *Energy Plus* used to build energy simulations - *SimaPro* 8.3 and *Ecoinvent* 3.0 software used for LCCA analysis
[111]	Fourteen locations in the European Union	To develop a simulation-based optimisation framework of cost-effective choices and EEMs for new buildings	Single-family detached structures in 14 European locations selected as archetypes; BES conducted	- *EnergyPlus* and *TRNSYS* used to run DTS - *BEopt* energy-simulation software used for economic evaluation of optimisation
[112]	Italy	To develop a multi-objective optimisation approach to address building-envelope energy designs in different climate zones: Palermo (*Zone B*), Naples (*Zone C*), Florence (*Zone D*) and Milan (*Zone E*)	Genetic algorithm approach adopted; newly built five-storey residential building chosen for BES	- *MATLAB* used to build optimisation studies - *EnergyPlus* used for DTS

Table 4 (b): Previously developed BES frameworks (Continued).

References	A. Study Location	B. Primary Aim of Model	C. Methodology	D. Selected Software
[113]	Rome, Italy Antofagatsa, Chile	To develop a chain strategy to model urban boundary conditions using DTS tools suitable for simulations in five urban textures of Rome, Italy and Antofagatsa, Chile	Exploratory case-study analysis adopted to investigate variability of urban conditions and relative energy-impact thereof on building-energy demand; detached houses and apartment blocks identified as archetype buildings	$TRNSYS\ v17$ used for energy simulations
[114]	Lyon, France	To develop a data-driven framework to systematically explore occupant activity schedules and presence probability in residential buildings	Eight apartment buildings selected as exploratory case-study approach; linear and logistic regression models developed	- Building-Energy Management System used to process raw dataset - Integrated Environmental Solutions used for DTS analysis
[115]	Netherlands	To develop a simulation framework based on multi-objective optimisation and sampling strategies to devise robust optimal designs for low computational costs	Dutch residential buildings selected; semi-detached house identified as archetype housing typology; genetic algorithm approach adopted	- $TRNSYS$ used for building-energy modelling - $MATLAB$ used for building-optimisation studies
[116]	Kazakhstan	To develop a new ranking method to build façade applications using multi-criteria decision-making tools combined with energy simulations	Eight cities in tropical savanna climate zone selected; analytic hierarchy process adopted	- $EnergyPlus\ v9.1$ used for BES - Conduction finite difference solution algorithm employed
[117]	Quebec City, Canada (located in ASHRAE Climate $Zone$ 7, a cold climate)	To develop an assessment method to determine energy-consumption robustness and dwelling thermal comfort related to occupant behaviour	High-performance multi-residential building selected for exploratory case-study approach	- $TRNSYS$ used to construct thermo-physical models - A total of 1,000 annual occupant profiles were stochastically generated

Another thought-provoking study by scholars emphasised challenges in building-energy-calibration studies that are derived from the failure of regulatory provisions to capture occupants' real-life energy-use experiences [118]. This research investigated five high-performance state-of-the-art prototype houses in Australia for the purpose of assessing the thermal performance thereof to meet relevant regulatory housing standards and was similar to a research project that assessed the thermal performance of residential buildings in Canada [119]. These studies concluded that targeted regulatory concepts have failed to meet expectations due to occupants' behavioural activity, which were not considered during the BPE; another reason for this failure was that generic occupancy profiles that did not consider the climate and other localised effects on energy consumption were assigned in the simulation model [120, 121].

Several researchers have investigated the development of energy-calibration methods in BES that were employed to determine occupant thermal comfort by optimising indoor temperatures on a broad scale and reducing energy consumption with the aim of diminishing the overheating risks in residential buildings [122]. Furthermore, a significant number of steady-state analyses of BES studies have been conducted to assess the thermal performance of existing housing stock [123, 124]. Only a few studies, however, have sought to provide a better understanding of the importance of considering human-based factors in the DTS model and to properly calibrate the BES by using primary data sources gathered from longitudinal field studies [125, 126].

Recognition of the limitations and inherent contradictions of the development of a black-box model for the DTS analysis led a few studies to fully understand overheating and the impact thereof on occupants' thermal comfort, particularly in south-eastern Mediterranean EU member states, even though this issue remains unaddressed [127, 128]. Despite the decisive role of these factors in demonstrating variations of simulation input parameters and detecting uncertainty in the datasets for energy-calibration analysis, the results reveal a high accuracy for the nearly zero energy building prototype.

It was found that the analytical energy model offers a prediction accuracy of 2.2% and 7.03% for the energy use and indoor zone temperature, respectively [129]. The literature reviewed in this chapter outlined three key areas relevant to filling the knowledge gap in BPEs: overheating-risk assessment, thermal comfort and occupant behaviour in energy modelling. The IES software was selected for an energy-calibration analysis due to its accuracy in Section 5.3.

5. Passive Design Strategy: Roadmap for Retrofitting Residential Buildings

5.1 Passive Design Strategies: Shading, Thermal Mass and Cooling

Several studies have analysed the acclimatisation of a micro-climate and changes in the conditions of the immediate surroundings that can be applied to the urban fabric in order to decrease ambient summer temperatures [130, 131]. In fact, studies have highlighted the fact that solar gains lead to increased energy consumption and diminished occupant thermal-comfort levels in the summer. However, solar-control strategies should take space configuration, geometry and the orientation of the building into consideration **(see Appendix A.1).** Many techniques have been proposed and adopted to reduce the amount of solar radiation onto the building envelope (e.g., shading systems, louvres) [132]. This reveals that space configuration and floor-plan layouts affect the relationships of the sky-view area and the surface, and eventually the heat dissipation through long-wave radiation off of the horizontal and vertical surfaces.

At the same time, studies conducted on the effect of shading on surface materials recorded those shaded surfaces have lower temperatures than the air above them, and that variations among different materials have been shown to have less of an impact in the optimisation of indoor temperatures [133]. However, each material has distinct thermal properties that determine the amount of reflected, transmitted and absorbed solar radiation [134]. Furthermore, it is defined on the adaptive thermal comfort theory by an optimal configuration of shading devices with user-defined parameters, such as opacity, colour, air circulation and distance from the ground, any or all of which can affect both the convective and radiative heat exchanges between the shading device and occupant behaviour, especially during the long-term heatwaves that are experienced in the summer [135].

In order to reduce the risk of overheating experienced in each occupied space of the home, an improvement has been achieved by taking the different sun angles throughout the day into account [136]. It is evident that the flexibility and adaptability of shading systems is crucial to fully optimise the effectiveness thereof; furthermore, movable elements and/or combination systems can be introduced to achieve optimum shading during the day [137]. According to a study that was undertaken by Solgi et al. in 2018, vertical elements were proven to be more effective in the early morning and evening hours when sun angles are low, and long-wave radiation is reflected into the sky during the night [138,139]. Moreover, study by Ascione et al. [127] highlighted that the thermal mass of a building is essential to the heat transfer processes that take place in the urban climatic environment.

As was previously mentioned, the surface temperature of the thermal mass from convection, radiation and conduction affects the indoor temperature of dwellings. One of the main reasons for this is the surface albedo of a building, which affects the solar gains and surface temperatures thereof, particularly in the summer [138]. A study conducted by Doulos et al. [139] on the thermal performance of thermal-mass material in Athens indicated that colour was a basic parameter; for example, dark colours led to increased surface temperatures that were greater than 2°C, compared to light-coloured surfaces. Despite some constraints on the development of energy simulation models to assess thermal performance of building materials, other scholars have also investigated the correlation between surface albedo and surface temperature, and they confirmed that higher albedo surfaces display lower temperatures [139]. It is evident that the correlation between air and surface temperature revealed that high reflectivity and light-coloured materials led to lower air temperatures; this results in optimised occupant thermal comfort. Conversely, a comparative study between light- and dark-coloured albedo surfaces concluded that dark albedo surfaces led to an increase in air temperature that was 6.6% greater than light-coloured surfaces [140].

Studies carried out in residential buildings in densely built urban areas determined that high-albedo materials can reduce the cooling loads of a building [141]; hence, the amount of solar radiation reflected into the sky is maximised, and the quantity of absorbed solar radiation is diminished, which in turn results in reduced amounts of energy stored in the building fabric. However, occupant thermal comfort might be affected by implementing vertical shading elements with high-albedo surface materials [142]. Furthermore, other pilot studies have demonstrated that highly reflective surfaces will create an uncomfortable visual environment for occupants because of the excessive glare off of glazed surfaces [143]. Apart from the most energy-efficient building systems and applications, conventional passive-cooling strategies involve shading transparent elements and effectively ventilating rooms during the night.

When considering the exemplar studies described above and the applicability of different materials in retrofitting interventions, there are several examples that suggest this can reduce high indoor air-temperature fluctuations. In the south-eastern Mediterranean context, other scholars have emphasised that the implementation of a night-time cooling strategy during the summer season would have a greater impact on cooling demand when a dynamic analysis was performed [67, 127]. Studies have also shown the lower air temperatures are associated with a high daily air-change rate in monthly average thermal-comfort levels.

The simulation study conducted by Ferrari and Zanaotto in 2010 [144] indicated that the substitution of a standard setpoint with the daily air-change rate could lead to a decrease in the discomfort degree-hours assessment. According to these base-case studies, cooling demand varies between 10% and 50%, depending on the orientation of the considered building and the level of implementation of passive-cooling strategies [5, 67]. These studies revealed evidence that the increased energy consumption related to the active cooling of buildings poses a serious environmental danger, and it is therefore crucial to decrease high cooling demand in the summer by taking the implementation of appropriate building materials and/or passive-cooling design strategies into account.

5.2 Vernacular Revival of Passive Design Strategies and the Impact on Building Thermal Performance

In Cypriot vernacular architecture, the thermal mass of a building plays an important role in the optimisation of indoor comfort levels for occupants in both the winter and the summer **(see Appendix A.2)**. Many scholars have described the importance of thermal mass as the capacity of a building to store and release heat at different times of the day [51, 52]. This heat-transfer process leads to moderate climates and diminishes temperature fluctuations inside occupied spaces in heavyweight traditional buildings [73]. Although one of the key pilot studies on assessing overheating risk in the South-eastern Mediterranean climate that was undertaken in an inefficiently constructed residential building in a post-war social housing development estate in Famagusta, Cyprus highlighted that households predominantly rely on either portable fans or wall-mounted air-conditioning systems to cool their home, this study also concluded that this type of household had to pay high energy bills in the summer because of deficient building envelopes and inadequate air infiltration rates [79]. This could then lead to theoretical questions about the importance and effects of the particular study context on the decision-making processes associated with the implementation of passive-cooling design strategies in retrofitting interventions.

In doing so, it can be argued that the cooling-down process of an occupied space cannot take place through heat loss by the building envelope and that air dissipation can be enhanced by night-time ventilation. It is evident that heavyweight buildings have certain advantages due to the efficient thermal-property characteristics thereof, specifically in hot and humid climates [145]. Many of the most common methods used in overheating risk assessments, however, are associated with particular evaluation criteria, for analysing it, for designing evidence-based retrofitting scenarios. It should be mentioned at this point those thicker walls lead to increased indoor temperatures in the summer after periods of inoccupation in the winter. The aforementioned studies concluded that thermal mass cannot effectively work with internal heat gains because of the time that is needed to store or release this heat. It can therefore be stated that the irregularity of the thermal performance of occupied spaces creates thermal barriers between indoor comfort and occupant thermal sensations in vernacular buildings [145].

A key point of the previous paragraph is that a large proportion of the resulting research attempted to measure the relationship between energy use and the thermal properties of buildings without considering the thermal comfort of occupants. This is why the methodology that Michael [52] used in a recent relevant study tested the effectiveness of the thermal performance of vernacular buildings in order to assess the indoor temperatures of an occupied spaces; the findings of this study imply that thermal mass is more effective when the diurnal variations of ambient temperatures exceed 10° Kelvin (K) [52, 76]. Table 5 summarises the overview of vernacular environmental design elements that were undertaken in extensive studies to assess the efficiency of bioclimatic design principles, which took shading, ventilation and cooling in four different climatic regions of Cyprus into account. In addition to this, the following section also illustrates the tested and simulated thermal performance of a vernacular house typology in order to highlight the importance of implementing vernacular environmental design elements into building retrofitting schemes.

Table 5. List of bioclimatic design elements and vernacular architectural characteristics of Cypriot vernacular structures, including a brief description of the four different climatic regions.

	Climatic Region	**Zone 1: Semi-mountainous**	**Zone 2: Coastal**	**Zone 3: Inland**	**Zone 4: Mountainous**
Cooling Strategies	**Protection against temperatures (i.e., moderation of indoor temperatures)**				
	High thermal-mass walls	+	+	+	+
	Small, limited windows	+	+	+	+
	Partially subterranean spaces	+/–	–	+	+/–
	High ceilings	–	+	–	+
	Protection against intense solar radiation (i.e., shading)				
	Timber shutters	+	+	+	+
	Timber lattices	+/–	+/–	+/–	+
	Dense courtyards with high boundary walls	–	+	+/–	–
	Arches	+/–	+	–	+

	Highly reflective external walls	+	+	–	+
	Semi-open spaces	+	+	–	+
	Protection against high humidity (i.e., air movement, cross-ventilation, stack effect, infiltration)				
	Dispersed/semi-dispersed building configurations	+	–	–	+/–
	Single-banked rooms, wide façade openings, shallow plans	+	+	–	+/–
	Double windows	+	+/–	+/–	+
	Pass-through semi-open spaces	+	+	–	
	Top-window openings	+	+	+	+
	Large courtyards with low boundary walls	+/–	–	–	–
	Mitigation of outdoor micro-climatic conditions (i.e., shading)				
	Semi-open spaces	+	+	–	+
	Arches	+/–	+	–	+
	Dense courtyards with high boundary walls	–	+	+/–	+
	Vegetation	+/–	+/–	+/–	+/–
Heating Strategies	**Protection against low temperatures (i.e., thermal buffering, insulation)**				
	Compact building configurations	–	+	+	+
	Small, limited windows	+	+	+	+
	Low ceilings	–	–	+	+
	Multi-storey buildings	–	–	+	+
	Timber shutters	+	+	+	+
	Thatched roofs	–	–	+/–	+/–

Table 5. List of bioclimatic design elements and vernacular architectural characteristics of Cypriot vernacular structures, including a brief description of the four different climatic regions. (continued)

Protection Against Rain	Projected roof eaves	—	—	+	+
	Small covers on entrance doors	—	—	+	+
	Large slopes of the roof	—	—	+	+
	Extensive balconies	—	—	+	+
Natural Lighting Strategies	Top-window openings	+	+	+	+
	Medium- and large-sized windows	—	—	—	—
	Double windows	+	+	+	—
	Single-banked rooms, wide façade openings, shallow plans	+	+	+	+/—
	Dispersed or semi-dispersed building configurations	+	—	—	—
	Large courtyards	+	—	—	—
Legend: + ▯ applied; +/— ▯ partly applied; — ▯ rarely applied					

As can be seen in the extensive taxonomy classification of vernacular design elements presented in Table 5, the main environmental design principles of vernacular construction in this particular Mediterranean region are related to the use of local raw materials and the use of heavy-wall construction systems as primary structural elements of vernacular houses, which takes solar energy into account. As was previously discussed, heavy walls provide high thermal inertia, which then enables optimising indoor air temperatures according to changing outdoor environmental conditions. In this study, it was determined that these types of heavy-wall construction systems were commonly built with either limestone or yellow-stone in order to provide effective solutions for reduced energy consumption. It is also important to specify at this point that these same building strategies were used in traditional vernacular architecture to lessen or avoid the risk of heat loss in the winter and to facilitate the optimisation of indoor air temperatures in the summer. This then indicates that the terracotta-made roof tiles in roof-overhang design systems also protect occupants from excessive solar radiation in the summer. Figure 10 demonstrates the workflow of vernacular houses and building energy model of simulation set-in put parameters.

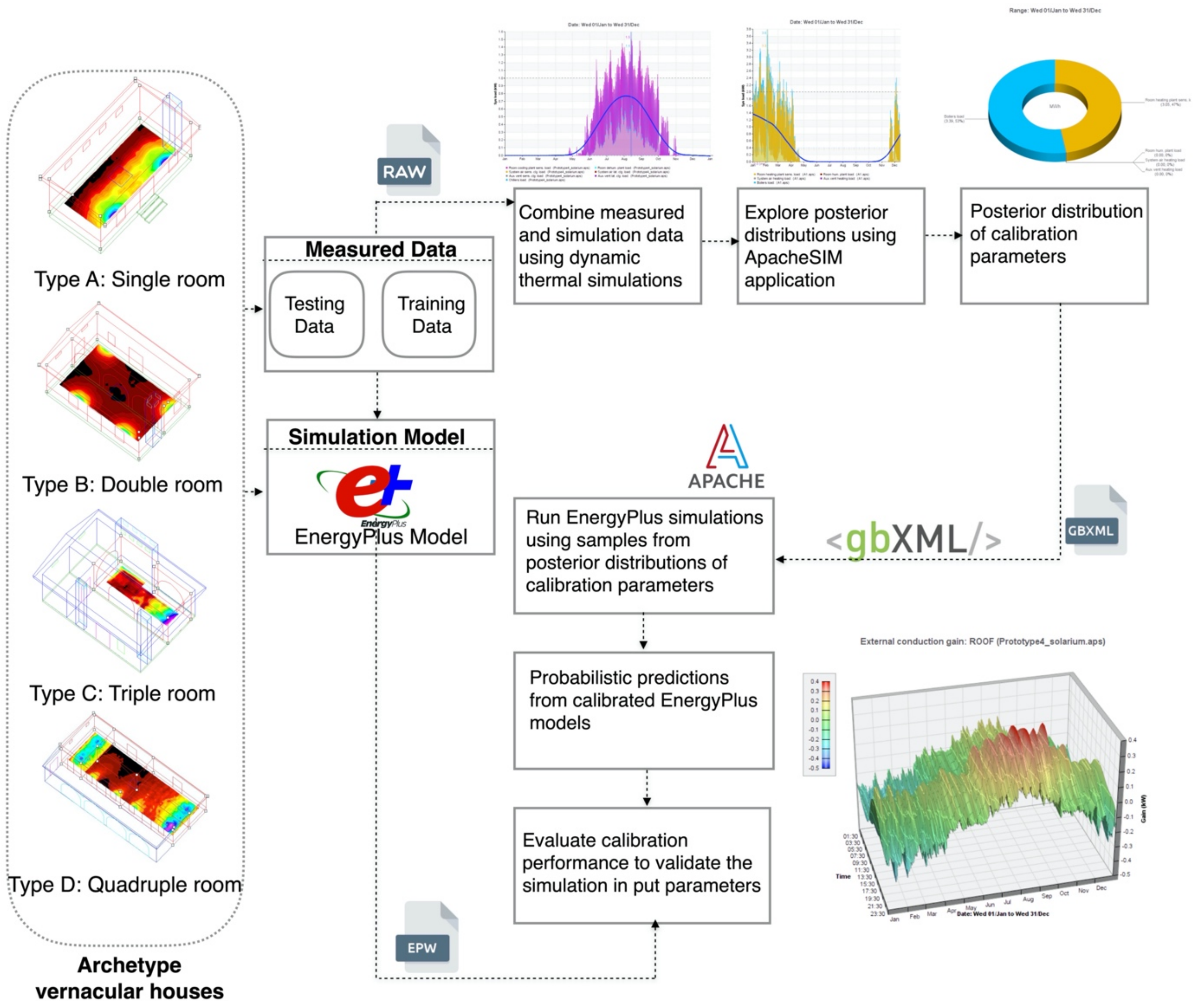


Fig.10. The workflow of energy calibration of vernacular houses before testing energy effectiveness of passive cooling design elements.

This empirical research revealed that an appropriate ventilation strategy and optimum indoor air temperatures and relative humidity fluctuations were shown to be deterministic factors to consider when assessing the thermal comfort of occupants. This can be explained by a combination of behavioural adjustments and the physical conditions of each occupied space in the home. Through a systematic literature review that was undertaken in the prototype base-case vernacular houses, it was determined that heavy walls with top-window openings could thoroughly perpetuate natural ventilation in occupied spaces. This could be in the form of a design element related to roof openings, chimneys, windows and/or wind-catcher systems that were constructed to facilitate adequate ventilation and dissipate dirty air, such as the air associated with home cooking, but these design strategies could also be applicable when seeking to improve the indoor air quality of modern residential buildings.

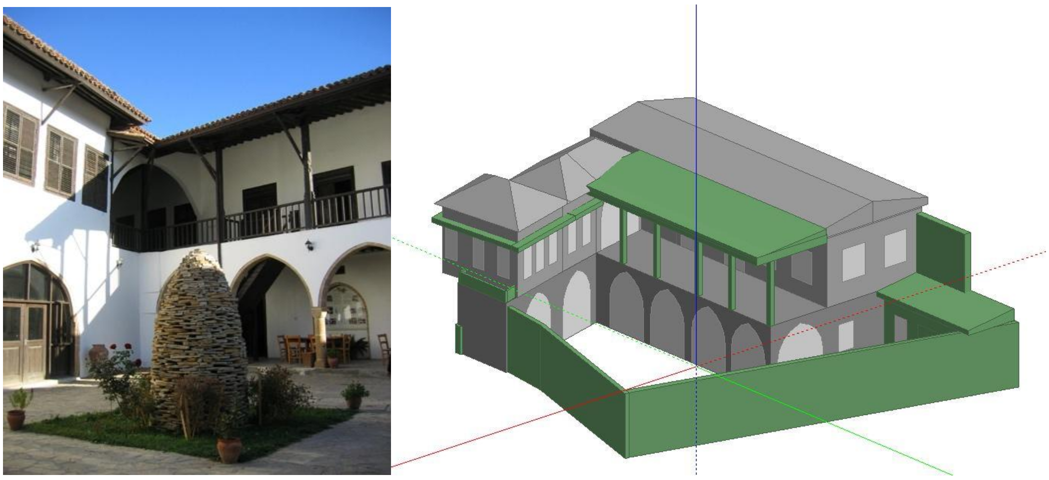
However, two important lessons can be learned from traditional building methods. First, an integrated, holistic consideration of the location, climate, building and occupants primarily led to sustainable solutions. Second, it is therefore logical to adopt similar holistic, integrated evidence-based theoretical and empirical design approaches when retrofitting buildings.

5.3 Thermal Performance of a Vernacular Courtyard House as a Base-Case Scenario Development

This section presents the efficiency of bioclimatic design elements within the context of the thermal performance of a base-case representative courtyard house in order to optimise energy consumption (see **Video C**). The aim of this phase of the study was to find alternative applicability of the implementation of several building materials and design strategies that were derived from the literature review, which considered vernacular house roofs and different design principles, walls thicknesses, colour choices, materials and window-opening ratios for building optimisation.

This section also explores several alternative passive design systems as solutions to reduce overheating, particularly in the summer. In order to identify the best solution for designing a prototype retrofitted housing model based on the most dominant representative vernacular courtyard house type, this section will also discuss and examine some potential adaptation scenarios and the appropriateness and potential applicability of each within the examined parameters. It concludes with potential adaptations and the feasibility of these adaptations by referring to the extant literature.

In order to properly understand vernacular environmental design systems and the integration thereof into contemporary residential buildings, it is essential to examine the effectiveness of the thermal properties of a vernacular building in Cyprus, as shown in Figures 11 (a) and (b). The steady-state building energy simulation study was undertaken in a representative vernacular courtyard house with *u*-values of 2.6 W/(m^{2}K) for the walls with 20cm-thick perforated brick walls, a 3.5 W/(m^{2}K) timber-framed roof and 2.5 W/(m^{2}K) floor surfaces.



(a) (b)

Fig. 11. (a) Representative base-case vernacular courtyard house typology, which was undertaken to understand the effectiveness of vernacular design elements associated with contemporary residential building retrofitting efforts; **(b)** analytical energy model of case-study building.

5.3.1 Different roof-design principles in courtyard house

Three bioclimatic design principles were taken from the literature reviewed in the previously stated sections: roofs, walls and windows (see **Dataset E** and **F**). Each was analysed in an attempt to determine the thermal efficiency of the courtyard house in this particular Mediterranean climate. In this section, the implications of different parameters are presented by employing the IES software suite to configure initial energy-model calibrations. First, the thermal efficiency of roof properties was tested when considering four different roof arrangements on a typical summer day. Table 6 delineates the base-case scenarios that were performed on a vernacular courtyard house.

Table 6. Tested roof thermal properties of a vernacular courtyard house.

Base-Case	S1: Vault	S2: Overhang	S3: Slope	S4: Flat
10cm clay tile	10cm, 2.7 W/(m^{2}K)	15cm, 0.40 W/(m^{2}K)	20cm, 1.8 W/(m^{2}K)	30 cm, 1.47 W/(m^{2}K)

It can be observed that when clay-tile material was implemented on the outer skin of the roof, the indoor temperatures significantly dropped; even increasing the roof thickness from 10cm to 20cm did not cause a noticeable change in the indoor comfort levels of an occupied space. The study demonstrated that inner insulation or timber-framed overhanging roof design strategies lead to considerable temperature differences. Moreover, changing the colour of the outer roof colour to a light hue (i.e., white) was shown to be a practical solution to help decrease indoor temperatures during the hottest hours of the day. The findings also highlighted that the height differences from 2.2m to 4m and from the ground floor to the exposed roof surfaces were tested in order to identify the overheating risks of a vernacular courtyard house.

As can be seen, this variable did not have a substantial effect on indoor temperatures, except that the calibrated indoor air temperature reached as high as and only decreased 2°C. Furthermore, an investigation of the timber-framed roof slab revealed that for every 3cm increase of thickness in roof thermal properties, the indoor ambient temperature decreased an average of 0.3°C. Significant temperature variations were only achieved when 30–40cm roof thickness was implemented, with an average deviation of 1.7°C. Table 7 summarises the percentage of hours the space is needed for cooling in the summer and heating in the winter. To reach the base-case scenarios, which state 21% of the annual cooling degree hours and 6% of the annual heating degree hours exceed the acceptable benchmark criteria recommended by the Chartered Institution of Buildings Services Engineers Technical Memorandum – TM 52 for Overheating risk assessment of European Buildings. Here, it is worth noting that the materials used for roof surfaces have a greater impact on indoor temperatures, followed by the thickness of the thermal mass and the height of the building.

Table 7. Comparison of percentage of hours above 26°C for cooling assessment criteria and under 16°C for heating assessment criteria.

Material	Cooling	Heating
Base-case	12%	3%
Base-case + Vault	10%	4%
Base-case + Overhang	8%	3%
Base-case + Slope	18%	5%
Base-case + Flat	8%	9%
Thickness	12–21%	4–6%
Height	18–21%	6%

5.3.2 Walls

Apart from roof thermal-performance studies, the walls were also investigated to compare the two types of bricks and the two types of masonry stones. The commonly used wall thickness of 30cm was assigned to test the performance of an occupied space in the hottest and coldest period of the year, as shown in Table 8.

Table 8. Comparison of different wall elements during the hottest period of a year.

Base-Case	Clay	Limestone	Masonry
30cm, 2.38 W/(m^{2}K)	30cm, 2.87 W/(m^{2}K)	30cm, 3.5 W/(m^{2}K)	30cm, 1.19 W/(m^{2}K)

It can be observed that 30cm exterior-facing clay tiles led to a decrease of 4°C from the base-case, and a 25cm clay tiles without any cavity between the exterior cladding and heavyweight brick material can decrease by as much as 2°C. It is important to emphasise, however, that these perforations did not create any significant variances from the results obtained from a brick-building envelope. It can be seen that stone-masonry wall properties did not have a significant impact, compared to clay walls. There also were no significant changes when the thickness of the walls was increased, especially in the exterior-facing limestone panels. The base-case scenario demonstrated that 3°C differences can be achieved when a 25cm wall thickness was assigned to the thermal properties. Table 9 demonstrates the percentage of hours the occupants need to heat and cool their indoor spaces.

Table 9. Comparison of percentage of hours above 26°C for cooling assessment criteria and under 16°C for heating assessment criteria.

Material	Cooling (> 26°C)	Heating (< 16°C)
Clay/terracotta	14–20%	3–6%
Masonry/local stone	16–23%	3–6%

5.3.3 Window-opening ratios and orientations

The window-to-wall ratio in courtyard houses was represented in two building-envelope surfaces in order to simultaneously take into account the different building orientations. In the present case study, the worst-case scenario was undertaken to obtain the effectiveness and potential impact of solar gains on the building envelope. In both orientations—which in the present analytical study was southeast and northwest—the window-to-wall ratios were approximately 30%.

The representative base-case vernacular courtyard house was performed according to the thermal properties of the archetype vernacular building that was oriented on a southeast–northwest axis, which experienced several hours of overheating. To test how and if the orientation factor impacted indoor temperatures, four different scenarios were undertaken. First, an opening study was performed, which started with a 30% window-to-wall ratio in both orientations; when the opening ratio was increased to 40%, indoor temperatures significantly increased, and when the value was lowered, temperatures remained somewhat similar to those presented in the base-case. It can therefore be observed that a window-to-wall ratio between 30% and 40% is an effective solution to optimise comfortable indoor temperatures in an occupied space.

In order to analyse the impact of orientation, the north-to-south, south-to-north and west-to-east orientations all demonstrated similar indoor temperature fluctuations. The only discrepancy was found in the east-to-west orientation with small top-window openings. It can thus be seen that the solar gains received in a direct western orientation leads to increased indoor temperatures of as much as 3°C in occupied spaces with no protective shading elements.

In general, five variables were examined by Philokyprou et. al in order to test the efficiency of vernacular design elements, considering a vernacular courtyard house and concluded that the compactness of building geometry and roof properties have a significant impact on the indoor temperatures of occupied spaces in the summer [76]. Moreover, the present analytical study determined that orientation and window-to-wall ratios must also be addressed to properly assess the thermal comfort of occupants, especially those in southwest-facing occupied spaces. Table 10 summarises the findings from the representative base-case vernacular courtyard house environmental design elements and the applicability thereof to contemporary residential building retrofitting efforts.

Table 10. Proposed guidelines from the present analytic study for retrofitting measures and upgrading the efficiency of residential tower block developments.

Variables	Findings
Roof	Use of 20cm brick vaults or a minimum of 10cm otter insulation layer
Windows	10% window-to-wall ratio; average 30% window-to-wall ratio
Walls	Thickness > 10cm; recommended 18–20cm brick
Orientation	Avoid small west-facing areas, unless protection is present
Height	Same or similar heights to prevent exposure

The results of this study demonstrated that building materials and the size of window openings play an important role in hot, humid climates. It was determined that smaller top-window openings and walls with a higher thermal mass were important determinant bioclimatic design elements that contributed to optimum thermal performance in the summer (see **Dataset G** and **H**). It should also be noted that smaller window openings can lead to increased heating demand due to a lack of sunlight being allowed in occupied spaces of the home.

As is shown in Table 7, the orientation of vernacular houses significantly correlates with the design of effective retrofitting solutions. This confirms that different courtyard house typologies enable inhabitants to protect themselves from excessive solar radiation and perpetuate adequate natural ventilation when combined with fenestration design, window-opening ratios and/or wind-catcher systems that are used in vernacular houses. These findings could be generalised and applied to modern residential building retrofitting efforts. Understanding this and the theoretical basis for implementing the revival and applicability of passive-cooling design systems could also result in significant reductions in energy use. This has led many scholars to recognise the efficiency of traditional building methods and to validate many approaches, which has in turn resulted in the proliferation of alternative ontological and epistemological positions in the decision-making processes for retrofitting interventions.

5.4 Low-carbon Design

To validate the systematic literature review findings that are described in Section 4.2.1, dynamic thermal simulations (DTS) were undertaken to assess the CO_2 concentration levels of the occupied spaces in the base-case prototype house. These dynamic thermal simulation studies were conducted between January and December of 2020 to determine the overall CO_2 concentration and create reliable data sets for the present study. Figures 12 (a) and (b) demonstrate the pattern fluctuations of CO_2 that were recorded in a ground-floor bedroom and a first-floor living room.

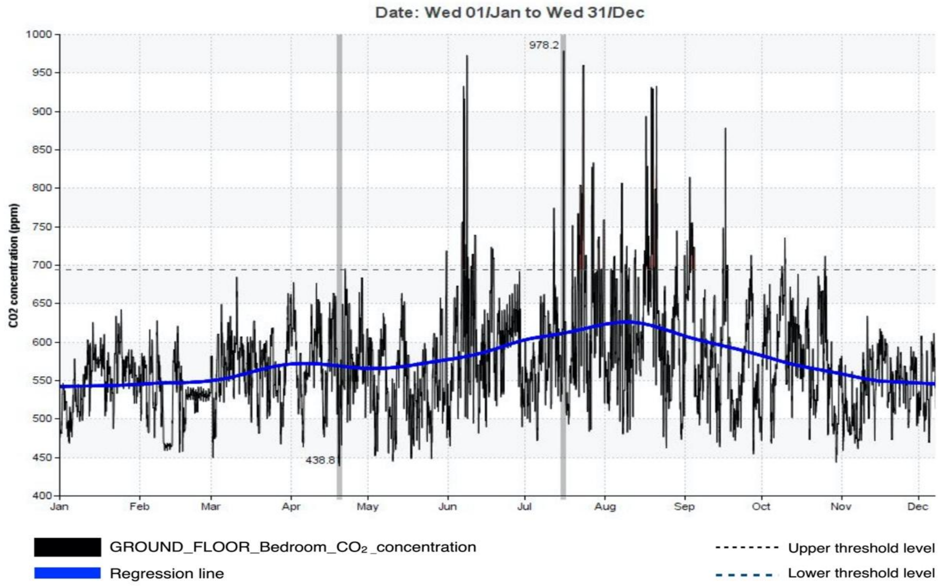


Fig. 12. (a) Annual CO_2 concentrations in the first-floor bedroom.

The annual CO_2 emissions for the first-floor bedroom, which are shown in Figure 12 (a), fluctuated between 550–700 ppm from January through June of 2020, peaked above 950 ppm in mid-June then dropped to 600 ppm. In mid-July, CO_2 concentrations in this space peaked at the highest level of 978.2 ppm, then dropped and fluctuated around 700 ppm until September; from mid-September to January, levels decreased from 700 ppm to 550 ppm. It should be noted that the benchmark CO_2 emission level for this occupied space is 700 ppm, which was significantly exceeded to 978,2 ppm in mid-July; according to CIBSE guidelines, however, the benchmark level is 1.000 ppm. Consequently, even at their peak, the CO_2 emissions in this bedroom space were shown to be just below the *CIBSE Guide A* benchmark level [146].

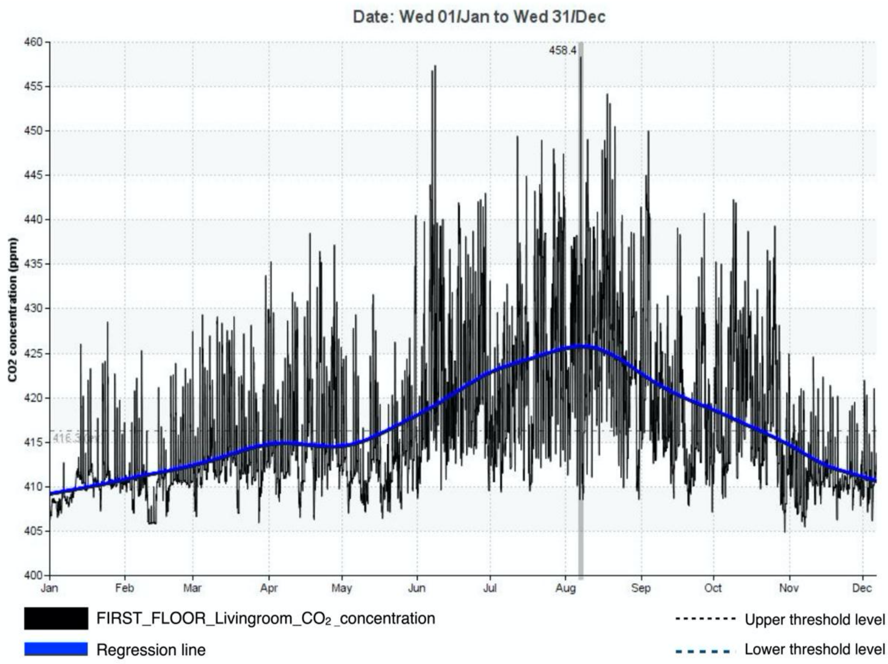


Fig. 12 (b). Annual CO_2 concentrations in first-floor living room.

In January, the annual CO_2 concentration levels in the first-floor living room, which are shown in Figure 12 (b), were at 410 ppm, and levels fluctuated between 400–410 ppm until June. From June through November, CO_2 concentrations it peaked at 460 ppm and fluctuated around this level throughout this time; between November and January, levels dipped to 410 ppm. The living room CO_2 concentration benchmark level is 415 ppm, but according to these simulation measurements, the CO_2 concentration levels in this room always remained above the generated benchmark, which *CIBSE Guide A* recommended should be 1.000 ppm for dwellings.

One of the most prominent limitations of this study was an inability to specifically focus on all the vernacular building typologies, construction processes, spatial floor-plan layout configurations and uses of bioclimatic design strategies in the study area; rather, the present exploratory case study only investigated the most commonly built vernacular courtyard houses and the implications thereof for solar power control in homes.

In the present study, therefore, the geographic domain of the base-case representative vernacular buildings and local climate characteristics were considered to better understand climate-change projections and the factors thereof that are interrelated with the thermal properties of buildings. To address excessive temperatures in current and future climate-change projections, effective passive-cooling design strategies in retrofitting interventions play a decisive role in reducing energy consumption and CO_2 emissions.

6. Conclusions

According to the reviewed literature and the exemplar traditional vernacular houses investigated in this study, both of which primarily focused on locations on the southern Mediterranean island of Cyprus were presented. A systematic literature analysis was undertaken to better understand the different bioclimatic design strategies that have developed and evolved in existing vernacular courtyard houses in order to be able to implement them in modern residential building retrofitting efforts. To fulfil the research aim and objectives, a review of passive-energy measures associated with vernacular buildings, which can be found in other selected reference books, particularly those that discussed the significance of the building materials used in traditional houses. For this reason, this study was conducted to analyse the energy efficiency of bioclimatic design elements and the impact thereof on the thermal comfort of occupants according to the location, orientation and typology of their living spaces in order to provide subsequent information in building-energy simulations.

This study aimed to offer an analysis of the thermal performance of these base-case vernacular buildings after different optimisation strategies were undertaken to assess energy use in the summer and in the winter. The current energy performance of selected representative vernacular courtyard house type was modelled in the IES–VE software suite platform and was simulated by concurrently using dynamic thermal simulations with material changes assigned into the simulation interface. The buildings were initially modelled under a different selection of building materials, and the results in every case demonstrated that the physical properties of the building simultaneously led to significant energy-consumption reductions and optimised indoor air temperatures.

The findings of this study concluded that a detailed analysis of the thermal transmittance of building materials and different design principles of roof surfaces were investigated in order to identify effective retrofitting interventions. According to the familiarisation study, it was determined that increased thermal mass led to decreased temperatures significantly less often with smaller diurnal indoor temperature swings than did appropriate roof design due to higher roof insulation material and greater wall thermal mass. This scenario also resulted in slightly less comfortable indoor air environments, but it also enabled occupants to diminish or avoid the risk of overheating for longer stretches of occupancy hours on hot, humid evenings. At the same time, the findings emphasised that top-window openings provide adequate ventilation gains with constant heat rejection throughout the day and night.

The analysis also found that the thickness of external walls could result in high daytime ventilation gains and night-time heat rejection. The results demonstrated that consideration of the orientation and internal gains of each room was shown to be an important design criterion. In relation to passive heat-evacuation measures, this study findings suggested that night-time cross-ventilation is the most effective measure on acclimatisation of indoor air environment, except in urban areas where this efficiency is questionable due to high minimum temperatures at night. As such, it seems as if both the longevity of building materials and the implementation and procurement of construction details are important factors in the incorporation of effective retrofitting interventions. This is because the design of modern materials can mimic and improve upon traditional material performance, which was shown to be the most determinant decision criteria at the time that the thermal comfort of occupants was assessed.

A thorough economic appraisal is still needed to select the best environmentally and economically viable interventions in building retrofitting efforts. The findings of this study demonstrate that reclaiming and integrating locally available building materials and bioclimatic design principles derived from existing vernacular houses into current residential building retrofitting efforts will improve awareness of energy-consumption reduction strategies. This paper also described the knowledge and practice gaps that must be closed in order to reintroduce the use of the design principles of vernacular courtyard houses as mainstream sustainable building material into architectural practices and public procurement policies. Although these passive measures are relatively well known, previous scholars have not sufficiently quantified the benefits and challenges thereof; as such, it would be a worthwhile endeavour to conduct additional research in this area.

By recommending these measures, this study explicitly questions the value of implementing passive-cooling strategies that are inherited from vernacular buildings for purposes of innovating building materials, when natural and traditional materials can offer equal or nearly equal levels of energy efficiency while providing additional benefits to households, local communities, wider society and the environment.

Declaration of Competing interest

The authors declare they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

CRediT authorship contribution statement

Bertug Ozarisoy: Writing – original draft, Conceptualisation, Methodology, Investigation, Writing – review & editing. **Bertug Ozarisoy** conducted the field surveys, computational analysis, analysis of the numerical experiments; and **Bertug Ozarisoy** provided sources (e.g. illustrations, tables, datasets and video), comments, and major edits to the paper. **Prof. Hasim Altan** supervised the research project and provided his intellectual input on the development of the research paper and he also provided necessary recommendations and technical support to the author at the time of writing this paper and **Prof. Hasim Altan** supported the author at the time of developing the research methodology for the paper. **Prof. Hasim Altan** (he recommended the topic) for his inputs in the design and comments on the preparation of the manuscript and writing of the cover letter to explain the novelty of this study.

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Graphical abstract – The methodological flow diagram for the present study.

Supplementary Material – Evaluation of Passive Evaporative Cooling Systems in Traditional and Modern Architecture

Video
Video A – On-site photographic documentation of vernacular buildings.
Video B – Energy modelling of bio-climatic design systems.
Video C – Audio presentation: Building energy modelling of vernacular houses

Datasets
Dataset A – Vernacular building – type 1
Dataset B – Vernacular building – type 2
Dataset C - Vernacular building – type 3
Dataset D – Vernacular building – type 4
Dataset E – Bioclimatic design system 1
Dataset F – Bioclimatic design system 2
Dataset G – Bioclimatic design system 3
Dataset H – Bioclimatic design system 4

Appendix A.1

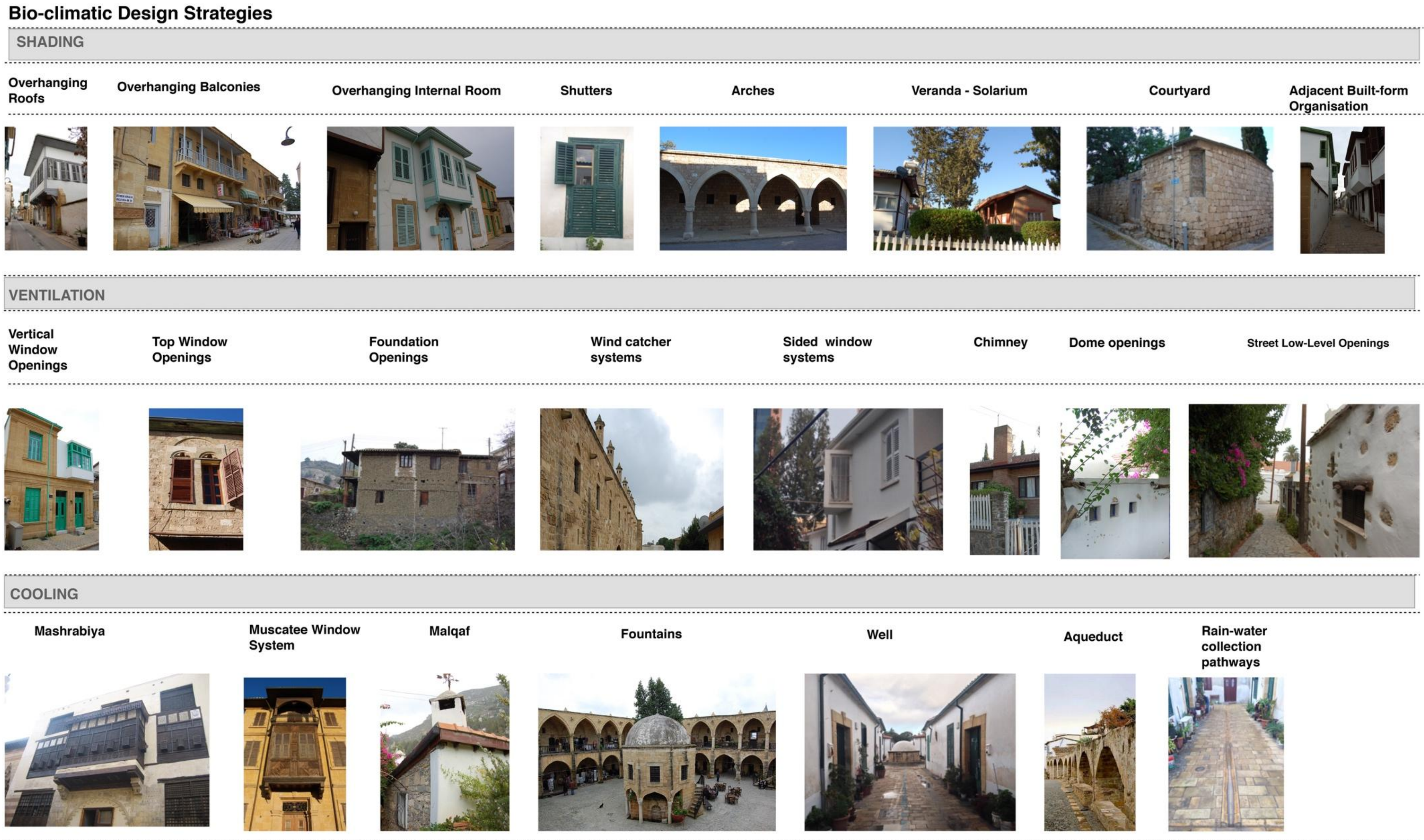

Fig. A.1. *On-site* photographic documentation of bioclimatic design systems in the South-eastern Mediterranean climate of Cyprus.

Appendix A.2

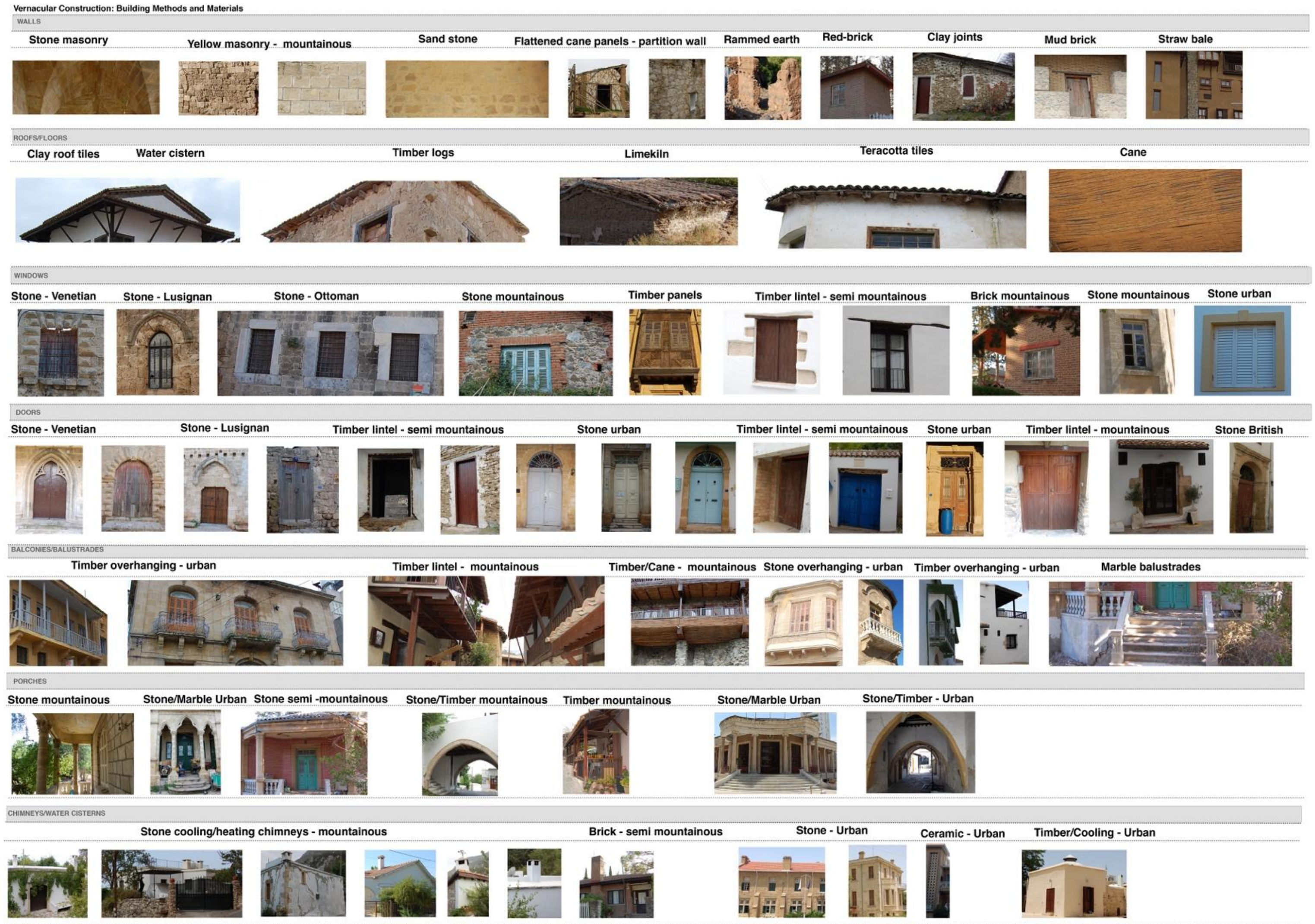

Fig. A.2. *On-site* photographic documentation of vernacular buildings' construction elements in the South-eastern Mediterranean climate of Cyprus.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

To the readers' information:

This paper presents the outcomes of self-funded research project undertaken at the Graduate School, School of Architecture, Computing & Engineering, University of East London (UEL) between 26/09/2016 and 20/09/2019. The paper is devised after the completion of the research project between 05/01/2020 and 12/07/2021. Therefore, at the time of writing up the research paper related to this case study location due to the project period is extended slightly beyond the targeted timeframe, the first author has provided additional financial flow from his own budget to complete this project successfully.

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