Developing an evidence-based energy-policy framework to assess robust energy-performance evaluation and certification schemes in the South-eastern Mediterranean countries

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Abstract: The United Nations Sustainable Development Goal 7, which calls for universal access to affordable, reliable, sustainable clean energy for everyone, is expected to influence near-future trends in many countries across the European Union. Retrofitting buildings is an important milestone in the evolutionary development of energy-efficient residential buildings, yet a significant proportion of the south-eastern European social-housing stock is obsolete in this area; in addition to effective retrofitting strategies for these buildings, the occupants thereof, who represent different socio-demographic backgrounds, also require in-depth study. Even though this subject has been widely investigated, new approaches that consider connections between technology and the behavioural responses of residents are needed to continuously update retrofitting design strategies and energy-efficiency solutions. This paper aims to fill a research gap in the area of developing an evidence-based framework for energy-policy decision-making mechanisms related to the integration of the Energy Performance Building Directives at the level of conceptual and nationwide implementation schemes.

In general, properties in this particular sector account for approximately 38% of the total housing stock and demonstrate some of the worst housing standards in Europe. The objective of this study is to focus on the interaction of such attitudes and the underlying determinant factors thereof with socio-cultural and contextual factors. A socio-technical-systems (STS) approach is used as a theoretical framework to integrate household socio-demographic characteristics related to energy use, the thermal-conductivity level of buildings and environmental factors; and to address the question of how different contexts influence motivation to develop energy-efficiency strategies. Drawing on the STS, this study investigates domestic energy use and measures thereof in post war social housing stock in the south-eastern Mediterranean, where the climate is subtropical (*Csa*) and partly-semi-arid (*Bsh*); these designations are according to the Köppen climate classification system; to improve the energy efficiency of archetype residential tower blocks (RTBs) that are embedded and interpreted in the socio-cultural local context of Cyprus.

Feed-forward interviews of 100 flats revealed a moderate negative correlation ($r = -0{,}329$, $p < 0{,}01$) between household income and tenancy status, and there was a moderate positive relationship ($r = 0{,}252$, $p < 0{,}05$) between household income and length of residency; this indicates that household income is a determinant factor related to energy use. Of the surveyed flats, 73% were owner-occupiers whose ages ranged between 55–65 and 65-years-of-age and older; these age bands were in the high-income group, and the energy consumption of these households was higher than the national average, all of which demonstrates an association between the age and level-of-income factors. A moderate negative correlation ($r = -0{,}229$, $p < 0{,}05$) was found between the occupants' ages and their complaints related to thermal discomfort, which suggests that built-environment factors and household socio-demographic characteristics should be evaluated before any type of building retrofitting is developed. The study findings were implemented to develop policy design that considers the UN Sustainable Development Goals related to energy-and-recovery plans; implications on domestic energy use in the south-eastern Mediterranean climate are expected to influence future trends in EU countries.

Keywords: Energy efficiency; Energy governance; Mixed methods; Policy design; Retrofit delivery; Socio technical systems

Introduction

Retrofitting the buildings and upgrade the thermal efficiency of existing housing stock are gaining momentum the Energy Performance Directives of Buildings (EPBD) requires that the domestic built environment cut CO_2 emissions, reduce national energy demands, and improve building performances in the EU-27 Member States (Pylsy *et al*., 2020). Currently, heating and cooling and the use of home appliances in existing homes accounts for 28% of all anthropogenic carbon emissions in Europe, and a space conditioning of our homes is accounted 56% of CO_2 emissions (Mata *et al*., 2018). Notably, retrofitting the existing residential buildings is a socio-cultural importance of each EU countries in order to tackle the occupants' socio-demographic characteristics, thermal properties of buildings and environmental conditions due to the geographical position of each member is different and this has led to the differences in their buildings codes, regulations and the structure of implementation of the EPBD mandates during the decision-making process of retrofit policy design (Florio & Teissier, 2015; Morton *et al.*, 2020).

In order to tackle the diversity of each EU notion and the variances of the housing typology, the EPBD schemes are influenced by many factors, including the diversity of the thermal properties of buildings, range of occupant behaviour, energy governance structure and energy subsidisation goals and schemes adopted by the EU countries (Galvin, 2014). Therefore, there is no any stringent building regulations nor any type of control mechanism available to follow-up the effective energy efficiency subsidisation schemes in the Republic of Cyprus (RoC). The result is that there exists a shortfall between the full potential and awareness of the adoption of energy-efficiency measures, a knowledge gap termed the 'Energy Efficiency Gap' (EEG) in the residential sector (Tagliapietra *et al*., 2019; Thomas & Rosenow, 2020).

Several scholarly research projects have investigated the associations between governmental policy on thermal retrofitting and current energy-efficiency awareness related to the energy use of residential buildings for which the policy was intended, specifically that of EU countries (Goulden *et al.*, 2020; Tziogas *et al*., 2021; Evcil & Vafaei, 2017). A lack of control mechanisms and implementation frameworks has arisen due to the variety of European laws that were put in place for each country taking into consideration the political agenda and international relations of each EU member state, which has led to a communication gap between the policy design and the community-level of energy subsidisation schemes (Nematchoua *et al*., 2021; Fokaides *et al*., 2017). To address this energy-policy gap, EU countries have adopted the goals of the Paris Agreement to overcome climate change owing to anthropogenic emissions of CO_2 and associated greenhouse gases and future energy security caused by depletion of fossil-fuel reserves (Haley *et al*., 2020).

In accordance with the Paris Agreement, upgrading the energy efficiency of existing housing stock has increasingly gained momentum in the last two decades, particularly cutting zero-carbon emission targets by 2050 (Hamborg *et al*., 2020). The 2020 Eurostat data reported that in 2019, the EU residential sector accounted for 77% of all CO_2 emissions from the existing building stock (Sonetti *et al.*, 2020). Previous studies have reported that Europe's existing building stock is responsible for 40% of overall energy use and 36% of CO_2 emissions, especially the purpose-built post-war social-housing stock (Cristino *et al.*, 2021; Olaussen *et al.*, 2017; Bertoldi & Mosconi, 2020). These studies emphasise that a priority should be given to introduce energy subsidies that improve the feasibility of various developed energy-performance certification (EPC) schemes within the grounds of sustainable development goals (SDGs) in the built environment (Fawcett & Hampton, 2020).

The 2019 nZEB Plan indicated that there are currently only 17,814 EPCs issued for the residential sector (Hardy & Glew, 2019). To increase the nationwide implementation of EPCs, the 2020 Energy Efficiency Watch Report stated that the RoC has an action plan to achieve a 30% reduction of energy use by 2030 in order to attain the Energy Statistical Development reference period (Feng *et al.*, 2019); the initial target for 2019 was 3.3%, which was exceeded when 3.57% was achieved. This policy report highlighted that government bodies are targeted to achieve the EPBD goals within the recommended time frame, depending on time constraints for assessing energy efficiency measurements and inspections of the thermal properties of each household at the community level in the implementation of urban energy policies (Ionescu *et al.*, 2015). According to the National Energy Efficiency Action Plan (NEEAP), however, additional measurements are required for Cyprus because of the technical procurement gap that was identified in the EPBD to assess building-performance evaluations of post-war social-housing stock (Yeatts *et al.*, 2017).

Another technical constraint is a lack of availability of primary databases to record and demonstrate the impact of EPCs on home-energy performance and household energy bills; this dearth of data becomes evident in many ways, such as legislation and regulations for issuing EPBDs and relevant training material, including the development of software tools and an online open-source platform to disseminate the outcomes of each country (Alexandre *et al.*, 2011; Tronchin & Fabbri, 2012). In this regard, we noticed an additional issue with the integration of EU mandates, because the representativeness of housing stock in Cyprus was not thoroughly classified, primarily because it was based on a random selection of case-study buildings for an archetype analysis of local initiatives and energy agencies (Ferreira & Pinheiro, 2011; Gabe, 2016; Ozarisoy & Altan 2017a).

Given this challenge, a comprehensive energy-performance evaluation of housing stock can only be assessed at the building-level; as such, there is an urgent need for effective nationwide implementation of EPCs, control mechanisms to achieve policy targets and actions related to future holistic retrofitting efforts for urban neighbourhoods, all of which must put into place by stakeholders and government initiatives in Cyprus (Ballarini *et al.*, 2014).

The aim of this empirical study was to identify the RoC's social householder's energy saving awareness towards occupant behaviour on home energy performance in order to develop energy-efficiency regulations and to set current legal standards and benchmarks for the implementation of EPCs that are in line with the EPBD recommendations for EU countries. This was achieved by investigating household awareness of energy use, the type of heating and cooling devices used at home and the socio-demographic characteristics of different households, as well as identifying feedback related to thermal comfort at home and linking this feedback to retrofitting policy design and the implementation of energy-efficiency schemes, as shown in Figure 1.

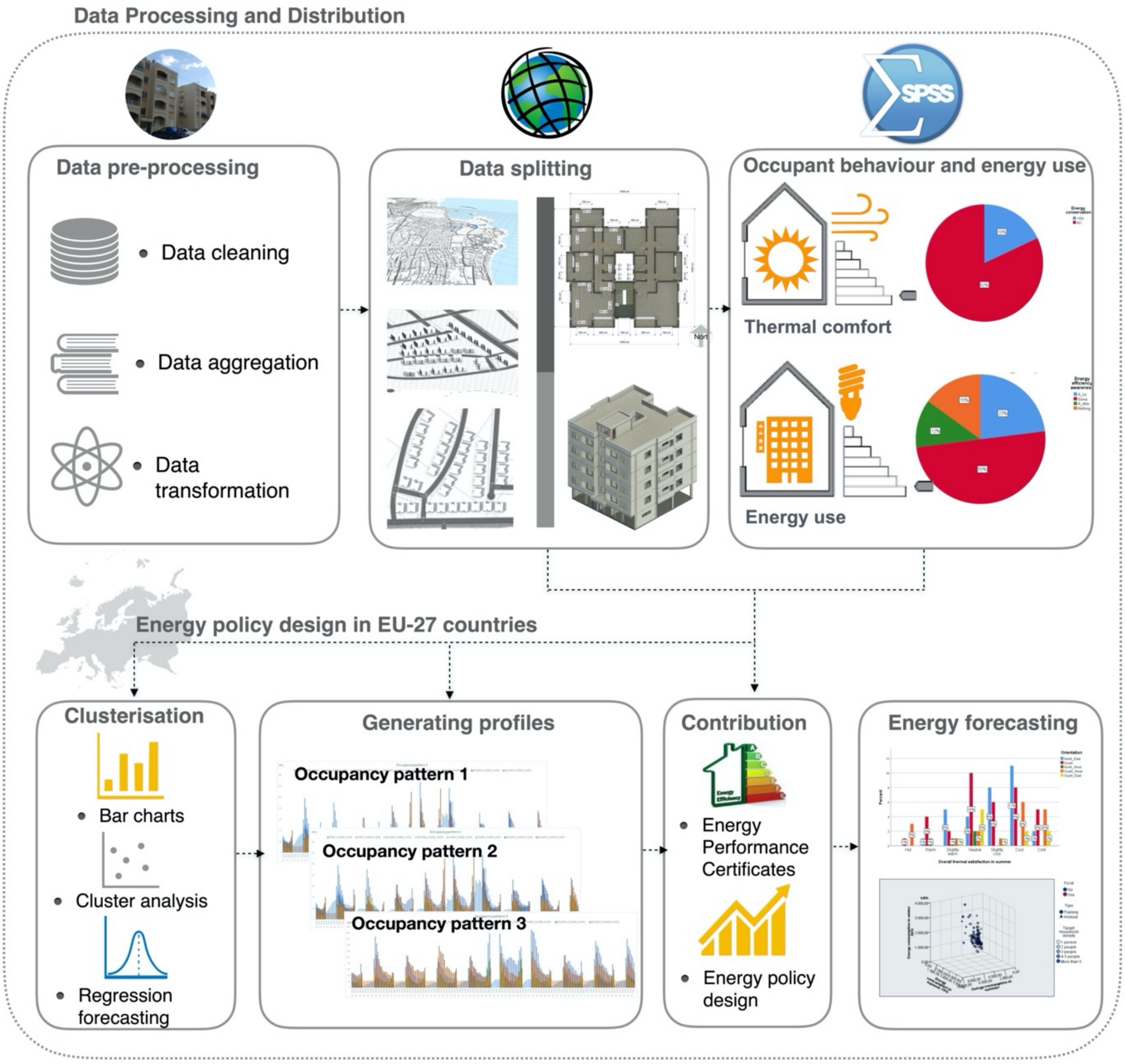

Fig.1. The conceptual framework developed for this study.

One of the technical constraints is the lack of available primary databases to record the impact of EPCs on home-energy performance and household energy bills; this dearth of data is evident in many areas, such as legislation and regulations for issuing EPBDs and relevant training materials, which include the development of software tools and an online open-source platform to disseminate the outcomes of each EU-27 countries. The objectives are threefold:

(i) To identify technical issues arisen in the implementation of energy efficiency upgrade schemes in the Republic of Cyprus (RoC) and fill the knowledge gap in order to devise effective roadmap for developing energy performance certificate of buildings in the south-eastern Mediterranean climate.

(ii) To fulfil the knowledge gap in order to identify the differences between existing European methodologies applied in similar climates in Europe with considering an establishment of novel energy assessment criterion in the EU-27 member states.

(iii) To examine the state of existing research into the validity of the Energy Performance Certificates (EPCs) as an effective tool to accelerate the transformation of the social housing stock into low-energy high performance dwellings in Europe.

The research questions (RQs) in this study focused on the domestic-energy use and occupant thermal comfort in purpose-built RTBs to determine what information was necessary to properly calibrate building energy performance, to provide guidelines, tools and policy implications to improve the energy efficiency of post-war social-housing estates in NC. The primary RQ that was addressed was: What is the most effective and universally applicable energy-policy framework to implement the EPBD mandates recommended by EU and improve the energy efficiency of existing housing stock in NC?

The following RQs are outlined to develop a bottom-up energy-policy framework to upgrade the thermal efficiency of the existing Cypriot housing stock:

- ***RQ-1:*** Which household socio-demographic characteristics and home-energy performance factors influence household energy use?
- ***RQ-2:*** Which occupant energy-consumption behaviours have an impact on the energy performance of social-housing estates?
- ***RQ-3:*** How do environmental factors affect occupants' thermal comfort?
- ***RQ-4:*** How will this study contribute to and inform the design of nZEBs in the EU countries?

This paper is structured as follows: Systematic literature review provides the step-by-step development of conceptual framework on energy efficiency and retrofitting scenarios across the EU in order to provide a thorough understanding of economically viable EPBD implementation schemes and the efficacy of energy-efficiency upgrades of existing housing stock; regarding the latter, the barriers to and motivations for the adoption of energy-efficiency measures (EEM) are also introduced. Materials and Methods describe the mixed-method research design that was used to study the internal, intrinsic motivation embedded in the context thereof, specifically the household socio-demographic characteristics (e.g., age, gender, occupation etc.). In Analysis and Results, the socio-cultural contextual factors are described, particularly those related to energy-use awareness and home energy systems, based on the survey data; after which the qualitative findings of household feedback that are structured by the conceptual framework are presented. Discussions present the results of this study, structured by the research questions posed above; the findings raise questions of the best way to develop and apply effective energy-efficiency scenarios to ensure the reliability of EPC methodologies when heating and cooling are required for residential buildings. Finally, Conclusions delineate implications for long-term holistic retrofitting programmes and policy design for evidence-based sustainable urban energy systems with the implementation of the EPBDs in the RoC and other EU countries at the household- and building-levels.

Contribution to knowledge in energy for sustainable development

The main contribution to the body of knowledge is the integration of data to identify the empirical analysis of the STS conceptual framework to develop a new method of design for the EPBD mandates that can be applied to the universal databases, as listed in Table 1.

Table 1
The impact of key research areas to the contribution to knowledge.

Key Concepts		Contributions
Energy policy	-	EU energy governance by integrating EPCs into building-energy-performance development of social-housing stock
Thermal comfort	-	Donation of the neutral adaptive thermal comfort identified for the Cyprus climate to the EU Smart Controls and Thermal Comfort (SCAT) online database
	-	Dissemination of the optimum thermal-comfort level thresholds that were developed as a result of a field investigation in the south-eastern Mediterranean climate and can be applied to the European Norm EN 15251 standards—which are related to indoor environmental input parameters associated with the design and assessment of building energy performance and address indoor-air quality, the thermal environment, lighting and acoustics—as an updated methodological framework
Energy use	-	Integration of the archetype housing stock into the EU's *Horizon 2030 TABULA/EPISCOPE* national database
Sustainable development goals (SDG)	-	Development of energy-calibration methods for archetype housing stock and analytical BEM with integrated human-based data from the questionnaire survey to demonstrate a policy design tool to the applied sciences field in energy use in accordance with the United Nations Sustainable Development Goal 7.

The study provides new insights into the EU energy governance and presents the outcome of comprehensive methodology developed by adopting the STS design approach, which is not found in other EU countries holistic retrofitting projects. Hence, this is the first study to be adopted and developed in the south-eastern Mediterranean climate of Cyprus. Thus, the findings should make an important contribution to the research subject of energy policy in the development of retrofitting schemes. One of the unique features of the research technique developed in this empirical study is that it adopts the STS approach to create a novel methodological workflow to assess domestic-energy use and thermal comfort, neither of which is well-defined in traditional building physics or in regression-based forecasting for policy-making decisions. As a result, the building performance evaluation (BPE) remains largely unpredictable when considering real-life occupant energy-use experiences.

An evidence-based STS approach was developed for the study to determine the feasibility of the retrofitting design interventions when human-based considerations could have impact on the development of feasible EPBD policy regulations in the EU-27 member states. The findings of this empirical study will create the prerequisites and the background information for the development of critical research and educational core of knowledge in the area of development and design, energy policy and the drafting of subsidization schemes and other targeted actions for improving energy efficiency of social housing stock in the south-eastern

Mediterranean climate. The effective energy measures developed as an outcome of this empirical study for the reduction of energy consumption in residential buildings would benefit from conceptual level analysis and prioritisation in accordance with the climate characteristics of the regional context of each EU notion.

Systematic literature review

Under the scope of EU's 2050 net-zero emissions targets, various policies aimed at encouraging energy-efficiency measures in domestic buildings have been implemented in the last few decades (Willan *et al*., 2020). There is growing concern, however, that zero-energy buildings often underperform when compared to design specifications due to discrepancies in the building-fabric thermal performance, systems efficiency and occupant behaviour (Castaño-Rosa *et al*., 2020; Berger & Höltl, 2019; Brown *et al*., 2019). To address the knowledge gap in the STS design approach, the dearth amount of pilot study projects was undertaken to identify the difficult-to-quantify of the factors that related to multi-family households due to the variance on the occupancy patterns and their socio-demographic structure (Betto *et al*., 2020; Arbolino *et al*., 2019; Franke & Nadler, 2019). This is the reason that the present empirical study was premised on an STS approach to develop 'bottom-up' energy-policy tools for the government in the South-eastern Mediterranean climate.

In the context of this driver, the main conceptual target of the United Nations Sustainable Development Goal 7 comprises future energy demand scenarios envisioning major instabilities (e.g., oil crisis, climate change and environmental unbalance) which are prejudged, taking into account of societal tensions and personal discomfort as parallel habitual behaviour to be anticipated and managed. Through the decades, the terminology of 'sustainability' evolved from due considerations of a 'green economy' to include issues of households' well-being, human quality of life and public ethics. In this respect, the overall objectives aimed within this socio-cultural driver envisage both the 'green factor' as well as the 'human factor', with particular focus on the need for personal freedom as a basic enabler of fundamental human rights.

To address the knowledge gap in EU residential-sector energy-consumption governance, previously scholars the findings demonstrate an urgent need to consider household socio-demographic characteristics, occupant behaviour and thermal conductivity level of building's properties to provide effective retrofitting solutions in residential sector (Ratinen, 2019; Semple & Jenkins, 2020). These study schemes highlighted that implementation of EPBD mandates and financial incentives are important measures that improve the energy performance of the domestic built environment (Mortensen *et al*., 2014; Moore *et al*., 2019; Cabeça *et al*., 2021). Importantly, occupants also play a critical role in the implementation of the EPCs at the community- or policy-level (Zhao & Carter, 2020). Specifically, the social and cultural considerations of the manner in which social households interact with energy in their homes have largely been left unexplored by engineering professionals (Hess & Sovacool, 2020).

The result is that there exists a shortfall between the full potential of adopting retrofit design technologies and realised developing a novel methodological framework to improve energy efficiency of buildings (Cockbill *et al*., 2020). In Cyprus, which is an EU member state, and Northern Cyprus, which is not an EU member state, government initiatives have attempted to tackle the burden of the existing housing stock by changing the legislative framework for adopting the EPBD guidelines and net-zero energy building schemes to upgrade the thermal efficiency of existing building stock (Serghides *et al*., 2015). This indicates that such legislative frameworks were not devised by taking the occupant habitual adaptive energy-use behaviour into consideration, which would provide effective guidelines to reduce energy consumption and optimise occupant thermal comfort in the residential sector even though this are not yet mandatory (Serghides *et al*., 2016).

Building-energy-performance gap

Government initiatives at various levels have been made globally, which seek effective solutions to the problems related to household energy consumption and CO_2 emissions, especially for vulnerable households in energy poverty and underlying with health conditions in all spheres of the economy (Government Office of Science, 2016a). Understanding the importance of the energy performance of existing housing stock constitutes a cultural and societal challenge (Government Office of Science, 2016b). Zero-carbon targets must be achieved to reduce the detrimental impact of greenhouse emissions and mitigate climate change (Pylsy *et al.*, 2020). Neither developed nor developing societies will be able to meet the range of targets set by the European Union (EU) and other countries related to the design and procurement of built environments to reduce CO_2 emissions to 80% of 1990 levels by 2030, or the mandates set forth in the 2018 U.K. *Climate Change Act* to limit CO_2 emissions to 20% by 2050 (Thomas & Rosenow, 2020).

In Cyprus specifically, there are several post-war residential-housing stocks that must attain the EU's 2030 energy-consumption-reduction targets, all of which are worthy of an investigation. Various studies have demonstrated the potential benefits of a greater reduction of energy consumption and the increasing value of the built asset (Domínguez-Amarillo *et al.*, 2019; Fernández-Agüera *et al.*, 2019). None have attempted to understand the overheating risks in NC residential buildings and the impacts thereof on occupant thermal comfort, and this issue remains unaddressed. Despite this paucity, it is not important to initially evaluate the energy performance of existing housing stock and assess occupant thermal satisfaction, since these variables can have a significant impact on energy use (Escandón *et al.*, 2017).

By exploring different variations of building-energy-performance assessments, the *European Union Statistics on Income and Living Conditions* and the 2018 Household Budget Survey both indicated that different assessment indicators related to energy use, such as whether or not occupants are in arrears on their utility bills or are unable to keep their homes adequately warm, which homes are uncomfortably hot in the summer, hidden energy performance, energy costs that consume a large proportion of one's income and the presence of a leak, damp or rot, should all be considered, as shown in Figure 2.

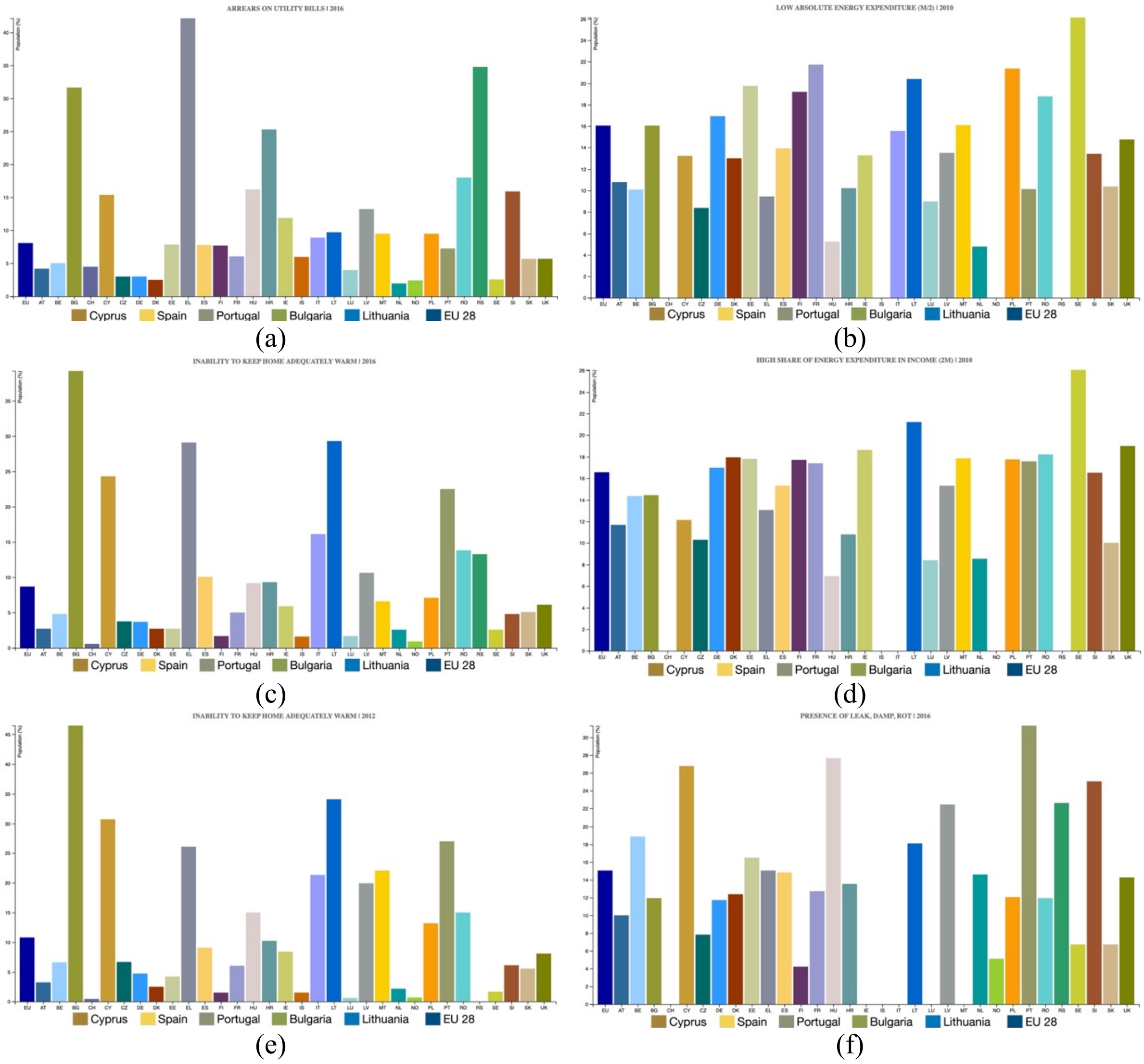

Fig.2. Energy-performance assessment indicators in EU member states; **(a)** arrears on utility bills in 2016. **(b)** low absolute energy expenditure in 2010. **(c)** inability to keep home adequately warm in 2016. **(d)** high share of energy expenditure in income in 2010. **(e)** home uncomfortably hot in summer 2012. **(f)** presence of leak, damp, rot in 2016. ***Image Credits:*** EPOV, Indicators & Data, (2018). https://www.energypoverty.eu/indicator (Accessed on 20 July 2021).

Alonso *et al.* (2017) and Sánchez-Guevara (2018) argued that energy-performance assessment indicators undertaken in EU countries are based on household self-assessment evaluation of their dwellings. to explain the survey results, it can be seen that the case studies showed slightly low-performing indicators in comparison to the EU overall average. Spain was shown to have better home-energy performance than the EU, which enabled respondents to keep their homes thermally comfortable (San Miguel-Bellod, 2018). While many other countries, particularly those in south-eastern Europe that share the subtropical (i.e., *Csa*) and partly semi-arid (i.e., *Bsh*) climate characteristics of Cyprus, showed significant thermal discomfort; Spain showed a similar approximation to the European overall average with respect to maintaining thermally comfortable indoor environments in the summer. It can therefore be deduced from the above graph that 29% is higher than in the EU average of thermal discomfort (Kyprianou *et al.*, 2019).

More significantly, Bulgaria had the worst overall thermal-performance for both of the assessment indicators related to the thermal-comfort aspect of residential buildings, including the criterion related to being in arrears on utility bills; Cyprus also showed a higher percentage of arrears on utility bills than in the EU. Nevertheless, it is evident that Portugal had a slightly better performance than many other countries due to stringent policies that were put into place in 2015 to thoroughly implement energy-performance directives; it should be considered, however, that many Portuguese households rely heavily on biomass burning for space heating and are therefore not properly accounted for in the energy-bills assessment. In terms of assessing the influence of the presence of leaks, damp or rot in residential buildings, Bulgaria has the lowest percentage of its population living in such conditions; this is followed by Spain, which also showed lower indicators than the remainder of the EU.

Lithuania was slightly above average, while households in Cyprus and Portugal have faced thermally uncomfortable indoor environments due to thermally deficient building envelopes and ageing residential-building stocks; these findings strongly correlate with the population consensus, because distinct deviations between these two Mediterranean countries have been observed. Notably, Lithuania was found to be the only country with an energy-performance indicator that was higher than the EU average; this can be further corroborated by the fact that Lithuania was shown to have one of the highest income coefficients, which indicates unequal income distribution across the total sample size in both surveys from which the results were taken as base-case reference indicators of home-energy performance (Guardigli *et al.*, 2018).

Couched within this emerging energy debate, the EU Framework Programme for Research and Innovation for 2014–2030 includes an action plan that underscores the need to legislate the policy priorities put forth in the EU's 2030 strategy (Bertoldi & Mosconi, 2020). This plan incorporates long-term aims to address major energy-demand concerns that are shared by citizens of Europe and elsewhere (Fawcett & Hampton, 2020). This strategy plan consists of different policy implications related to energy use, including the significance of occupancy patterns and various socio-demographic characteristics that should be considered during the decision-making process for retrofitting efforts of existing housing stock (Erell *et al.*, 2018; Kumareswaran *et al.*, 2021; Morton *et al.*, 2020).

Table 2
Field-investigation studies on adaptive thermal comfort.

References	A. Study Location	B. Primary Aim of Model	C. Methodology	D. Main Findings
Vellei *et al.* (2017)	ASHRAE Global Thermal Comfort Database II	To determine a clear explanation for lack of humidity signal or convincing formulation of the effect of humidity on adaptive thermal-comfort development.	Global thermal-comfort datasets investigated, including meta-analysis of summary data from 63 field studies and field data from 39 naturally ventilated buildings in eight climate-types; experimental study established from ASHRAE RP-884 data.	The new adaptive thermal-comfort model increased the comfort envelope of naturally ventilated buildings because its overheating prediction was 30% lower than that of the current model.
Ličina *et al.* (2018)	ASHRAE Global Thermal Comfort Database II	To document origins, scope, development, contents and accessibility of ASHRAE Global Thermal Comfort Database II.	Dataset created from field studies conducted from 1995–2016; 81,846 rows of paired subjective comfort votes and objective instrumental measurements data included in global database development framework; Query Builder used with Javascript to develop visual tool.	Web-based interactive thermal-comfort visualisation tool that allows end-users to quickly and interactively explore the data was developed.
Jin *et al.* (2020)	Harbin, Northeast China	To explore gender-related thermal-comfort differences in severely cold regions.	Physical measurements conducted; thermal-comfort questionnaire survey distributed to pedestrians; correlations among psychological parameters explored.	In transitional seasons, female neutral temperature was 23,2°C, and male neutral temperature was 19,8°C.
Gautam *et al.* (2020)	Hariwon, Nepal	To examine differences in indoor thermal environments of local and migrant people and evaluate differences or similarities in perceptions of neutral adaptive temperature.	Longitudinal thermal-comfort survey conducted over one month: TSVs collected from 395 individuals living in 122 houses in sub-tropical climate zone.	The upper limit of thermal acceptability for local people was 3°C higher than that of migrant people.
Stopps & Touchie (2020)	Toronto, Canada	To identify occupant behaviour to reveal opportunities for improved thermal comfort and energy efficiency.	Thermostat data obtained; building-occupancy survey conducted with 55 occupants in two contemporary high-rise residential buildings; weather station installed to monitor actual environmental conditions.	Of the respondents, 48% reported thermal discomfort in their flats in the winter and 53% reported thermal discomfort in the summer.

As shown in Table 2, a significant proportion of the current literature on thermal comfort specifically focusses on the physical environment and physiological conditions to predict comfort levels and quantitatively produce a number of thermal indices to thoroughly assess occupant thermal-comfort levels (Liu *et al.*, 2012; Taleghani *et al.*, 2013; Toe & Kubota, 2013). Nicol *et al.* (2012) explained that these models, known as 'heat-balanced models', are predominantly based on physics and physiology and are able to rationally analyse the heat flow between the human body and its surroundings.

Humphreys and Nicol (2000) insisted that occupants' thermal sensations strongly correlate with age, gender, economic and cultural aspects and location and climatic conditions. In an analysis of the influences of dependent and independent variables on occupant thermal preferences and sensations, Humphreys (2005) identified specific groups of people with more demanding needs—such as children, the elderly, people with disabilities and people who are sick—who are more likely to be vulnerable. This led to a significant contribution toward the assessment of thermal comfort in different climate regions under investigation by many other scholarly articles in this field (Nicol & Humphreys, 2010).

In this regard, this empirical study seeks to identify key features of energy policy instruments and retrofitting initiatives across EU members states that could foreseeably improve the reduction of energy consumption and optimise the thermal comfort level of occupants in the housing sector in Cyprus, where the climate is subtropical (*Csa*) and partly semi-arid (*Bsh*). This paper presents the importance of adopting a comprehensive, interdisciplinary collaboration to develop a novel methodological framework in order to implement the EPBD and EPC schemes in the residential sector. Such a methodological approach strives to identify gaps in the existing knowledge by considering occupant real-life energy-use experiences and identifying measures that can optimise their thermal comfort and reduce energy consumption via policy instruments for retrofitting interventions.

The original contribution of this empirical study lies in its implementation of energy efficiency and offering evidence-based energy policy framework into the decision-making process of domestic energy use, which primarily considers the objectives of the EPBD indicators on increasing energy efficiency awareness and upbringing quality of social housing stock. This study sits on the grounds of understanding the notion of sustainability in terms of energy performance, energy efficiency and thermal comfort. Sustainability is main conceptual framework of this empirical study corresponding to the sustainable development goals 7 set by the United Nations.

Anecdotally, sustainability must be accessible to everyone and climate resilient actions must be applicable to the practice of everyday life of citizens. To-the-date consumers respond poorly to browbeating activism and need fiscal incentives to use less, and to be given greater control over the energy they use. It is in the nature of this kind of research to manifest an awakening call-in domestic energy use for energy performance assessment and, most importantly bringing control mechanisms and effective networking in the newly-formed or actively-motivated multi-family households in high-density post-war social housing estates with interest in energy efficiency.

Methodology

Research design

This empirical study employed the STS approach to develop a bottom-up energy-policy framework for the residential sector. The focus of the study was to statistically determine occupant behavioural patterns that are associated with heating- and cooling-energy consumption and to identify household socio-demographic characteristics that contribute to the development of energy-user profiles. This study initially adopted a mixed-method research design that primarily utilised a thermal-comfort assessment and questionnaire-based surveys of households to gather information related to home-energy performance and to determine optimum thermal-comfort levels before developing EPC schemes. In an attempt to meet the target research objective and answer the research questions (RQs), a social-science framework was put into place at the start of the present study; this, in turn, provided a rationale for quantitative and qualitative components in the development of an energy-policy framework that is based on this empirical analysis, as illustrated in Figure 3.

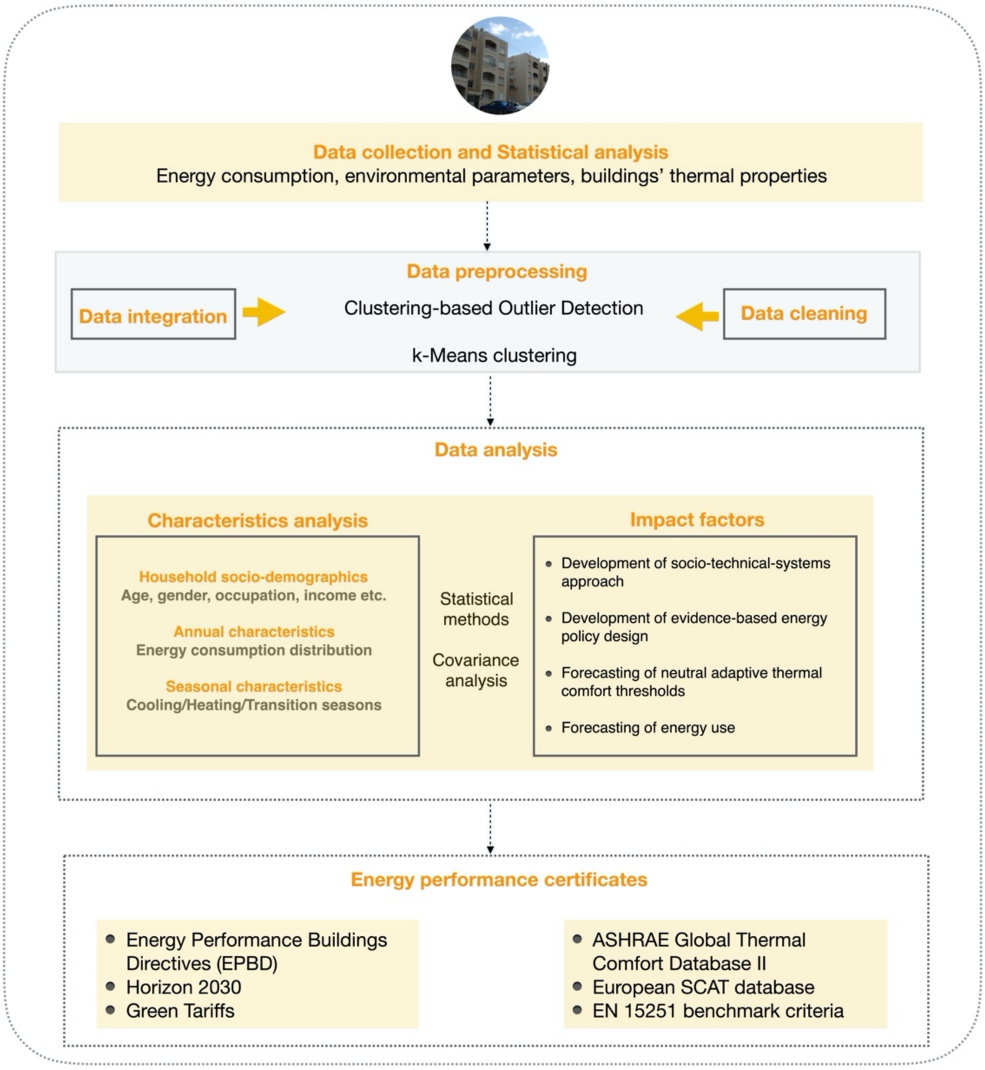

Fig.3. The set-up of the field study investigation and data processing.

The field work for the study consisted of examining first-hand experiences to fully understand current EPBD implementation schemes and the impact thereof on home-energy performance in NC (Darby, 2017; Renner & Giampietro, 2020). Before conducting the semi-structured interviews with households, *on-site* site observations were recorded to analyse the taxonomy of the housing stock (Mould & Baker, 2017; Wolff *et al*., 2017). The empirical framework is premised on an analysis of the feedback that was collected in 2018 from the households during the hottest summer month of August. The study was intended to assess the participants' real-life energy-use experiences to develop an evidence-based energy-policy framework.

This research consisted of interdisciplinary cooperation in an area where single-discipline studies are typically conducted; in this endeavour, there was communication and collaboration between the research, design and implementation of energy-efficiency retrofitting efforts and challenges that were the result of the EPBD mandates (Cunha *et al*., 2020). To identify the EEG in this empirical study, data were primarily collected through feed-forward interviews with households. Additionally, objective data, such as household socio-demographic characteristics and occupancy profiles, were also collected to aid in the interpretation of the study results with the *on-site* observations that were concurrently recorded with the interviews. The pragmatist research approach that was designed for the present study is illustrated in Figure 4.

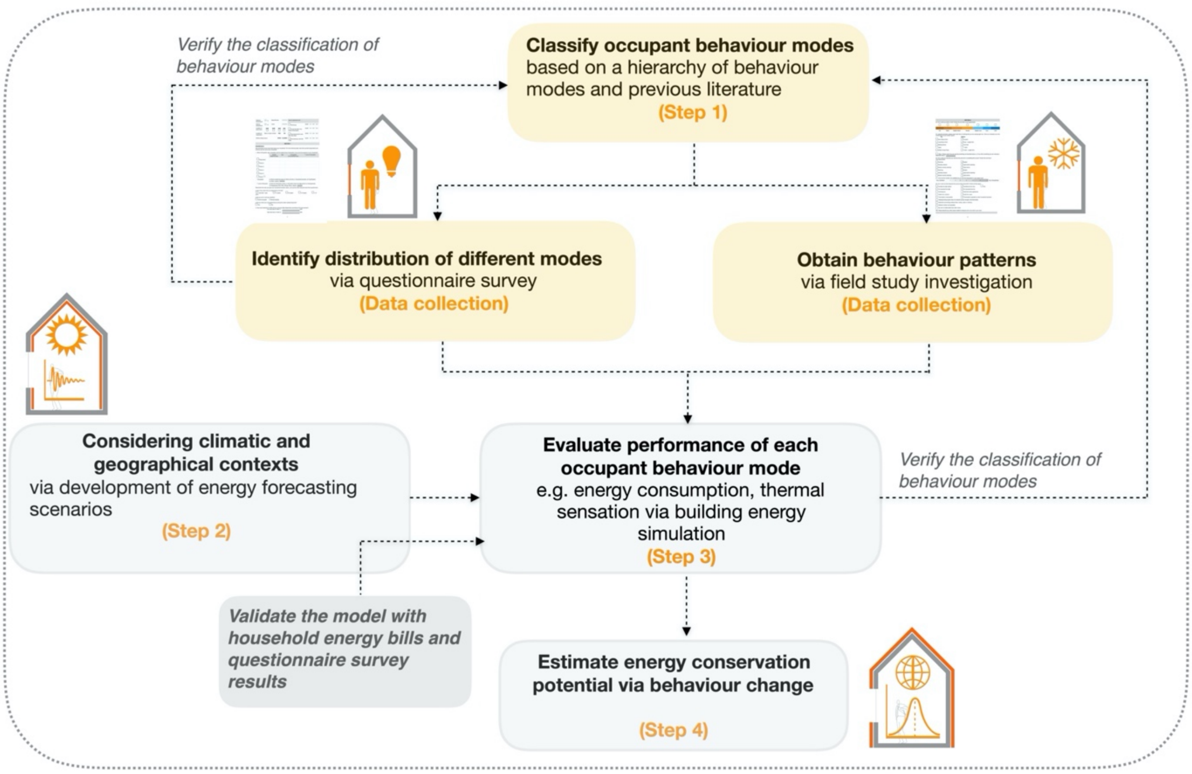

Fig.4. Research design and model showing interconnections between three components of this study.

As a mixed-model approach, a convergent parallel mixed-method was considered to be the most appropriate strategy that could be employed in the present study; this is a variation of a mixed-method design in which the researcher converges or merges often-ignored quantitative and qualitative data to provide a comprehensive analysis of the research problem (Flowerdew & Martin, 2004; Ingeborgrud et al., 2020; Wolf et al., 2017).

In this research approach, the researcher collects both types of data at approximately the same time, then integrates this information and interprets the overall results; contradictions or incongruent findings are explained or further probed in the survey design. After collecting necessary data via on-site observations, the study focused on an explanatory case-study approach of the prototype base-case post-war social-housing development estates in Cyprus. Semi-structured interviews, which were in the form of a questionnaire survey, were conducted with selected households to provide evidence-based retrofitting design policies and recommendations for energy-efficiency guidelines in the residential sector.

Socio-technical-systems design approach

The concept of the study is to integrate a design method into the STS approach to develop a bottom-up energy-policy framework for the implementation of the EPBD objectives through holistic retrofitting schemes across the EU member states. Several studies have addressed the analytical framework that was used to model household-energy consumption at the national level by selecting archetype buildings to conduct energy-demand scenarios in different EU countries (Abokersh *et al*., 2021; Gatt *et al*., 2020); these energy-consumption forecasting and modelling methodologies are frequently used by scholars to devise policy recommendations (Bracht *et al*., 2021).

Several recommended methodologies—such as genetic algorithms, meta-analyses and sensitivity analyses—employ machine-learning techniques to quantify home-energy performance factors (Roccotelli *et al*., 2020; Yang *et al*., 2020). It has also been suggested that the development of a novel methodology to calibrate building thermal performance would require a longitudinal field investigation to conduct BES studies and measure the predictive ability of an analytical energy model that was devised to recommend cost-effective energy-efficiency scenarios to policymakers.

A significant theoretical issue that has dominated the field of energy research-and-design for many years is related to building energy-modelling approaches that failed to consider the STS conceptual framework for a bottom-up energy-policy design that is worthy of an investigation. This is due to a lack of information about household socio-demographic characteristics, occupancy patterns and interactions with the built environment that could be addressed through a BES study. Mahdavi (2020) pointed out that BES tools provide effective retrofitting policy design scenarios, but household energy-use behaviour and thermal-comfort assessments have not been thoroughly investigated to determine the outcomes based on a novel analytical energy-modelling approach; this indicates that energy-demand scenarios from top-down and bottom-up approaches can be aggregated to fill the EEG, as shown in Figure 5.

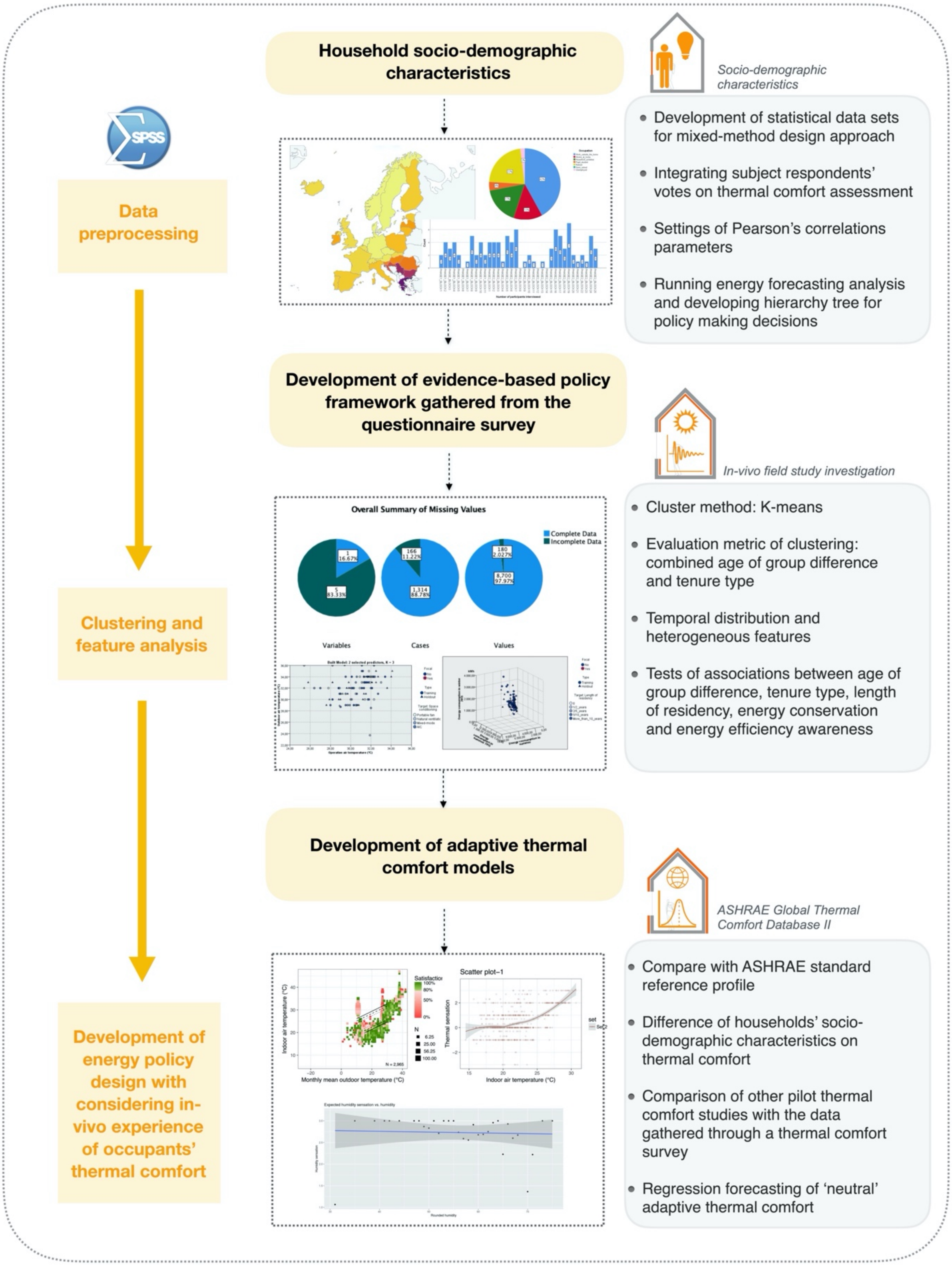

Fig.5. The novel methodological workflow developed for this study.

A comprehensive understanding of the manner in which an STS approach contributes to bottom-up energy-policy design is still lacking. To date, several hybrid models of these two approaches have been developed and employed for more-robust building-energy models, but none of these studies considered concurrently optimising occupant thermal comfort as buildings are being retrofitted. According to Geels *et al*. (2018), a bottom-up approach would be applicable to empirical studies that utilise limited secondary-data sources to develop an analytical framework that will support energy policies at the local and national levels. Alternately, the top-down approach is recommended when data are used to identify the knowledge gap related to energy use and undertake a statistical analysis, as shown in Table 3.

Table 3
Benefits and limitations of top-down and bottom-up energy-modelling approaches.

Characteristics	Top-Down	Bottom-Up Statistical	Bottom-Up Building Physics
Benefits	- Focusses on the interaction between the energy sector and the economy at large - Uses aggregated economic data - Does not require detailed technological descriptions - Capable of modelling relationships between different economic variables and energy demand - Able to model the impacts of various social cost-benefit energy-and-emission policies and scenarios	- Includes macro- and socio-economic effects - Able to determine typical end-use energy consumption - Easier to develop and use - Does not require detailed data, only billing data and a simple survey	- Describes current and prospective technologies in detail - Uses physically measurable data - Enables policies to more effectively target consumption - Assesses and quantifies the impact of different combinations of technology related to delivered energy - Estimates the least-cost combination of technological measures to meet given demand
Limitations	- Dependent upon past energy–economy interactions to project future trends - Lacks the necessary level of technological detail - Less suitable to examine technology-specific policies - Typically assumes efficient gaps	- Does not provide much data or flexibility - Limited capacity to assess the impact of energy-conservation measures (ECMs) - Relies on historical consumption data - Requires large samples - Multi-collinearity	- Poorly describes market interactions - Neglects the relationship between energy use and macro-economic activity - Requires a significant amount of technical data - Does not determine human behaviour within the model, but by external assumptions

Source: Adapted from Kavgic *et al*. (2010)

The comparison revealed that forecasting a household-energy model for the integration of the bottom-up approach would improve nationwide policy subsidisation schemes while considering the EPBD mandates (Balest *et al*., 2019; Li & Strachan, 2019). A thorough analysis of the STS approach would provide versatile data sources that are compatible with a wide range of BES tools that are available to researchers engaged in steady-state and dynamic thermal analyses. According to Sahakian *et al*. (2021) and Kunc *et al*. (2018), integrating a bottom-up approach requires input sources that are based on quantitative data or assessment criteria variables that are measurable on a Likert scale, such as the energy efficiency of hot-water systems and the fabric insulation of dwellings, for building-performance evaluations (BPEs).

It should be noted that a similar approach could be applied to energy-policy designs by adopting Forrester's systems dynamic approach that is only based on qualitative data to undertake BES studies (Forrester, 1976); it should be noted that Forester's tradition in building physics, which was developed in 1946, is widely acknowledged by scholars and is a matter of a conceptual analysis needs a new STS approach design method related to energy use (Forrester, 2007). Notably, the present study contributes to Forester's systems dynamic approach by exploring correlations between household socio-demographic characteristics and occupancy patterns that influence home-energy use.

A debate has taken place in many energy-modelling studies related to the selection criteria of archetype housing stock and household energy-use behaviour (Bienvenido-Huertas *et al*., 2021). As a consequence, the STS approach has been challenged by energy-research studies that demonstrated the usefulness of the bottom-up approach, which is widely used for BES studies (Marzouk & Seleem, 2018; Shih & Tseng, 2014); these studies concluded that the development of an evidence-based STS conceptual framework would establish a novel design method in line with Forrester's tradition.

Scholars have long debated integrating Forrester's dynamic approach to develop effective energy-policy designs and subsidisation schemes while delivering an assessment of EPCs that should be addressed. Turning now to the experimental evidence for the STS approach, Forrester (2016) argued that disaggregated quantitative data correlate with the thermal-conductivity levels of building materials, household socio-demographic characteristics and climate characteristics of the built environment to provide additional information for the development of energy certification schemes in the south-eastern Mediterranean climate.

Strategy of inquiry

To address the energy efficiency gap, Lopez *et al*. (2015) noted that the regression analysis (RA) technique facilitates the development of a quantitative design method that contradicts the theoretical philosophy that undergirds Forrester's systems dynamic approach. This empirical study highlighted a series of difficult-to-quantify factors, especially those related to household socio-demographic characteristics and the occupants' real-life energy-use experiences, that have not yet been thoroughly considered for a home-energy performance evaluation, which could help to establish a novel research design approach for building-retrofitting initiatives (Brown *et al*., 2019). This study therefore adopted the STS design model to gather feed-forward feedback from households to integrate household *in-vivo* experiences into the decision-making processes associated with energy-use policies. To develop the STS design model, we examined all available mixed-method approaches in order to develop a plan of action that linked philosophical assumptions to specific methods, as illustrated in Figure 6.

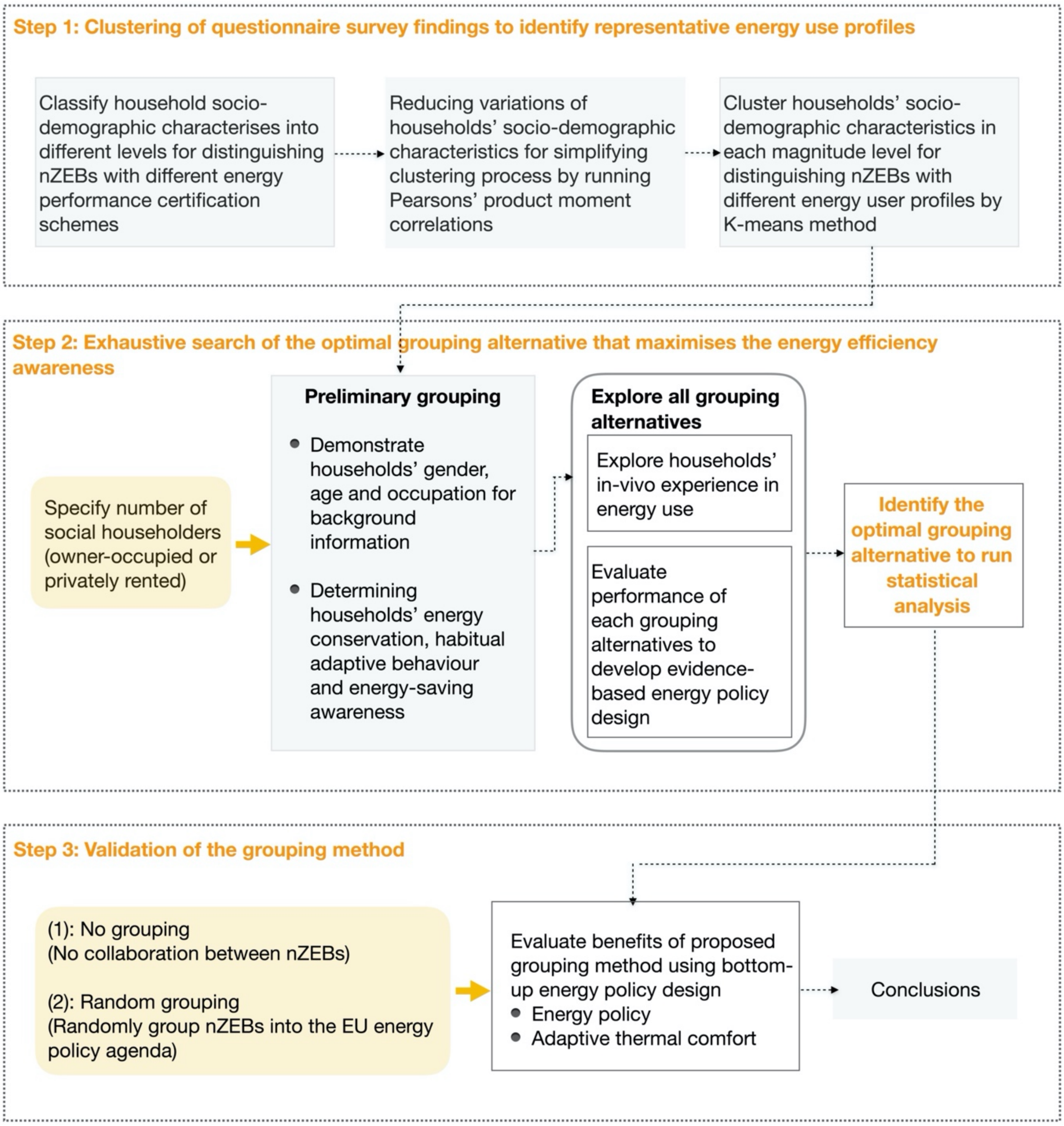

Fig.6. Development stages of evidence-based energy policy framework.

The concept of mixing-method studies was derived in a 1959 study by Campbell and Fisk (Creswell & Plano, 2007; Blackwell, 2013). For this reason, the use of a mixed-methods approach could bring about a significant contribution toward a full understanding of the correlations between dependent and independent variables within the statistical analysis (Brown, 2017; Moezzi *et al.*, 2017). This is due to the fact that 'triangulating data' sources, which are a way to seek convergence across qualitative and quantitative methods, have been born (Warren-Myers *et al.*, 2020). In general, each phase was carried out in a sequential order to facilitate a discussion of the systematic literature review that was conducted as part of the main research scope. Table 4 outlines the development of a novel STS conceptual framework.

Table 4
Step-by-step development of socio-technical-systems conceptual framework.

STS Development Structure	Guidance to Develop a Method for Current Design Approach
Step 1: ***Systematic literature review***	To undertake a literature review based on selected key terms—'energy governance', 'energy efficiency' and 'thermal comfort'— to address the knowledge gap in the field of energy efficiency and to develop a new design method for the STS approach.
Step 2: ***Questionnaire survey***	To conduct a questionnaire survey that will assess household-energy performance and the energy-use patterns of occupants prior to and following the energy-saving measures implemented in the selected archetype buildings.
Step 3: ***Thermal-comfort survey***	To make recommendations that will support successful delivery of current and future policy schemes related to retrofitting efforts for existing residential buildings that take occupant thermal comfort into consideration to promote evidence-based retrofitting interventions.
Step 4: ***Measurements and Monitoring***	To concurrently conduct *in-situ* measurements and *on-site* monitoring through semi-structured interviews with households to assess the degree of thermal discomfort.
Step 5: ***Retrofitting policy design***	To develop a novel design guideline for retrofitting efforts in post-war housing stock and to demonstrate the feasibility of implementing effective energy performance certification schemes

The rationale of the study is that the importance of developing an evidence-based energy-policy framework to assess robust energy-performance evaluation-and-certification schemes in south-eastern Mediterranean EU countries has not yet been addressed. A theoretical investigation of the STS design model and the integrity thereof in a multi-criteria decision-making process have gained momentum in research endeavours related to energy and the social sciences. A thorough empirical analysis of the energy-planning systems and energy-efficiency investments were the result of strategic policies and political issues that arose because of multi-disciplinary research and were developed within the scope of the EPBD mandates.

Sample representativeness and Selection of archetype buildings

Cyprus as a case study

Cyprus is situated in the north-eastern part of the Mediterranean Sea between latitudes 34' 33" and 35' 41" north and longitudes 32' 15" and 34' 35" east, as shown in Figures 7 (a) through (c). It is located approximately 40 miles north of Turkey, 60 miles east of Syria, 250 miles south of Egypt and 300 miles west of the Greek islands (Kottek *et al*., 2006). The coastal city of Famagusta was chosen case study location in the South-eastern Mediterranean climate, as shown in Figures 7 (d) & (e). One of the prominent factors is that the Famagusta is a frontier coastal town in the eastern part of the island which is consisted of the variance of high-density mass scale social housing developments were built in the mid 1980s and early 1990s without distinction of its urban peripheries (Yorucu & Keles, 2008; Yapicioglu & Wright, 2014), as illustrated in Figure 7 (f). Therefore, from the beginning of this study, there were limited pre-existing sources available for the Cyprus context, and this study was aimed at primary data collection to develop the methodological framework (Safakli, 2011). Thus, a case study was necessary to enable the research consortium to achieve the intended aim of demonstrating the condition of the post-war social housing structure, as shown in Figure 7 (g).

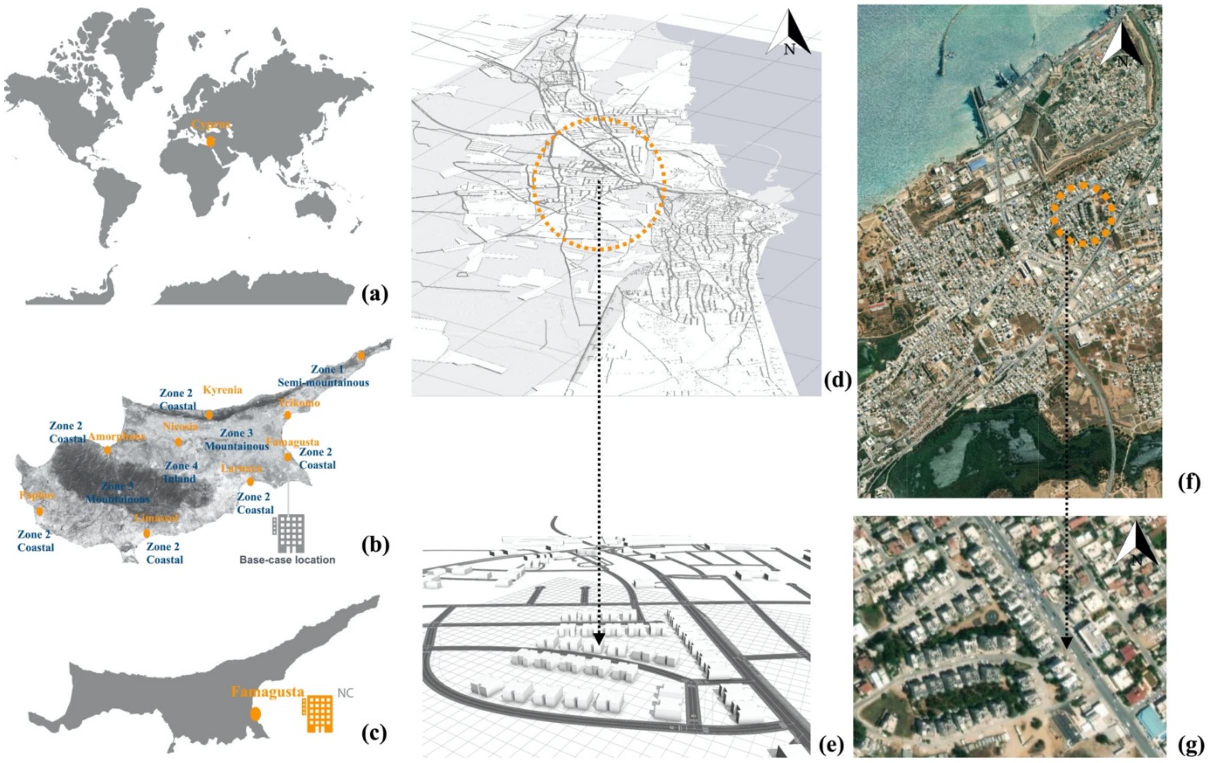

Fig.7. **(a)** Cyprus geographic position and **(b)** geological characteristics; **(c)** Northern Cyprus; **(d)** Famagusta vulnerable neighbourhood, **(e)** 3D model of medium-rise RTBs and **(f)** residential area urban tissue; **(g)** base-case morphology characteristics.

Source: Maps extracted from ArcGIS Pro Version 2019.01; software suite developed in 2018 by Esri (UK).

Figure 7 (f) illustrates the Famagusta city centre, which is dependent on a continuous, densely populated area in which the rapid construction of medium-rise residential tower block (RTB) developments was continued by the SMEs after 1998 when the government's social housing scheme ended. In the early 1950s, the urban agglomerations of Famagusta included approximately 34.000 units, which was the highest amount of residential stock built in Cyprus from 1960–1974.[1]The Famagusta population in 1973 was 38.960[2]; including remote rural locations, the overall island population was 146.740 (Oktay, 2002; SPO, 2019). Notably, a continual urbanisation process commenced in the mid-1980s in the form of high-density urban blocks, as shown in Figure 7 (g); this is due to the growth of the local population as a consequence of housing demands from the displaced Turkish and Greek Cypriot communities, which lead to an expansion of the boundaries to rural regions and agricultural lands.

Socio-demographic structures

The first census data for Cyprus were recorded in 1901, at which time the island population was 51.309 (Statistical Service of Republic of Cyprus, 2014). The RoC was established on August 16, 1960 with the involvement of two major ethnic communities: the Turkish and Greek Cypriots. After declaring independence from the Great Britain, the first census data were recorded on December 11, 1960, at which time the overall population was 104.942 with an annual growth rate of 1,9% (Moeschberger & Phillips, 2014; SPO, 2020). After NC declared itself a *de facto* state in 1983, the first census data were recorded in 1996, at which time the overall population was 200.587.[3] A second nationwide census survey was conducted in 2006, and at that time, the population was 256.644 with a 2,6% annual population growth rate.

As a consequence of a property boom and high demand for housing by foreign buyers wishing to take over control of the construction industry, the most-recent nationwide census data were collected by the NC government in 2011; this effort was intended to provide necessary figures on housing-stock data to the Union of Cyprus Turkish Engineers and Architects (UCTCEA). At that time, the overall population was 286.257 with a 2% annual population growth rate (SPO,2011).

Currently, this background information is used every year to estimate population projections; the most recent population and housing-unit census data were updated on December 31, 2019 (SPO, 2020). According to this census data, the NC population was 382.230 in 2019; the male population was 207.149, and the female population was 175.081, as shown in Figure 8. As can be seen, there were 62.299 individuals in the 20–24 age group, which comprised a large proportion of the overall population; there were 37.972 males and 24.372 females in this age group. The 70–74 age group consisted of 9.465 individuals: 4.551 males and 4.914 females.

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[1] Data represents number of housing units built on Famagusta shoreline; this area is currently fenced off and closed for human habitation due to the 1974 division of the island. In literature, this city is also known as 'Varosha', which translates to 'ghost town'; and it was the centre of international trade and tourism until August 16, 1974. The Turkish military currently controls this territory, which opened to pedestrians on October 8, 2020. Notably, this territory plays a prominent role in the negotiations and peace talks in international affairs of Cyprus.

[2] This census data was recorded on April 1, 1973 before the outbreak of civil war on July 20, 1974. The data detailed the island's overall population and included all ethnic groups: Greek, Turkish, Maronite, Armenian, British, and others. Data were extracted from the distribution of population by location during census years and is available in a reference document that was published in 1983 by the Chamber of Commerce and Industry.

[3] Data represent overall NC population, including settlers sent by the Turkish government after the 1974 civil war to increase the Turkish population in NC. Notably, this data does not include Greek Cypriots living in the RoC.

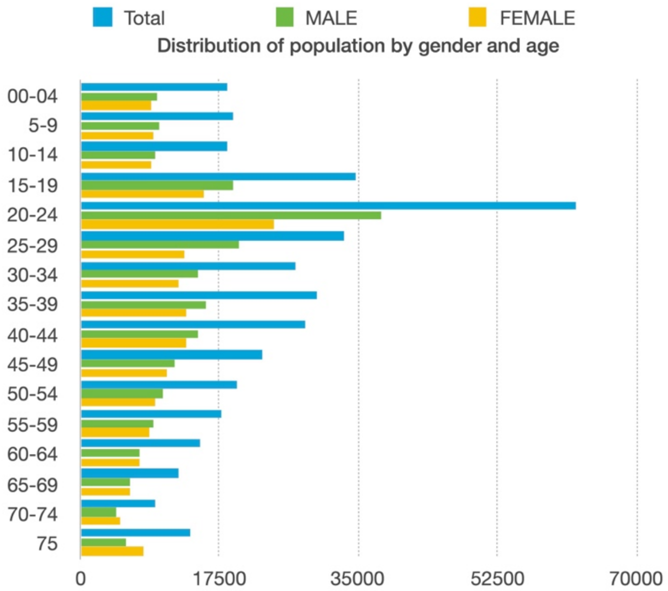


Fig.8. Distribution of Northern Cyprus's population by gender and age. ***Source:*** Annual Statistical Report for 2019, published by the Northern Cyprus Statistical Office.

The 2019 demographic statistics in the RoC indicate that the estimated population was 888.000, compared to 875.000 at the end of 2018, with an increased annual growth rate of 1,4%[4] (Statistical Office of the RoC, 2019). The census data were distributed according to gender and age in an effort to foresee birth rates and determine the percentage of the ageing population. The data show that the proportion of children who were 0–4 and 10–14 years of age were both estimated to be 16%; the proportion of age groups older than 65 years of age increased to 16,3% in 2019, compared to 22,3% and 11,3%, respectively, in 2000. These results indicate that there was a notable increase in the proportion of age groups 65 years of age and older and a decrease in the proportion of age groups younger than 15 years of age, which suggests that the size of the ageing population will increase in the RoC over the next few decades.

Residential-building stock characteristics

To represent the nationwide representative housing stock, the government's social housing estates, which were built under the social housing schemes between 1984 and 1996 was chosen for base case scenario development. According to the Housing Association in Cyprus, the post-war social housing stock represent 56% of entire housing stock which are 4 or 5 storey medium-rise RTBs without considering climatic zone differences of the island (State Planning Organisation, 2018). These mass scale housing estates were built to answer the needs of the housing shortage for young generation in early 1980s. Within a decade of implementing the

[4] RoC data include the following ethnic groups: Greek Cypriots, Armenians, Maronites and Latins. Per the 1960 constitutional agreement, Turkish Cypriots who hold EU citizenships were not included in the census data because their permanent residency was in Northern Cyprus.

same residential building typology, these types of housing estates were repeated in all five major cities across the country namely: Famagusta (coastal), Nicosia (inland), Kyrenia (coastal & mountainous), Omorphou (semi-mountainous) and Lefke (coastal & mountainous).

A number of RTBs corresponded to five development phases in terms of their building envelope material, age of housing stock and location of large-scale housing estates (Yorucu & Keles, 2007); in this way, the statistical data that represented the overall building stock—including five different archetypes—were identified. Age corresponds to the construction year and was divided into five periods: 1950–1974 (Phase 1), 1980–1997 (Phase 2), 1997–2002 (Phase 3), 2002–2004 (Phase 4) and 2005–Today (Phase 5). Medium-rise RTBs built in the early 1980s and the mid 1990s comprised new archetypes (Phase 2) that included high-density post-war social-housing development estates. Figure 9 delineates the stages of housing developments from 1950 to 2017 in Cyprus.

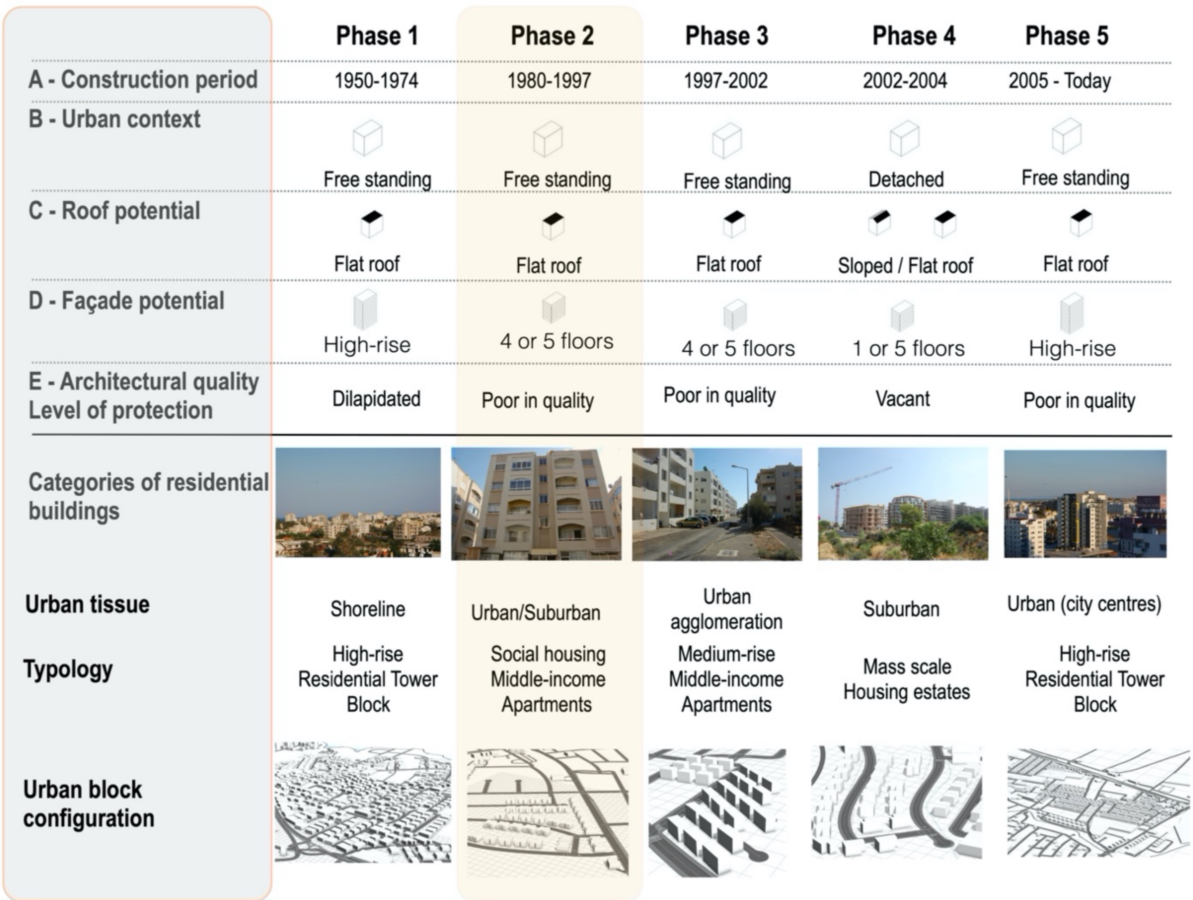


Fig.9. Taxonomy of existing housing stock to identify archetypes in Cyprus for case-study selection and sampling criteria. ***Source:*** Images were collected from the first author's personal archive. 3D dimensional urban block configurations were modelled in ArcGIS Pro software suite – version 2019.1.0.

In this study, the Archetype 2 was chosen as representative base case RTB prototype to recruit households in order to gather *in-vivo* experiences on their energy use and represent the nationwide sampling data to validate findings within the secondary data resources for policy making decisions in energy use. The study was aimed to consider the STS conceptual framework related to local energy policy that highlighted the importance of implementing the EPCs in high-density social-housing estates throughout five major cities in Cyprus. To ensure a comprehensive study, adequate building data and a comprehensive scope for the survey was also necessary. A total of 36 RTBs with the same floor-plan layout, construction materials and architectural style were selected to conduct a field study and recruit social households, as illustrated in Figure 10.

Fig.10. Step-by-step identification of representative RTBs for base-case scenario development.

As shown in Figure 10, the study was intended to identify the most dominant representative housing typology; this was determined to be medium-rise RTBs, which represent 36% of the housing stock in Cyprus. The selected housing typology was the first to be built as a governmental social-housing scheme to address the housing shortage in early 1980s and mid 1990s. This explanatory case-study approach provided a reasonable sampling size and a comprehensive understanding of the building-fabric thermal performance of existing housing stock with different levels of determinant factors related to household socio-demographic characteristics and the thermal conductivity of the thermal properties of the buildings that were selected to develop the base-case scenario.

Representativeness of housing typology selected as base case scenario development

Rapid construction during the 'property boom[5]' led to a revived interest in the property market (Yorucu, 2013). The expectations of the Annan Plan and changing market conditions

[5] The 'property boom' resulted from the Annan Plan (i.e., peace talks for the unification of Cyprus) from 2002–2004. During this period, there was a gap in Cyprus's international law as a consequence of the restructuring plan for Cypriot settlements in the northern and southern territories. This led the SMEs to construct an abundance of

throughout the world was evidence that people from such countries as Russia, Turkey, Greece, the U.K and Germany began to show significant interest in buying a second home in NC (Yorucu *et al.*, 2010). Increasing energy demands from the residential sector were mostly observed in rapid construction activities and a renewed focus on economic improvement (Moutsiou, 2020; Zachariadis, 2010); in Northern Cyprus (NC), the rapid and varied activity throughout the construction sector resulted in economic growth (Aloala, 2019).

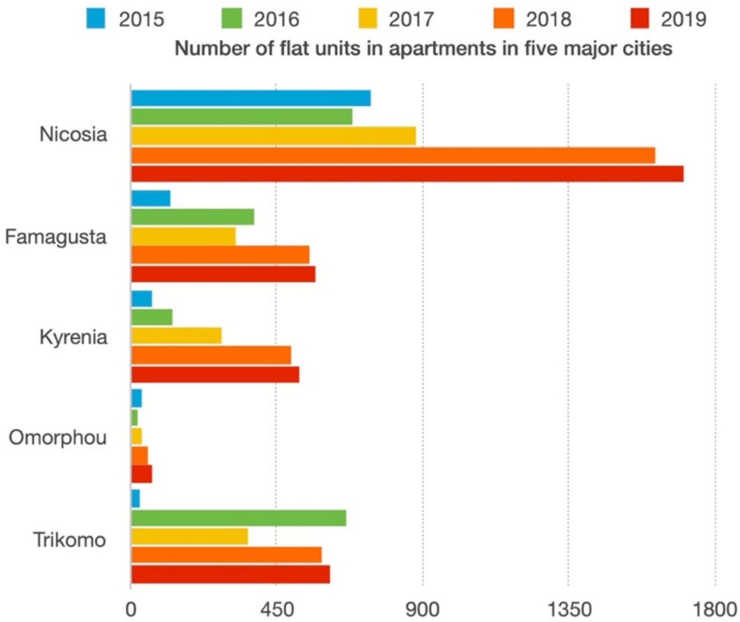


Fig.11. Total number of flat units completed in five major cities in NC between 2015–2019.

Figure 11 shows the number of apartment units built between 2015–2019 in five major cities in NC. A majority of the housing projects in 2019 were built in the capital city of Nicosia; approximately 1800 apartment units were completed within that year. This is due to land shortages and a high demand from the population of homebuyers who were 20–24 and 25–29 years of age. A significant rise in the number of completed flat units in Famagusta and Trikomo due to demands on the property market from the large foreign enterprises can also be observed; approximately 2500 apartments were constructed between 2015–2019. The analysis reveals that the trend of building apartments was always significant in Nicosia because it is the capital city and has a large population; hence, the demand for new housing projects is always on the rise. In comparison, the construction of apartment housing stock in Famagusta only steadily increased between 2018–2019, but this is still remarkably high, considering the local population numbers.

To conclude, most of the residential buildings are of the RTB typology with a mean gross floor area of 105 m^2; this corresponds to an average of 75 m^2 per occupant (SPO, 2019). According to 2018 EU Housing Statistics, the equivalent average numbers are significantly

mass-housing estates without the approval of the Chamber of Architects and Town Planning Department in major cities in NC.

lower than those recorded for Cyprus and are equal to 84,5 m^2 and 33,8 m^2 per occupant, respectively (Eurostat, 2018).

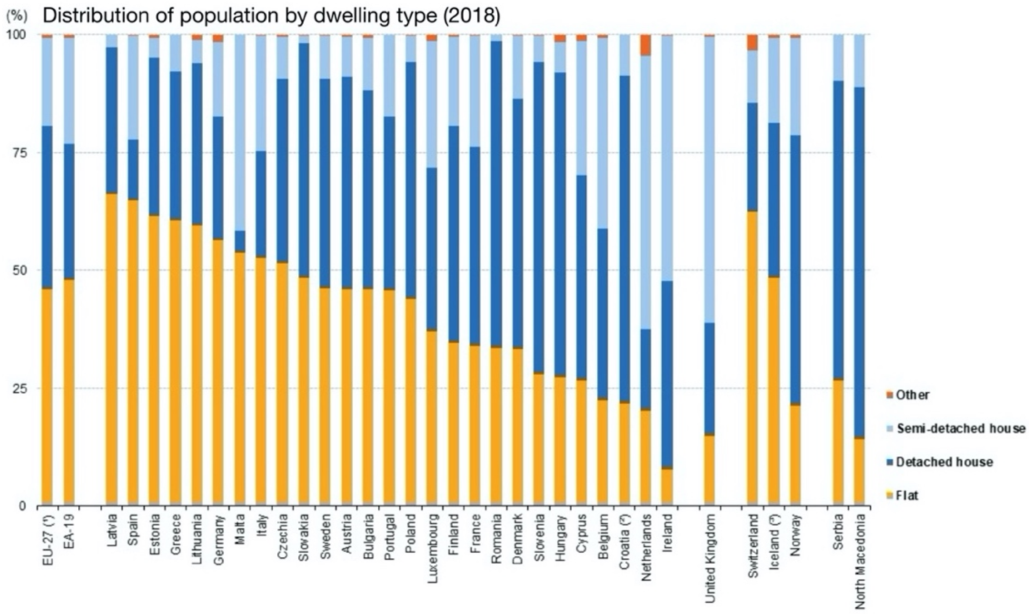


Fig.12. Distribution of population by dwelling type in EU member states in 2018.[6]

As shown in Figure 12, to compare the NC housing stock with that of the RoC and other EU countries, the study examined the 2018 housing statistics available via Eurostat. Figure 12 shows that in 2018, 46% of EU citizens lived in flats, 18,6% lived in semi-detached houses, and 34,7% lived in detached houses. Among the EU member states, the proportion of people living in flats in 2018 was 66,2% in Latvia, 64,9% in Spain, 61,5% in Estonia, 60,6% in Greece, 59,5% in Lithuania, and 62,5% in Switzerland. In the RoC, 27% of people lived in the flats; the present study found that 56% of people in NC lived in flats between 2015–2019, which was significantly higher than in the RoC. The findings prove that political events and demand on the property market by foreign investors led to a notable increase in housing stock in NC.

To properly understand the composition of NC housing stock, a sample distribution according to the housing typology classification was presented in Figure 9. Medium-rise RTBs (i.e., Phase 2) constructed between 1984–1996 were the dominant representative housing typology of the residential-building stock in NC. Currently, the construction projects undertaken by SMEs and large foreigner investors in large quantities utilise similar floor-plan layout designs and scale-of-construction projects, all of which were first introduced under government social-housing schemes. This RTB typology was chosen for the present study to represent a reasonable proportion of the overall housing stock, and the statistical results prove that RTBs comprise a majority (i.e., 56%) of housing stock in NC.

[6] Data on the distribution of population by degree of urbanisation, dwelling type and income group extracted from 2018 EU SILC survey in Eurostat database. Data only represents population and housing stock in the southern territory of the RoC; NC housing stock is not included due to being an isolated *de facto* state.

Current physical condition of social-housing estates

The building-taxonomy analysis determined that the most representative construction type of the investigated RTBs was the single-leaf brick façade, where neither cavity-wall insulation nor any type of insulation material were implemented to reduce energy consumption and optimise thermal comfort. The physical conditions of the building envelopes at the time of this study can be seen in Figures 13 (a) through (d); due to the lifespan of the buildings, these were not constructed according to any kind of building regulations that complied with recommendations from the Chamber of Architects.

Fig.13. (a) Kitchen balconies and double-glazed, aluminium-framed window systems installed by occupants; **(b)** wall-mounted A/C systems installed on building envelope; **(c)** kitchen balcony closure on upper-floor flat; **(d)** structural failures in junction details between columns and beams on roof.

Figure 13 (a) depicts refurbishments that were completed by households wishing to maximise their living spaces. Figure 13 (b) shows the types of cooling appliances that were added by occupants after the completion of the RTBs; service shafts were neither taken into consideration during the decision-making process nor installed during the construction phase of these buildings. Figure 13 (c) illustrates aa kitchen-area balcony closure, which was the most common refurbishment activity; it should be noted that there were no maintenance guidelines to regulate these illegal activities by the households due to a lack of control mechanisms in the social-housing estate. Figure 13 (d) reveals decay on the major structural elements of the RTBs; the *on-site* observations revealed significant cracks on the walls and foundations of all 36 RTBs, which should be further investigated (see **Appendix A.1**). In summary, the buildings that were constructed under the governmental social-housing scheme can be described according to the occupants' energy-consumption patterns, the building's thermal performance and the occupants' thermal-comfort levels. The long-term viability of these RTBs will require the incorporation of energy-efficient and -saving features within the methodologically planned energy-policy framework.

Survey design and Data acquisition

Survey

A standardised questionnaire survey was developed to collect subjective data from the building occupants related to their domestic cooling-energy use and to evaluate the thermal-comfort levels in specific orientations (see **Supplementary Material**); a total of 200 households from 288 flats were randomly selected, which represented the social-housing stock in other municipalities in NC (Black, 2006). A number of research methods were employed in the present study to collect and analyse the research data (Campell & Fiske, 1959; Creswell, 2010; Goodchild *et al.*, 2017). For this reason, a series of quantitative and qualitative research methodologies were considered and designed, as delineated in Table 5, and the RQs were devised according to the research methods that were chosen to generate quantitative and qualitative data.

Table 5
Data required to gather household feedback.

Research Questions	Research Methods	Data	Reason for Methods
RQ-1: Which household socio-demographic characteristics and home-energy performance factors significantly impact household energy use?	Literature review	Qualitative	To obtain accurate primary data collection, answer research objectives and identify occupant socio-demographic information
	Questionnaire survey	Quantitative	
	Semi-structured interviews	Qualitative	
RQ-2: Which occupant energy-consumption behaviours might have an impact on the energy performance of the social-housing estate?	Literature review	Qualitative	To obtain accurate primary data to identify dominant representative occupancy profiles and the significance thereof on home-energy use
	Questionnaire survey	Quantitative	
	Semi-structured interviews	Qualitative	
RQ-3: How can environmental factors affect occupant thermal comfort?	Literature review	Qualitative	To identify the reasons for thermal discomfort and household thermal-sensation votes (TSVs)
	Environmental monitoring	Quantitative	
	Thermal-comfort survey	Quantitative	
	Semi-structured interviews	Quantitative	
RQ-4: How can the present study contribute and inform the design of nearly zero-energy buildings in EU countries?	Questionnaire survey	Quantitative	Mixed interpretations of research findings in both cases
	Semi-structured interviews	Qualitative	

Source: Adapted from (Creswell & Clark, 2011)

As can be seen in Table 5, the questionnaire survey with structured questions and open-ended questions was intended to collect quantitative and qualitative data throughout the standardised means to further probe the details of specific questions. Notably, the data gathered during the qualitative phase of the present study informed the findings of the quantitative phase (Creswell & Clark, 2011). Similarly, the quantitative results demonstrated outcomes related to household energy use and the thermal comfort reported by participants to assist in the findings from the qualitative data (Kieft *et al.*, 2020).

Participants

The subject respondents (*P*-set) for the development of an STS conceptual framework were drawn from all 36 RTBs in the post-war social-housing estate in Famagusta, Cyprus, as was shown in Figure 14 (see **Data set 1** – 3D rendering model of a base case RTB in .rvt file formatting). The area boundaries were defined by the demographics and housing-stock datasets associated with the national census of the Office for National Statistics State Planning Organisation. These secondary-data resources were utilised to determine the representativeness of sampling criteria included in the statistical model; 118 households[7] were recruited through a field investigation, which was then extrapolated to represent NC households.

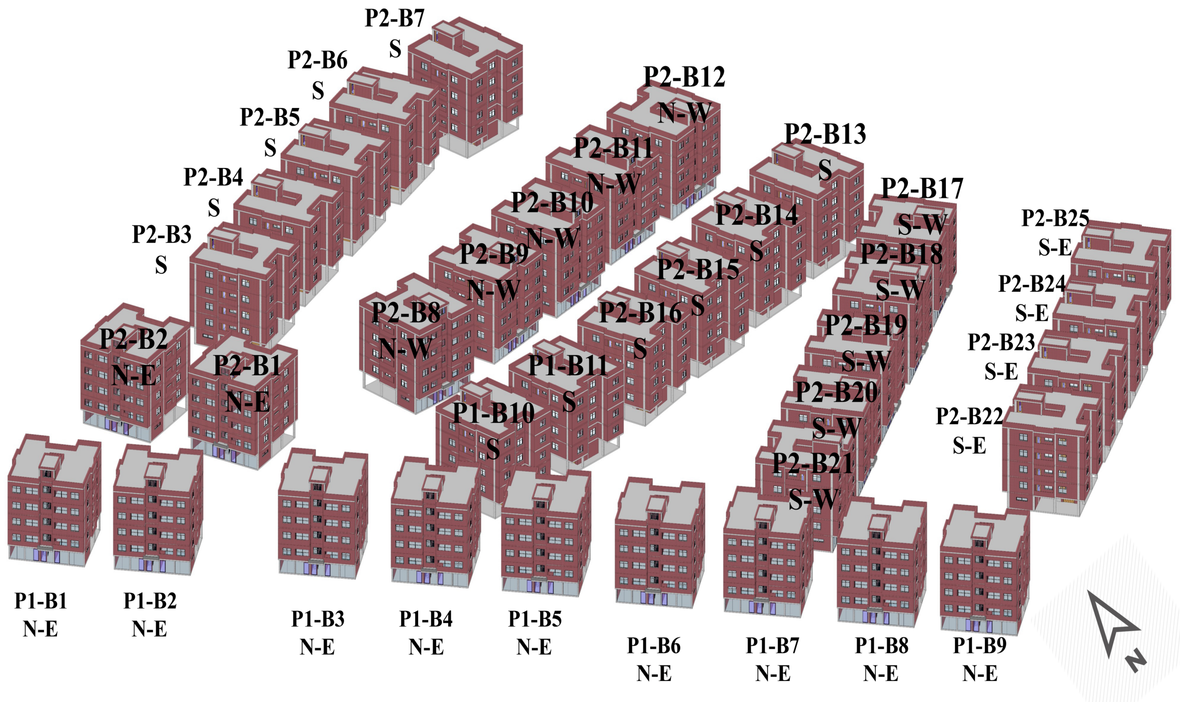


Fig.14. The location map of interviewed RTBs in the social housing development. *P1-B1-11: Phase 1-11, **P2-B1-25, ***N-E: Northeast, N-W: Northwest, S-W: Southwest, S-E: Southeast, S: South

[7] The households represent the flats recruited for the present study. Throughout the questionnaire survey, the researcher requested that the households nominate one of their family members who felt confident responding to the questions.

All variable differences were calculated to identify the worst-case scenario, and the medium-rise RTB estate with the highest total number of flats was selected; this area represented typical neighbourhoods in Nicosia (i.e., urban), Kyrenia (i.e., urban), Omorphou (i.e., rural) and Trikomo (i.e., rural), rather than randomly selected neighbourhoods. The census variables are shown in Table 6.

Table 6
Household socio-demographic characteristics collected from questionnaire survey.

Socio-Demographic Variables	
Tenure type	Year of construction
Housing stock with the council tax band	Household occupancy type (i.e., OP1, OP2 and OP3*)
Housing type	
Space conditioning and different floor-levels	Household energy bills

*Occupancy Patterns: Low occupancy (OP1), moderate occupancy (OP2) and high occupancy (OP3)
Source: Restructured in 2018 according to data from the Office for National Statistics.

As can be seen in Table 6, all variables were related to household socio-demographic characteristics and the type of housing stock that was chosen. To design standard development models and compare them to the city average, the best approach was to only select one case-study location to represent the entire social-housing stock as a base-case scenario (Muresan & Attia, 2017). This deliberate sampling was undertaken to meet the research objective of investigating the effect of household socio-demographic characteristics on home-energy performance in a typical representative neighbourhood (Cross *et al.*, 2017). Each variable was integrated into the statistical model to predict the energy-policy forecasting design scenarios is briefly described below:

i. Ownership status referred to the overall percentage of social-housing stock who were social-house homeowners or private renters.
ii. RTB age referred to the five different archetypes that represented a nationwide sampling for a fraction of overall household population.
iii. Housing typology classification was based on to council tax band in accordance with the council tax rating indicators obtained from the Famagusta municipality.
iv. Household occupancy type referred to the number of family members lived in the same property.
v. Space conditioning of occupied spaces included NV, mixed-mode ventilation, mechanical ventilation heat-recovery systems and A/C split units installed in the property.
vi. Actual household electricity bills obtained from the Cyprus Electricity Authority.

These variables include all available physical built-form and demographic information related to the home at the local level to provide subsequent information for the development of an evidence-based STS conceptual framework. Data collection was guided by a preliminary thematic analysis of key concepts prompted during the interviews with participants. The applied methodology considered the post-war social-housing stock by exploring correlations between the household socio-demographic structure, the actual environmental conditions of the built environment and the thermal-conductivity level of building thermal properties. It should also be noted that semi-structured interviews were only conducted with occupants in selected building typologies so the findings of the present study could be generalised and applied to other post-war social-housing stock in the Republic of Cyprus and in Europe.

Data analysis procedure and set up for statistical analysis

Semi-structured interviews and participant feedback were transcribed and translated. The Statistical Package for Social Sciences (SPSS) Version 25.0 software (IBM: Armonk, NY, U.S.) was utilised to conduct the quantitative analysis; and tests-of-associations were conducted between the numeric factors and the questionnaire responses to join the questionnaire results with the statistical analysis. Previous studies used analysis-of-variance (ANOVA), multivariate analysis-of-variance (MANOVA), Pearson's correlation and regression analyses, and these statistical tests effectively explored correlations within a set of variables designed in the dataset (see **Data set 2** – questionnaire survey inputs developed for the empirical analysis in .sav file formatting). A total of 188 households were successfully recruited, but a 100-sampling size was utilised in the SPSS dataset, because it was determined that 18 households did not provide accurate information when the questionnaire survey was distributed; to avoid a biased interpretation of the field-survey results and to run a parametric-statistical analysis for the present study, these households were disregarded in the dataset.

To run the parametric tests between the dependent and independent variables, the present study adopted the following statistical conventions: an assumed degree-of-confidence interval of 95%, a level of confidence of 0,05, and a significance level (p) of 0,000. Table 7 summarises the data types associated with each of the questionnaire variables and the association test or test statistic that was applied to correlate every variable in the questionnaire survey.

Table 7
Set of determinant factors included in statistical model.

Questionnaire Variables	Data Type	Test of Association
Thermal-comfort preference	Ordinal, Likert scale	Spearman's rho
Thermal sensation	Ordinal, Likert scale	Spearman's rho
Energy-saving awareness (yes or no)	Dichotomous nominal	Point-biserial
Gender	Dichotomous nominal	Point-biserial
Age	Ordinal	Spearman's rho
Education level	Nominal	ANOVA (F-test)
Ethnicity	Nominal	ANOVA (F-test)
Household income	Ordinal	Spearman's rho
Tenure	Nominal	ANOVA (F-test)
Length of residency	Nominal	ANOVA (F-test)
Number of household members	Interval	Pearson's correlation

Table 7 lists all tests-of-association that were employed in the present study. The Benjamin–Hochberg procedure was utilised to adjust the final *p*-values and control the false-discovery rate (FDR) in the statistical analysis; FDR procedures were implemented in the present study to detect discrepancies in the statistical model (Gimpel *et al.*, 2020). The adjusted *p*-values helped to correct for errors that were introduced by multiple comparisons and were a more accurate reflection of significant correlations. The number of iterations was determined using a 95% confidence level for each index and following the methods presented in the present study, thereby ensuring that a random sample of 100 inputs for each variable was generated; this sample size strengthened the analysis and improved the overall precision of estimations of the correlation coefficients (Mertens, 2009).

A 95% interval-confidence level was chosen to measure the impact of variables in the statistical analysis, which was designed in accordance with the RQs. This confidence level is a conventional method, and it was selected for the present study because it is a traditional, well-known, established statistical technical information method; moreover, in the event that an insufficient sample is available for a statistical analysis, it is compatible with the process whereby a small sample size is extrapolated to larger datasets to provide nationally representative data.

It must be noted that the available sample size for the present study was not transformed into a large dataset by multiplying the data to comply with the recommended sampling size. The 100 questionnaires were correctly identified and deemed to be a reasonable fraction of a sampling size to conduct a statistical analysis. Pearson's correlation coefficient was used to identify the difficult-to-quantify home-energy performance factors and occupancy profiles gathered through a questionnaire survey and to interpret data within other field instruments that were implemented in the present study; the *on-site* environmental monitoring and *in-situ* measurements were also included in the dataset, which allowed the researcher to test the determinant factors between household socio-demographic characteristics and the environmental factors of the built environment. Another important reason to conduct a Pearson's correlation analysis was to determine the main dependent factor that influenced the RQs and explore a conventional statistical technique to conduct correlation and regression analyses. The statistical test findings provided additional evidence to identify simulation input parameters for a BES study.

Results and Discussions

The aim of the questionnaire survey was to fully record the age, gender, occupation, ethnicity, socio-demographic characteristics, home energy use and thermal comfort preferences of the occupants (see **Supplementary Material**). We structured the results according to the comprehensive information related to the socio-demographic characteristics of each household that was collected via the survey and feedback that was collected from occupants living in flats of every orientation and floor level, as shown in Table 8.

Table 8
Questionnaire details.

Developmental Stages	Questions
Step 1: ***General background information***	· Number of interviewed RTBs · Unit orientation · Floor level
Step 2: ***Socio-demographic information***	· Gender · Age · Tenancy status and length of residency · Number of household members, including non-family members · Employment activity · Income · Education · Ethnicity · Health status
Step 3: ***Energy-saving awareness***	· Did respondent receive energy advice from any type of public or private institution? · Availability of electricity meter readings and frequency of checks · Did the respondents consider any type of energy-saving methods in their daily activities?
Step 4: ***Household energy use and performance***	· Types of domestic heating appliances, available heating-system controls and frequency of use · Types of domestic cooling appliances, available cooling-system controls and frequency of use
Step 5: ***Occupancy patterns***	· Weekday and weekend heating-consumption patterns · Weekday and weekend cooling-consumption patterns · Window-opening patterns in the summer and winter
Step 6: ***Energy consumption***	· Average amounts of monthly utility bill

A step-by-step statistical analysis was undertaken in accordance with the narrative order of the set of questions that were developed to better understand the multiple levels of household socio-demographic characteristics and home-energy performance. For parametric variables (i.e., the normal form), Pearson's product–moment correlation coefficients were utilised to determine the effects of the occupants' energy-use patterns, and Pearson's correlation coefficients were implemented for continuous variables. Independent sample *t*-tests were applied for the dichotomous variables to determine the importance of household socio-demographic characteristics associated with energy use to identify threshold points and address the EEG. Finally, one-way ANOVA tests were utilised for categorical variables to determine the different levels of energy use among the groups.

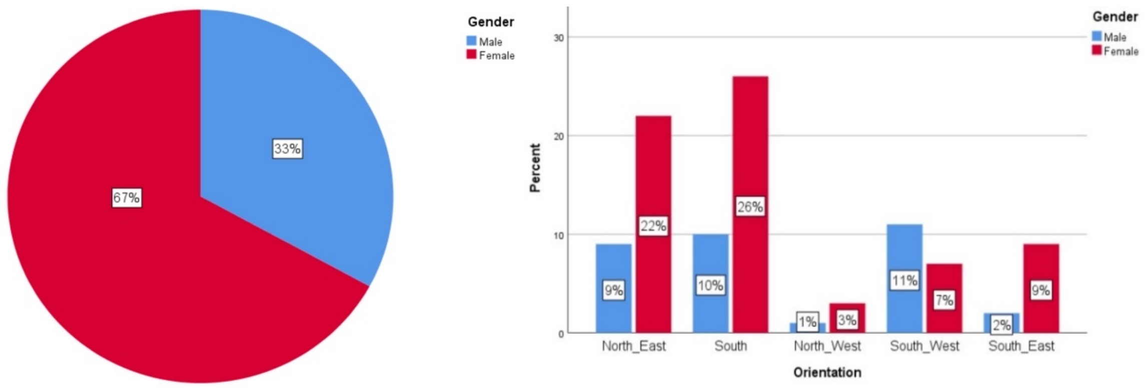
Household socio-demographic characteristics

This section provides basic information about the participants to delineate their demographic characteristics. An analysis of Questions 1–3, 28 and 29, which focused on the gender, age, socio-economic position, level of education, tenancy situation, employment status and health conditions of the household members and aimed to establish the participants' ability to provide quality information for this research, is included herein. The survey was developed as a result of a literature review of studies that were undertaken to investigate the influence of household socio-demographic characteristics on energy use, and it was intended to guide the design process of an STS conceptual framework for effective policymaking decisions in the built environment.

Gender and age distributions

The questionnaires were concurrently administered to the households with the semi-structured interviews. The completed questionnaires revealed that 67% of the responses that were received were from females, and 33% were from males, as shown in Figure 15 (a). It is important to note that the female occupants were more willing to respond to the survey questions on behalf of their family members, compared to the males; this resulted in nearly two times as many responses from female participants than from males.

According to the survey findings, 26% of the female respondents and 10% of the males lived in the south-facing RTBs, 22% of the females and 9% of the males lived in the northeast-facing RTBs, 7% of the females and 11% of the males lived in the southwest-facing RTBs, and 9% of the females and 2% of the males lived in the southeast-facing RTBs; a majority of the northwest-facing RTBs—approximately 88 households—were unoccupied when the survey was undertaken, and only 3% female respondents and 1% of the male respondents lived in these units, as shown in Figure 15 (b).



(a) (b)

Fig.15. Percentage distribution of households by **(a)** gender and **(b)** gender, taking RTB orientation into account.

Starting with the youngest common age, the six age groups that were deemed relevant for the present study were 20–25, 25–35, 35–45, 45–55, 55–65 and 65-years-of-age and older. The percentage distribution of these age groups, which are shown in Figure 16, shows that across the interviewed RTBs, only 1% of the respondents were in the 20–25 age group[8], 8% of the

[8] When this was divided according to gender, background information was provided when the degree of thermal discomfort was assessed.

females and 7% of the males were 25–35 years of age, 12% of the females and 4% of the males were 35–45 years of age, 13% of the females and 7% of the males were 45–55 years of age, 22% of the females and 10% of the males were 55–65 years of age, and 11% of the females and 5% of the male were 65-years-of-age and older.

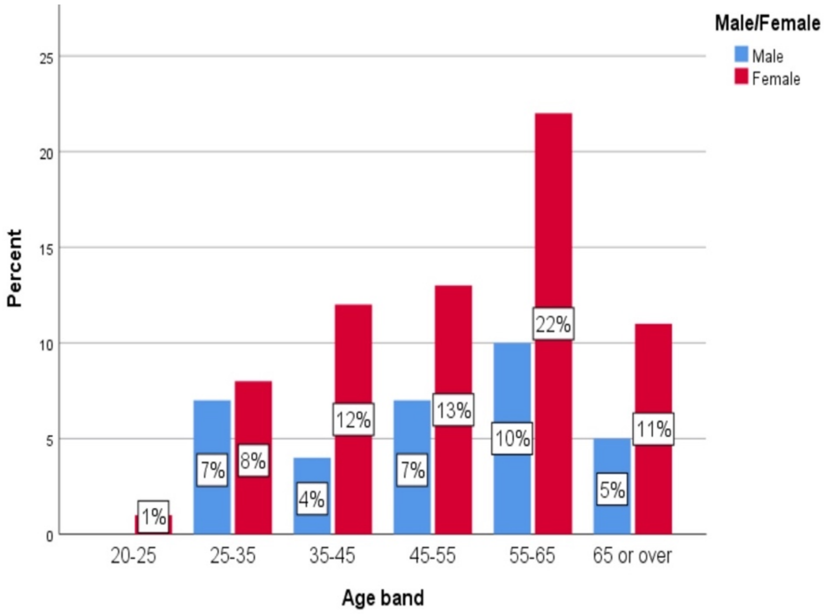


Fig.16. Percentage distribution of age groups by gender.

The frequency distribution of the age groups, which is shown in Figure 17, ranged from 20–80 years of age and older; the mean age was 52,07 years (*SD* = 13,96). The average age group of the respondents ranged from 20–65-years-of-age and older; the mean age was 49,93 years (*SD* = 13,93).

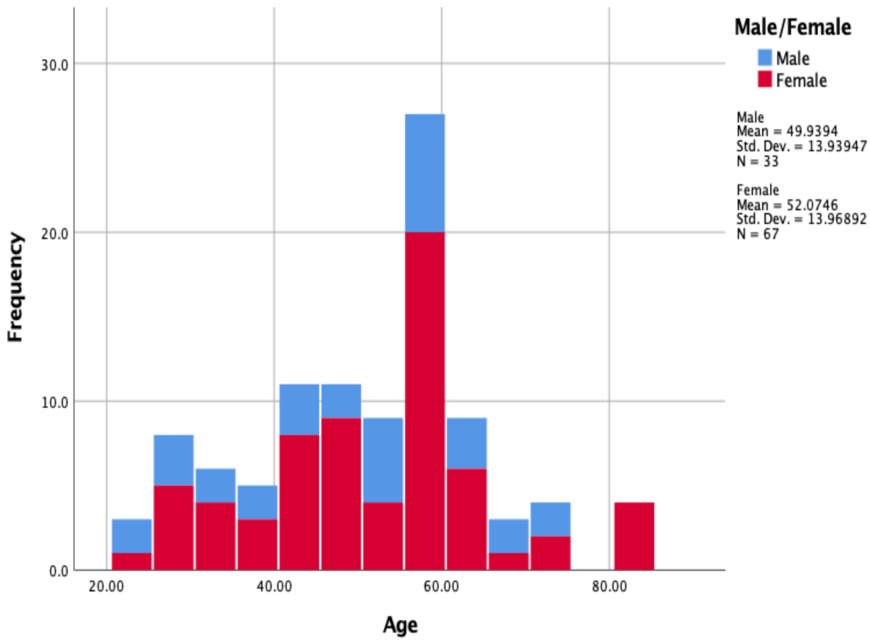


Fig.17. Frequency distribution of age groups by gender.

As shown in Figure 17, the results highlighted a cluster of participants in the 55–65 and 65-years-of-age and older age groups, and a cluster of respondents who were 40–60 years of age was also found. Based on these findings, it was determined that some variations in energy usage according to age group were due to the 22% of respondents who identified as retirees with high pensions and could therefore afford high energy bills; this is why this demographic demonstrated high levels of energy consumption throughout the year.

Research has shown that studies that consider the effects of age on energy consumption discovered significantly correlations with income level, but no evidence related to age has been documented (Indraganti & Rao, 2010). One of the main reasons to include the gender variable is because gender has been shown to affect an individual's degree of thermal discomfort; according to these data, in fact, gender is a dominant factor to consider when assessing thermal-comfort levels. In this study, the respondents' ages were also determined to be a significant variable that affected household-energy use.

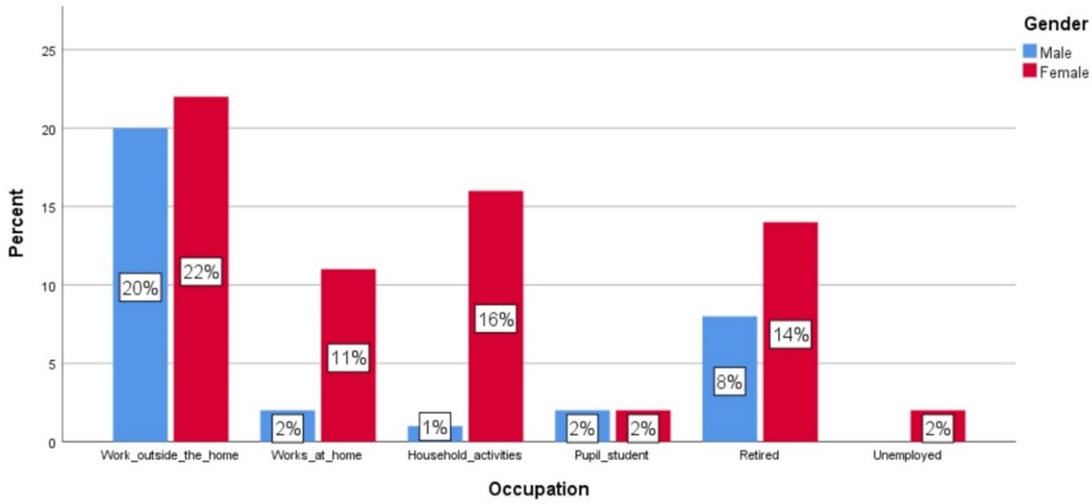


Fig.18. Percentage distribution of employment status by gender.

Figure 18 shows the percentage distribution of the employment status of the respondents, taking gender into account. The employment statuses identified in the surveyed flats were 'working outside of the home', 'working at home', 'doing household activities', 'pupil/student', 'retired', 'semi-retired' and 'unemployed'. Of the female respondents, 22% worked outside of the home, 11% worked at home, 16% were at home and stayed busy with household activities, 14% were retired, and 2% were unemployed. Of the male respondents, 20% worked outside of the home, 2% were students, 7% were retired, and 1% were semi-retired. The results demonstrated that 41% of the female respondents—of whom 11% worked at home, 16% focussed on household activities, and 14% were retired—spent a majority of their time throughout the year inside their dwellings.

The single most striking finding to emerge from the data showed that 2% of the respondents reported that they had no annual income and were therefore vulnerable to being unable to pay their electricity bills. This can be explained by the unemployment rates and income-generating opportunities in this region; for example, some people living in different states in NC are completely dependent on the government for their income and are therefore classified as a vulnerable group. In the present study, however, the employed (i.e., economically active) group included approximately 55% of the total sample size. Notably, only 2% of the economically inactive group suffered from fuel poverty, particularly in the winter. All field-survey analyses in this section are provide subsequent background information to develop evidence-based energy policy design, which is illustrated in Figure 19 (a) through (f).

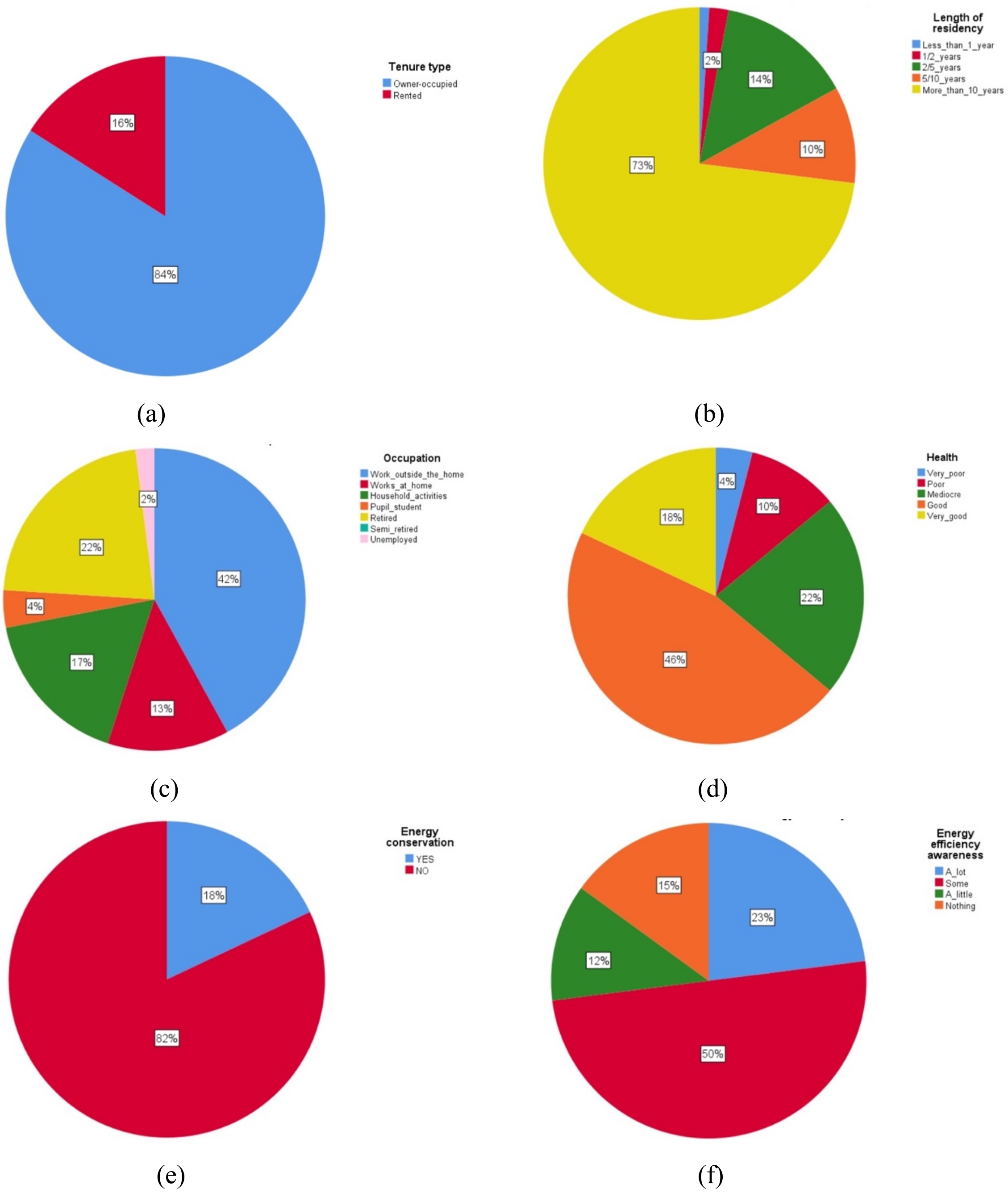


Fig. 19. Selected socio-demographic characteristics of respondents: **(a)** tenancy status; **(b)** length of residency; **(c)** employment status; **(d)** health condition; **(e)** energy conservation; and **(f)** energy-saving awareness.

Figure 19 (a) illustrates that 84% of the sample demographic owned their property, while 16% of the respondents were rental tenants. Of the surveyed households, 73% had lived in their flats for more than 10 years, as shown in Figure 19 (b). It appears as if the respondents' length of residency was correlated with their age group, and a majority of the occupants who owned their property were older than 55 years of age. The number of household members living in these flats also proved to be significant, because it led to a better understanding of the occupants' energy-consumption patterns when their energy bills were analysed, and the amount of heat gain of household members was calculated to validate the survey findings (see **Appendix A.2**).

Figure 19 (c) shows that 42% of the respondents worked outside the home, 13% worked at home, 17% were fully present at home, 4% were students, 20% were retired pensioners, and 2% were unemployed; in all, 63% of the respondents in the sample were economically active. These data correlate with household income levels and the occupants' ability to pay high energy bills that were the result of their desire to create thermally comfort conditions.

The health conditions and genders of the surveyed households are shown in Figure 19 (d): 57% of the female respondents and 29% of the males reported that their health was between mediocre and very good, and 10% of the females and 4% of the males were found to be in poor and very poor health. This was an important statistical finding that correlated with the energy consumption of these households as they attempted to achieve the optimum thermal-comfort conditions for their respective health conditions.

To investigate the energy-saving awareness of each household, the respondents were asked closed-ended questions to determine whether they frequently checked their electricity meter to monitor how much energy they had consumed. As can be seen in Figure 19 (e), 82% of the surveyed households reported that they did not check their energy consumption, and 18% reported that they frequently checked (see **Appendix A.3**).

The households were also asked about their awareness related to energy efficiency; as can be seen in Figure 19 (f), 20% of the respondents reported that they always took energy-saving methods into consideration, 50% of the respondents infrequently thought of energy-saving methods, and 15% never considered energy-saving methods. Based on these results, it can be concluded that the level of awareness related to energy-saving measures not only correlates with level of education, but also income level; many of the households who showed an awareness of energy efficiency were rental tenants and migrant workers with young children who took all possible energy-saving measures into consideration.

Investigating correlations between socio-demographic characteristics and other variables

Correlations between RTB block numbers and other variables

This section explores the relationships among the household socio-demographic characteristics, energy use and other variables collected from the respondents during the field-study period; and a set of questions developed to undertake statistical tests was utilised to determine the correlations between different of socio-demographic characteristics based on the survey findings. The results of the Pearson's correlation test that was carried out for the block numbers, orientations and floor levels of the surveyed flats are shown in Table 9.

Table 9

Means, standard deviations and correlations between respondents (*M* = 17,6, *SD* = 10,5), orientation (*M* = 1,4, *SD* = 1,3) and floor level (*M* = 2,03, *SD* = 1,5).

Variables		Participants	Orientation	Floor Level
Participants	Pearson's correlation	1	0,901**	−0,035
	Significance	—	0,000	0,731
Orientation	Pearson's correlation	0,901**	1	−0,078
	Significance	0,000	—	0,441
Floor Level	Pearson's correlation	−0,035	−0,078	1
	Significance	0,731	0,441	—

RTB scale: 0 (Phase 1, Block 1) to 35 (Phase 2, Block 25)
RTB orientation: 0 (north-east), 1 (south), 2 (north-west), 3 (south-west), 4 (south-east)
Floor levels: 0 (ground); 1 (first); 2 (second); 3 (third); 4 (fourth); 5 (fifth)
**Correlation is significant at 0,01 (two-tailed)

By exploring the correlations between the block number of each surveyed RTB, orientation and floor level, a strong positive correlation ($r = 0{,}901$, $p < 0{,}01$) was found between block number and orientation; this is notable, because a majority of the units had south, south-west and south-east orientations, and the building envelopes of these structures received direct solar radiation due to the RTB orientation. No relationship was observed between block numbers and floor level, which suggests that building orientation is the most important variable.

Table 9 illustrates the Pearson's correlations for orientation and floor level; as expected, the parameters were very close, which suggests that orientation from all directions was highly correlated. A weak negative correlation ($r = -0{,}035$, $p < 0{,}01$) was detected between the different floor levels in several of the interviewed RTBs. The orientation correlation factor ($r = -0{,}078$, $p < 0{,}01$) showed neither a moderate nor strong correlation with the block numbers, which reflects the findings in Table 9. A correlation between orientation and floor level would seem intuitive; however, it is noteworthy that orientation was also shown to be strongly correlated with household socio-demographic characteristics. Actual energy consumption was further determined by a statistical analysis of the household socio-demographic characteristics in the following sections.

Correlations between occupant age and other variables

Occupant age was correlated with economic status, education level, occupation, income and health conditions, as shown in Table 10.

Table 10
Means, standard deviations and correlations between age band ($M = 3,15$, $SD = 1,3$), economic status ($M = 1,7$, $SD = 1,58$), education ($M = 1,6$, $SD = 1,2$), occupation ($M = 1,6$, $SD = 1,7$), income ($M = 2,5$, $SD = 1,2$) and health conditions ($M = 2,6$, $SD = 1,02$).

Research Questions	Age Band	Economic Status	Education Level	Occupa-tion	Income	Health
Q 1.1: What is your age?	1	0,401**	−0,229*	0,454**	0,146	−0,594**
	—	0,000	0,022	0,000	0,147	0,000
Q 1.2: What is your economic status?	0,401**	1	−0,003	0,843**	−0,040	−0,373**
	0,000	—	0,766	0,000	0,693	0,000
Q 1.3: What is your highest level of education?	−0,229*	−0,030	1	−0,142	−0,066	0,057
	0,022	0,766	—	0,159	0,515	0,577
Q 1.4: What is your occupation?	0,454**	0,843**	−0,142	1	−0,094	−0,433**
	0,000	0,000	0,159	—	0,350	0,000
Q 29: What is your monthly income?	0,146	−0,040	−0,066	−0,094	1	0,192
	0,147	0,693	0,515	0,350	—	0,055
Q 28: How is your health in general?	−0,594**	−0,373**	0,057	−0,433**	0,192	1
	0,000	0,000	0,577	0,000	0,055	—

Age band: 0 (20–25) to 5 (65 and over)
Employment status: 0 (full-time) to 4 (pension)
Level of education: 0 (elementary school) to 5 (none)
Occupation: 0 (worked outside home) to 6 (unemployed)
Monthly income: 0 (< 1.500 TL) to 5 (> 10.000 TL)
Health condition: 0 (very poor) to 4 (very good)
*Correlation is significant at 0,05 (two-tailed)
**Correlation is significant at 0,01 (two-tailed)

Table 10 demonstrates that a weak positive correlation ($r = 0,401$, $p < 0,01$) was found between different age bands and economic statuses; the largest respondent age groups were 55–65 and 65-years-of-age and older, and most of those respondents were retired with good pensions, owned their property and were native Cypriots. A moderate negative correlation ($r = -0,229$, $p < 0,01$) was observed between age group and level of education; 82% of the respondents had a high school diploma, 11% had a university degree, and 6% had no diploma; this means that the overall education level of the occupants was moderate.

Correlations between occupant age and tenancy status

As was discussed, 84% of the sample flats were owner-occupied, and 16% of the households were tenants; it is important to explore correlations between household age and other variables, because meaningful correlations will facilitate an assessment of occupancy patterns and domestic energy use, which will in turn provide information to assess overheating risk and thermal comfort. Table 11 illustrates the Pearson's rank correlations between various household age bands and the tenancy statuses of the respondents; the findings validate the data and provide a better understanding of the correlations between various household socio-demographic characteristics and the respondents' degree of thermal discomfort.

Table 11

Means, standard deviations and correlations between household age band ($M = 3,15$, $SD = 1,3$), tenancy status ($M = 0,16$, $SD = 0,36$) and length of residency ($M = 3,52$, $SD = 0,88$).

Research Questions	Age Band	Tenancy Status	Length of Residency
Q 1.1: What is your age?	1	−0,355**	0,616**
	—	0,000	0,000
Q 3: Do you own or rent your dwelling?	−0,355**	1	−0,570**
	0,000	—	0,000
Q 2: How many years have you lived in this flat?	0,616**	−0,570**	1
	0,000	0,000	—

Age band: 0 (20–25) to 5 (65 and over)
Tenancy type: 0 (owner-occupied) or 1 (rented)
Years lived in house: 0 (less than one year) to 1 (more than 10 years)
**Correlation is significant at 0,01 (two-tailed)

In this parametric test, age band and tenancy status were correlated, and a moderate negative correlation ($r = -0,355$, $p < 0,01$) was found, because a majority of the occupants were the first legal owners of the condominiums in the RTBs. Age band and length of residency were also correlated, and because the rental tenants tended to be younger, a strong positive correlation ($r = 0,616$, $p < 0,01$) was found between these variables. Finally, a moderate negative correlation ($r = -0,355$, $p < 0,01$) was discerned between tenancy status and length of residency, because a majority of the occupants were the original legal owners and had lived in their flats for more than 10 years.

Correlations between energy-saving awareness and income

This section includes an analysis of Questions 4–7, which assessed household energy-use awareness while taking household income levels into account. This portion of the survey investigated whether the occupants obtained sufficient support in energy conservation, and their energy-efficiency awareness were also explored. The findings revealed that 69% of the respondents paid their monthly energy bills at the higher rate[9], and 31% paid at the lower rate; this result can be correlated with household income level and the number of family members living in the surveyed flats. Table 12 demonstrates the Pearson's rank-correlation analysis

[9] Cyprus Electricity Authority categorises energy consumption on weekdays in the winter period (November 1 through May 31) as follows: non-peak hours between 22:00–07:00 at 0,658 TL/kWh; working hours between 07:00–17:00 at 0,9873 TL/kWh; and peak hours between 17:00–22:00 at 1,2908 TL/kWh.

Tariffs are implemented on weekdays in the summer period (June 1 through October 31) as follows: non-peak hours 23:00–09:00 at 0,6508 TL/kWh; working hours 18:00–23:00 at 0,9873 TL/kWh; and peak hours 09:00–18:00 at 1,2908 TL/kWh.

conclusions that revealed a correlation between household income level and occupant awareness of energy consumption.

Table 12

Means, standard deviations and correlations between household income ($M = 2{,}5$, $SD = 1{,}2$), energy consumption ($M = 0{,}69$, $SD = 0{,}46$), energy advice ($M = 1{,}67$, $SD = 0{,}76$), energy consumption ($M = 0{,}82$, $SD = 0{,}38$) and energy savings ($M = 1{,}19$, $SD = 0{,}96$).

Research Questions	Income	Energy Consump-tion	Energy Advice	Energy Usage	Energy Savings
Q 29: What is your monthly income?	1	0,277**	−0,026	−0,009	−0,155
	—	0,005	0,800	0,927	0,123
Q 30: How much electricity (in kWh) did you consume in May through September according to this last overview?	0,277**	1	−0,092	−0,089	0,201*
	0,005	—	0,365	−0,379	0,045
Q 31: Have you received advice on how to reduce your energy bills?	−0,026	−0,092	1	0,583**	0,100
	0,800	0,365	—	0,000	0,323
Q 4: Do you check your use of electricity by taking frequent meter readings?	−0,009	−0,089	0,583**	1	0,284**
	0,927	0,379	0,000	—	0,004
Q 6: Do you know anything about energy-saving methods?	−0,155	0,201*	0,100	0,284**	1
	0,123	0,045	0,323	0,004	—

Monthly income: 0 (< 1.500 TL) to 5 (> 10.000 TL)
Household-energy cost rates between May and September: 0 (low rate) to 1 (high rate)
Received energy advice and wish to conserve energy: 0 (yes) or 1 (no)
Frequently check electricity meter: 0 (yes) or 1 (no)
Awareness of energy-saving methods: 0 (always) to 3 (never)
*Correlation is significant at 0,05 (two-tailed)
**Correlation is significant at 0,01 (two-tailed)

A moderate positive correlation ($r = 0{,}277$, $p < 0{,}01$) was found between income and energy consumption, because 69% of the households earned a moderate annual income and were therefore able to pay higher energy bills. The correlation between household income and whether the occupants had received information from any public or private authorities regarding energy-saving measures was examined, and a strong positive correlation ($r = 0{,}583$, $p < 0{,}01$) was found between receiving energy advice and checking the electricity meter; this is because a significant number of the surveyed households were low-income renting tenants or migrant workers who closely monitored their expenditures. This indicated that rented householders prefer to use less energy and save money through various everyday actions.

Respondents were asked about their level of awareness related to energy-saving methods and whether they applied these in their everyday lives. A moderate positive correlation ($r = 0{,}284$, $p < 0{,}01$) was detected between knowledge of energy-saving methods and the habit of checking electricity meters, and there was also a moderate positive correlation ($r = 0{,}201$, $p < 0{,}05$) between energy-saving methods and energy consumption; 23% of the renting respondents reported that they always checked their electricity meter, and 50% of the renting respondents checked 'sometimes'.

One occupant claimed an awareness and knowledge of energy conservation due to their expertise in electrical engineering; their family was unable to practice most energy-saving measures in their daily family lives, however, because of the number of people living in their dwelling. This interviewee also expressed their belief that the thermal comfort and health of their grandchildren were more important than their annual energy bill.

Another respondent alluded to the notion that energy conservation could help them reduce their energy usage; they reported, however, that because of the absence of thermal insulation and air leakage through the aluminium-framed, single-glazed windows, they felt thermally uncomfortable in the summer and preferred to turn on their air conditioning system. A common view among the interviewees was that the thermal comfort of their family members was an important factor that led them to want to provide an optimal indoor living environment, which resulted in excessively high energy bills throughout the year. The deeper relationship between household socio-demographic characteristics and associations with survey findings are discussed in the following section to validate survey findings.

Validation of correlations between socio-demographic characteristics and other variables

Independent samples *t*-tests were used to determine energy-use variations in different groups with dichotomous variables, and an analysis-of-variance (ANOVA) test was employed to determine the different levels of in energy use among the groups for categorical variables. Even though household socio-demographic characteristics were taken into account to determine the data collection that would validate the survey findings, these factors could affect the representability of the input parameters.

ANOVA: Age and other variables

To validate the survey findings, parametric tests between household age and other variables were undertaken. A one-way ANOVA test was conducted to predict discrepancies between the household age as the dependent variable and economic status and education level. Figure 20 (a) through (d) reveal the statistical results of a one-way ANOVA test frequency distribution of these socio-demographic factors.

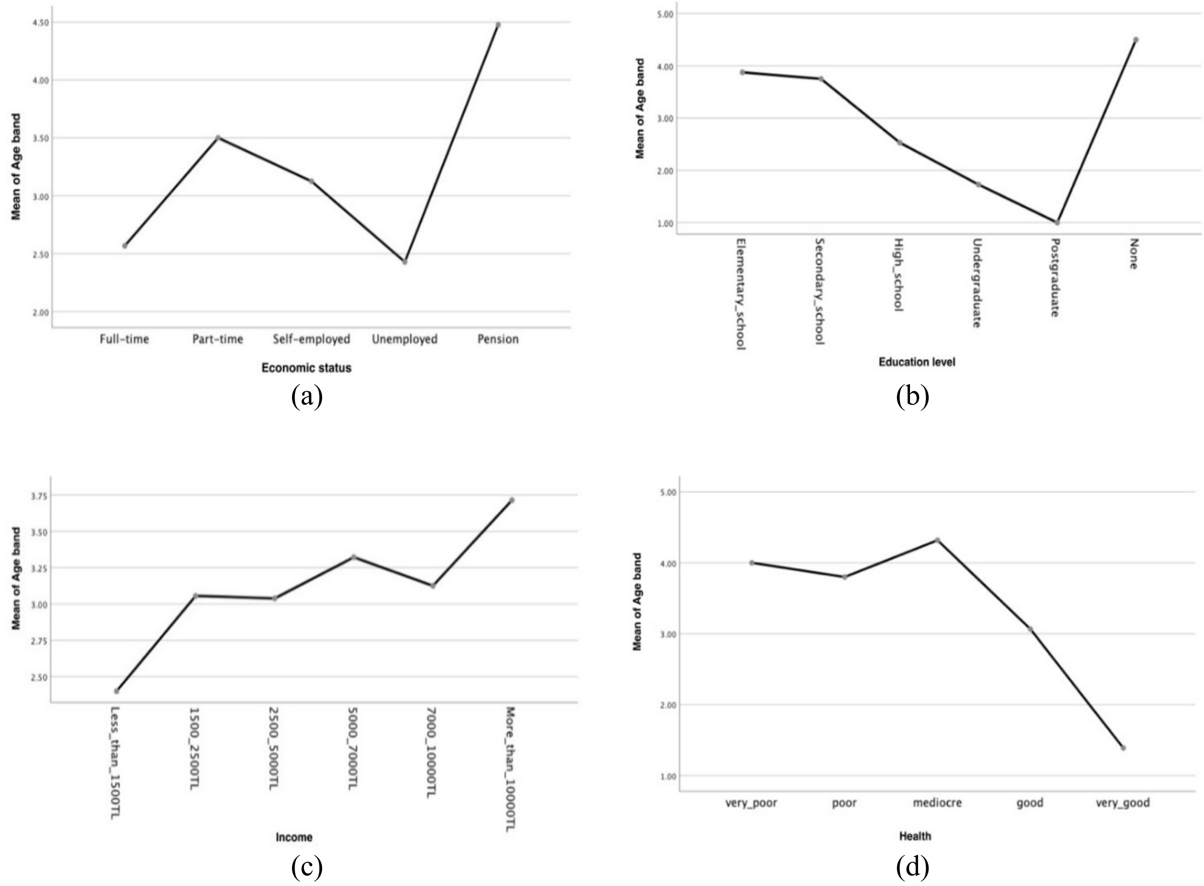


Fig.20. Statistical one-way ANOVA test frequency distribution between household age as dependent variable and **(a)** economic status, **(b)** education level, **(c)** income and **(d)** health condition.

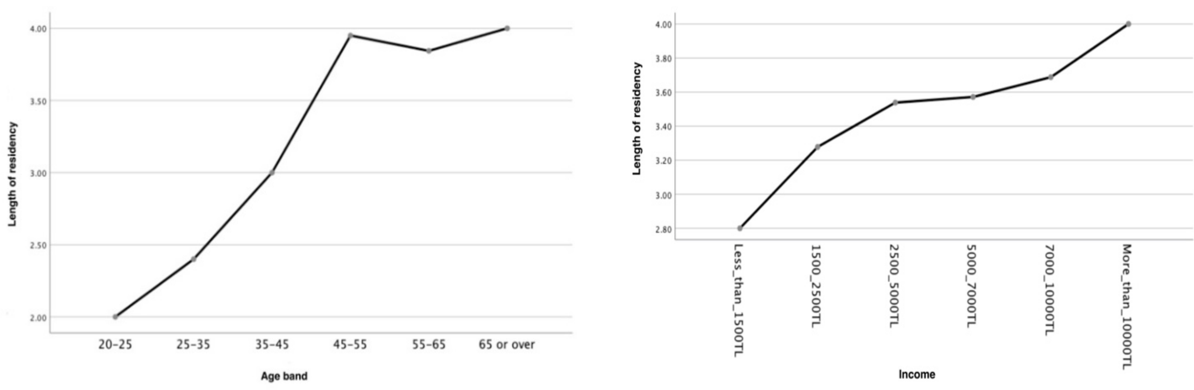
Figure 20 (a) shows that the unemployment rate was very low ($f < 2,50$), while the pensioner rate was the highest at $f = 4,50$; these different peaks were because a majority of the households were 55–65 years of age, which was validated by the correlation analysis. Figure 20 (b) shows the education levels of the households: The lowest peak depicts post-graduate education at $f = 1,0$, the highest peak shows the participants with moderate education (i.e., a high school diploma) at $f = 4,0$, and the second-highest peak shows households with little-to-no education at $f = 4,50$. There was a moderate positive correlation ($r = 0,454$, $p < 0,01$) between age and occupation, because most of the family members in most of the households were employed.

Notably, since the annual incomes of a majority of the households was above average, no significant correlation was observed between age and income. There was a strong negative correlation ($r = -0,594$, $p < 0,01$) between age and the health condition of the households; a majority of the respondents were middle-aged or older, but only 14% of the respondents reported that their health was poor or very poor. Based on the correlation results, it can be inferred that the occupants' socio-demographic characteristics influenced their domestic-energy use and affected their overheating risk and thermal comfort assessments.

Figure 20 (c) shows household income in relation to age. The lowest income peak was less than 1.500 TL per month, but as the respondents' ages increased, their income also reached the highest peak at $f = 3{,}75$; a majority of the households that were 55–65 years of age were retirees with high pensions. Figure 19 (d) shows the health conditions of the households: the highest peak was at mediocre and fairly good ($f > 4{,}0$), because a majority of occupants were newly retired and still active; the lowest peak revealed health conditions that were very good ($f < 2{,}0$), because few occupants were young.

Length of residency and Income

To develop scientific ground for the adopted STS conceptual framework, a one-way ANOVA test was undertaken to explore correlations between the lengths of residency and the income levels of the interviewed households. Figures 21 (a) and (b) demonstrate the statistical result of a one-way ANOVA test frequency distribution of socio-demographic factors and the impacts thereof on the decision-making process related to the implementation of the energy performance certificates (EPCs) in the residential sector.



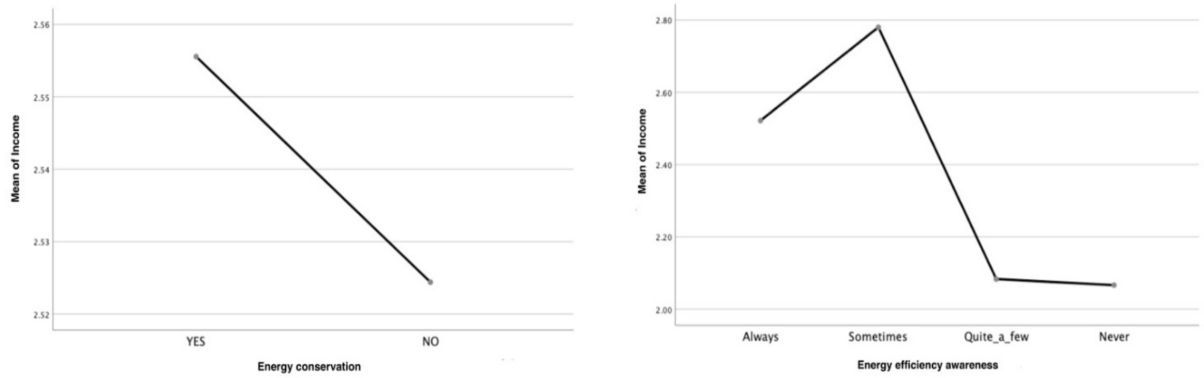
(a) (b)

Fig.21. Statistical one-way ANOVA test frequency distribution between length of residency as the dependent variable and **(a)** age group and **(b)** income.

Figure 21 (a) shows the age band of the households in relation to their length of residency. The highest peak in length-of-residency showed occupants who were 45–55 years of age at $f > 4{,}0$; occupants who were 65-years-of-age and older were at $f = 4{,}0$. As was discussed, this was because the occupants in this age group were the first legal owners of these flats; hence, as the occupants' age and length of residency increased, their income also increased at a rate of $f = 2{,}80$ to $f = 4{,}0$, as shown in Figure 21 (b).

ANOVA: Energy-saving awareness and Income

A one-way ANOVA test was also conducted to further interpret the correlations between the binary and ordinary variables and analyse the relationships within these categories in greater detail. Several moderate and strong correlations were found between household electricity-meter-reading habits and the occupants' awareness of energy-saving measures. The means plot diagram below shows the significant differences between a number of variables and the different categories of the chosen factors (i.e., ‘Do you check your use of electricity by frequently taking meter readings?’ and ‘Do you know anything about energy-saving methods?’). Figures 22 (a) and (b) demonstrate the statistical results of the one-way ANOVA test frequency distribution on household energy-saving awareness.



(a) (b)

Fig.22. One-way ANOVA test frequency distribution between household income as the dependent variable and **(a)** electricity-meter-reading habits and **(b)** awareness of energy-saving measures.

Figures 22 (a) and (b) illustrate the relationship between the different answers related to the meter-reading-frequency and energy-saving-awareness questions. The results showed that at $f < 2{,}53$, households with moderate-to-high incomes checked their electricity meters less frequently; while those with average or below-average incomes preferred to check their electricity meter frequently—at $f > 2{,}55$—to control their monthly expenditures. It was also noted that the households’ electricity-meter-reading habits were not related to their level of education. The present study found that each household’s habitual behaviour associated with checking their electricity meter was related to the ethnic background and tenancy status.

In the general survey, 50% reported awareness of energy-saving measures; of these occupants, 23% reported that they always tried to save energy, and 15% reported that they did not take any energy-saving measures in their homes. This highlights the remarkably high correlation between each household’s income level and their awareness of energy-saving measures: The lowest peak depicts ‘quite a few’ and ‘never’ answers related to the use of energy-saving methods at $f < 2{,}20$, the highest peak shows that respondents answered ‘sometimes’ at $f = 2{,}80$, and the second-highest peak shows that respondents answered ‘always’ at $f < 2{,}60$. Based on the survey results and these correlations, household income plays a crucial role in the consideration of energy-saving measures. However, no moderate or strong correlations were found with the household education level and their awareness of energy-saving measures; this could be due to their understanding that reduced energy use is directly related to reduced energy bills.

Household socio-demographic characteristics and Thermal comfort

The second part of the questionnaire followed up on the questionnaire survey developed for the field study focussed on the potential effects of occupant thermal comfort preferences, while taking household energy use and the energy performance of the units into account (see **Supplementary Material**). The survey designed for this portion of the study was intended to map the occupants' real-life energy-use experiences by taking the significance of ingrained habits related to household energy use and comfort-level preferences into account to help residents manage their home-energy use after their unit is retrofitted. Figures 23 and 24 illustrate the determinant factors that were used to analyse the households' thermal comfort in relation to the socio-demographic characteristics of the occupants.

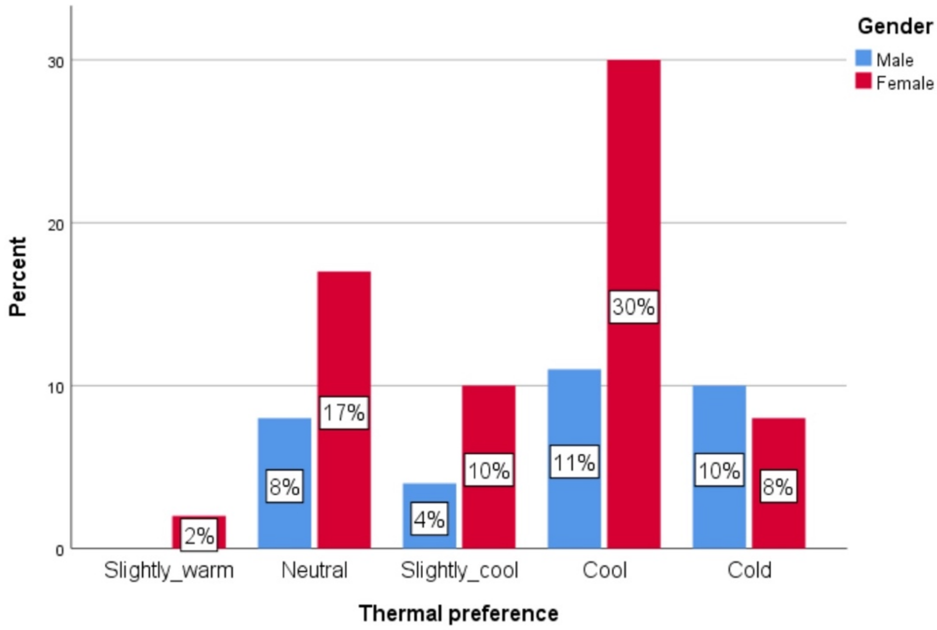


Fig.23. Percentage distribution of household thermal-comfort preferences by gender.

As shown in Figure 23, the respondents' TPVs were distributed in such a way that 10% of the male respondents and 8% of the females indicated that they preferred to feel cold, 11% of the males and 30% of the females preferred to feel cool, 4% of the male and 10% of the female respondents preferred to feel slightly cool, 8% of male and 17% of female respondents preferred to feel neutral, and 2% of the female and none of the male respondents preferred to feel slightly warm. The mean TPV was 0,7, which means that on average, the occupants preferred to feel cool in their living rooms in the summer. According to the general survey, 33% of the male participants and 67% of the females who were 25–83-years-of-age were recruited. It is evident from the results that the female participants' preferences in the TSVs were the dominant factor when assessing the occupants' thermal-comfort levels and understanding the overheating risks in their homes in the summer.

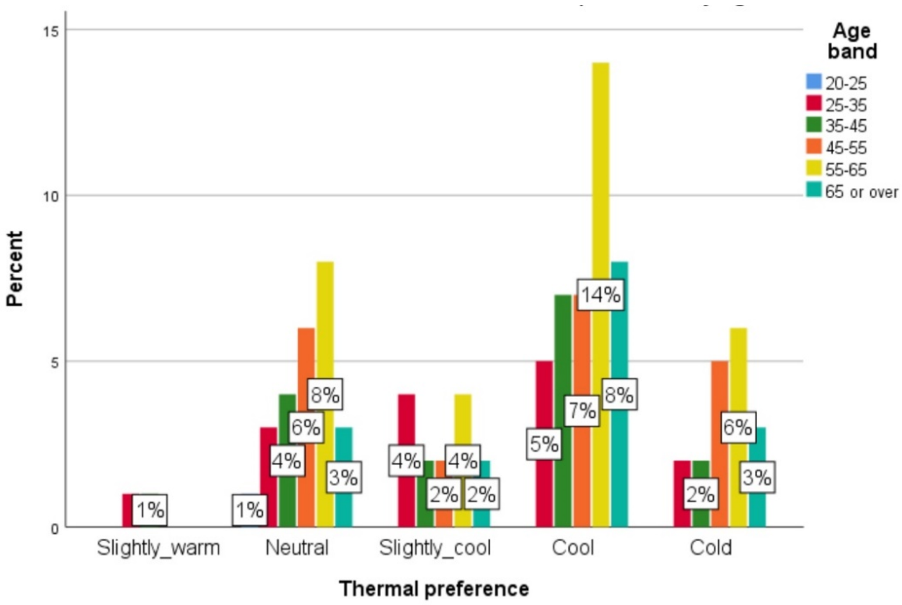


Fig.24. Percentage distribution of household thermal-comfort preferences according to different age bands.

Figure 24 shows the distribution of the household TPVs who voted on the ASHRAE seven-point thermal-comfort preference scale. It was determined that of the respondents who were 55–65 years of age, 6% preferred to feel cold, 14% preferred to feel cool, 4% preferred to feel slightly cool, and 8% preferred to feel neutral; this was because the indoor-air temperatures in all the surveyed flats ranged from 25–35°C, which did not correlate with the *CIBSE Guide A* benchmarks that assessed temperatures above 25°C as the overheating limit in residential buildings (CIBSE, 2015).

Of the respondents who were 45–55 years of age, 5% preferred to feel cold, 7% preferred to feel cool, 2% preferred to feel slightly cool, and 6% preferred to feel neutral. Of the respondents who were 35–45 years of age, 2% preferred to feel cold, 7% preferred to feel cool, 2% preferred to feel slightly cool, and 4% preferred to feel neutral. Of the respondents who were 25–35 years of age, 2% preferred to feel cold, 5% preferred to feel cool, 3% preferred to feel neutral, and 1% preferred to feel slightly warm. Respondents in the top-floor northeast-facing RTBs commented that their indoor thermal conditions were significantly improved at night by the high-speed prevailing winds that blew through their living rooms; this environmental condition allowed for good-quality natural ventilation (NV) in occupied spaces at night and is why so few of the respondents expressed a preference for feeling slightly warm. There were no TPVs observed in the warm or hot bands of the thermal preference scale, because the questionnaire survey was conducted in the summer (Olesen & Parsons, 2002).

There was a noticeable response related to thermal preferences across the interviewed households in the summer, with a total of 24% of occupants who were 55–65 years of age reporting a preference for feeling slightly cool, cool or cold. There was a noticeable shift in the thermal preferences in the 45–55 age group, however, with a total of 8% of the respondents stating that they preferred to feel neutral or slightly cool.

Investigating correlations between socio-demographic characteristics and thermal comfort

The questionnaire aimed to document the real-life experiences of different households related to the quality of the indoor-air temperature in their homes and identify the determinant factors of thermal-discomfort problems to map out the overall energy performance of all indoor occupied spaces. It should be noted that even though the individuals in the sample were all different, the physical characteristics of their RTBs were the same, and their socio-demographic makeup was largely comparable. This highlights the fact that their survey responses were the main determinant factors to consider when analysing the relationships between the different variables, and various methods were applied on the development of the EPCs.

Correlations between reasons for thermal discomfort and physical conditions

Pearson's correlation tests were carried out to investigate the main reasons for thermal discomfort, taking household genders into consideration, as shown in Table 13.

Table 13

Means, standard deviations and correlations between reasons for thermal discomfort ($M = 3{,}2$, $SD = 2{,}64$), household age band ($M = 3{,}15$, $SD = 1{,}34$), orientation ($M = 1{,}42$, $SD = 1{,}37$) and floor level ($M = 2{,}03$, $SD = 1{,}52$).

Research Questions	Discomfort	Age Band	Orientation	Floor Level
Q 35: How would you best describe the source of your thermal discomfort?	1	−0,185	−0,030	0,218*
	—	0,065	0,767	0,029
Age band	−0,0185	1	0,178	−0,229*
	0,065	—	0,076	0,022
Orientation	−0,030	0,178	1	−0,078
	0,767	0,076	—	0,441
Floor Level	0,218*	−0,229*	−0,078	1
	0,029	0,022	0,441	—

Age band: 0 (20–25) to 5 (65 and over)
RTB orientation: 0 (north-east); 1 (south); 2 (north-west); 3 (south-west); and 4 (south-east)
Floor levels: 0 (ground); 1 (first); 2 (second); 3 (third); 4 (fourth); and 5 (fifth)
*Correlation is significant at 0,05 (two-tailed)

It is important to consider the occupant age bands in the Pearson's rank-correlation analysis, because 48% of the households were in the 55–65 or 65-and-older age groups. It is also important to consider the impact of age on thermal comfort in the surveyed flats; since 48% of the households were elderly, a moderate negative correlation ($r = -0{,}229$, $p < 0{,}05$) was found between occupant age and complaints related to thermal discomfort. According to the survey, 24% of the occupants complained about high humidity in the southwest-facing RTBs in the summer, and 17% complained about incoming sun; this suggests that occupants experienced thermally uncomfortable conditions due to high outdoor-air temperatures and humid climate conditions.

The orientation analysis concluded that even though there was no significant correlation between the different floor levels and reasons for thermal discomfort, a moderate positive correlation ($r = 0{,}218$, $p < 0{,}05$) was found. This is due to poorly designed windows in the RTBs, which prevent NV throughout the indoor occupied spaces; this, in turn, leads to a difference of 2–3°C between the ground- and top-floor flats. Moreover, the orientation analysis determined that the different floor levels played a crucial role in the habitual adaptive behaviours of each household related to thermal comfort (Corrado & Ballarini, 2016). Interestingly, the correlation analysis concluded that RTB orientation was not a significant factor, even though the initial survey findings determined that orientation significantly affected energy consumption, which correlated with the findings related to the RTBs experiencing overheating risk (Csoknyai *et al.*, 2016). It is important to highlight the correlation of thermal discomfort with both the health statuses of each household and external climate conditions.

Correlations between reasons for thermal discomfort and socio-demographic characteristics

The occupants' health conditions were correlated with decisions related to their TPVs, and their ages and genders of each household were also correlated with their thermal comfort, as shown in Table 14.

Table 14

Means, standard deviations and correlations between reasons for thermal discomfort ($M = 3{,}2$, $SD = 2{,}64$), household age band ($M = 3{,}15$, $SD = 1{,}34$), gender ($M = 0{,}67$, $SD = 0{,}47$) and health conditions ($M = 2{,}6$, $SD = 1{,}02$).

Research Questions	Discomfort	Age Band	Gender	Health Conditions
Q 35: How would you best describe the source of your thermal discomfort?	1	−0,185	0,080	0,148
	—	0,065	0,427	0,141
Age band	−0,185	1	0,047	−0,594**
	0,065	—	0,643	0,000
Gender	0,080	0,047	1	0,003
	0,427	0,643	—	0,980
Q 28: How is your health in general?	0,148	−0,594**	0,003	1
	0,141	0,000	0,980	—

Age band: 0 (20–25) to 5 (65 and over)
Gender: 0 (male) or 1 (female)
Health condition: 0 (very poor) to 4 (very good)
**Correlation is significant at 0,01 (two-tailed)

According to Table 14, it appears that thermal discomfort is correlated with the age, gender and health conditions of each household. While a strong correlation between age and gender related to thermal discomfort was not found, there was a strong positive correlation ($r = 0{,}594$,

$p < 0{,}01$) between age and health condition, because 48% of the households were 55–65 or 65-years-of-age and older. A total of 14% of the respondents reported that their health was poor-to-very-poor, and 21% reported that their health was mediocre. The occupants' health conditions played an important role when determining their acceptable degrees of thermal discomfort. It was also noted that the building-fabric thermal performance of the RTBs was influenced thermal discomfort; importantly, the household socio-demographic characteristics were shown to be the most significant factor.

Forecasting Household Energy Use

To validate the simulation findings and address building-energy-performance gaps, the present study examined household energy bills and developed a prediction for a large sampling size through the main determinant factors that were discerned and recorded from the feed-forward interviews; the sampling size was limited to a 1.000 representative population. This statistical method was intended to provide evidence-based data and confirm the building-energy simulation (BES) model. Figures 25 (a) through (g) detail household energy consumption in the summer and winter, taking the household socio-demographic characteristics.

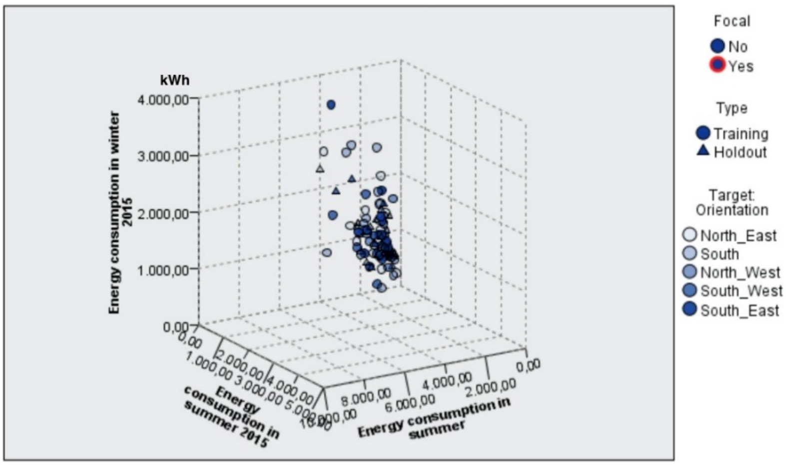


Fig.25. (a): Distribution of energy consumption by RTB orientation.

The household energy-consumption patterns in the southeast-oriented RTBs, which are shown in Figure 25 (a), were predominantly between 900–1.200 kWh; the southwest-facing RTBs was within the range of 1.000–1.800 kWh; and the south-facing RTBs consumed between 2.000–2.800 kWh. Of the participants, 36% were recruited from south-oriented RTBs, and 31% lived in northeast-facing RTBs. As it relates to the portion of the sampling size that lived in the south- and northeast-oriented units, the northeast-facing flats consumed more energy in the winter, and the south-facing flats consumed more energy in the summer; a similar energy-consumption pattern was detected in the BES analysis. This confirms that orientation is a determinant factor of household energy consumption, but because this physical feature is not limited to the built environment, household socio-demographic characteristics should also be considered.

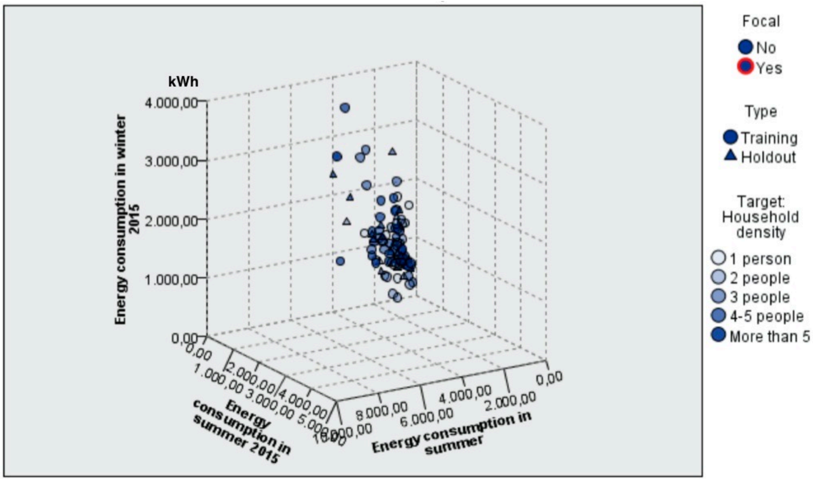


Fig.25. (b): Distribution of energy consumption by household density.

Figure 25 (b) illustrates the energy consumption according to the number of occupants in each household. For units with more than five occupants, which were designated as the OP3 (i.e., high) occupancy type in the BES model, energy usage was 900–1.200 kWh. Flats occupied by 4–5 people, which represented the OP2 (i.e., moderate) occupancy type, consumed between 900–2.800 kWh of energy. Flats occupied with three people consumed as much as 2.800,0 kWh of energy; these were owner-occupiers who were 65-years-of-age and older and in the high-income group (i.e., more than 10.000 TL), and they represented 16% of the sampling size. The occupants who reported high energy consumption were in the 55–65 age band and represented 32% of the sampling size, and these residents looked after their grandchildren in their homes on the weekends; the BES analysis also determined that this group represented the OP2 (i.e., moderate) occupancy type. These findings confirm that occupancy patterns are a determinant factor to consider when calibrating building energy performance for the development of energy-performance certificates (EPCs) in accordance with Energy Performance Buildings Directives (EPBD) recommendations.

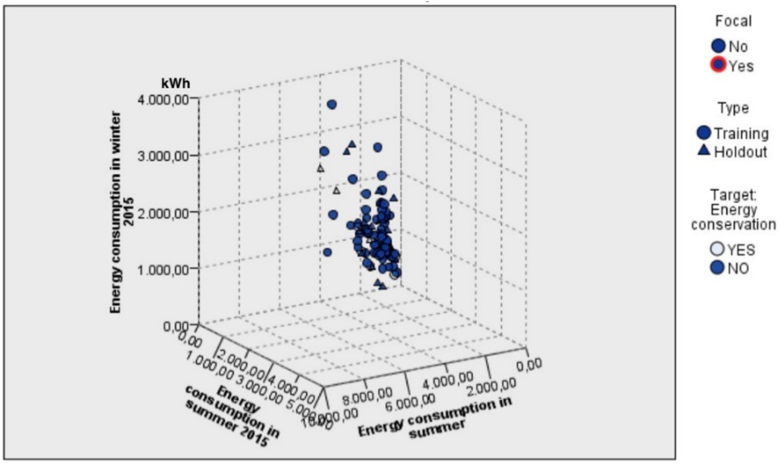


Fig. 25. (c): Distribution of energy consumption by energy conservation.

To prove the validity of the high energy consumption that was predicted in the BES, the present study examined data related to the energy-conservation of respondent households obtained through the questionnaire survey; the results of this analysis are shown in Figure 25 (c). Overall household energy consumption ranged between 900–3.800 kWh, with a majority of households in the 500–1.700 kWh range; this suggests that most of the households consumed greater amounts of energy than the national average, because of the socio-economic status of the occupants and the effect of the households' cultural assets (i.e., high-quality lifestyle, continuous presence at home) on their behaviour and their expectations for comfortable indoor-air temperatures.

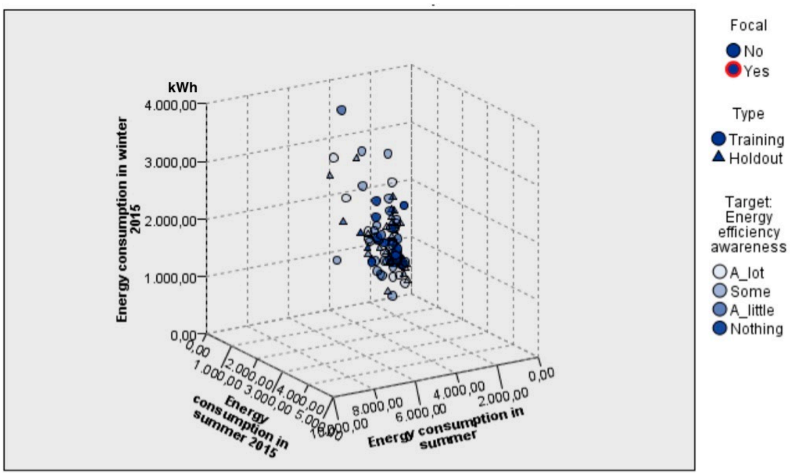


Fig.25. (d): Distribution of energy consumption by energy-efficiency awareness.

According to Figure 25 (d), which shows energy consumption in light of each household's awareness of energy-efficiency measures (EEMs), 15% of the households reported that they had no knowledge of energy efficiency and consumed between 900–1.800 kWh of energy, 12% claimed to have 'a little' awareness of this topic and utilised between 200–2.800 kWh, 50% stated that they had 'some' knowledge of energy efficiency and consumed between 900–2.100 kWh, and 23% asserted that they knew 'a lot' and used 500 kWh or less. After evaluating these results, it can be concluded that household energy consumption could potentially decrease when the occupants' knowledge of EEMs is increased.

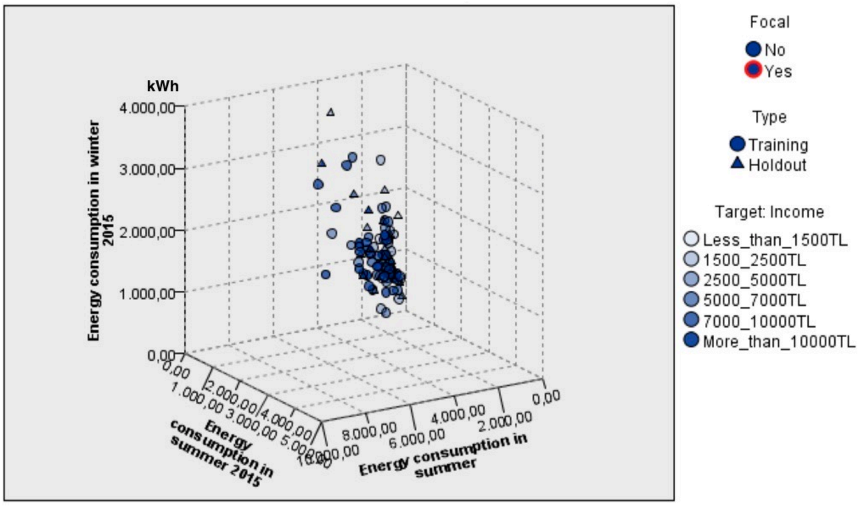


Fig.25. (e): Distribution of energy consumption by income.

Energy-consumption patterns according to income are shown in Figure 25 (e): Energy usage for high-income households (i.e., more than 10.000 TL) ranged between 900–1.600 kWh, energy consumption for those in the 7.000–10.000 TL income group ranged between 1.000–2.800 kWh, and households in the 2.500–5.000 TL income group utilised between 900–2.800 kWh of energy The wide range of usage for the latter group was due to different floor levels; the simulation study predicted that energy consumption in the upper-floor flats would be 9.869,0 kWh, but actual energy consumption was 10.004,0 kWh, which suggests that these flats experienced significant overheating risks that were exacerbated when the households used every type of cooling appliance.

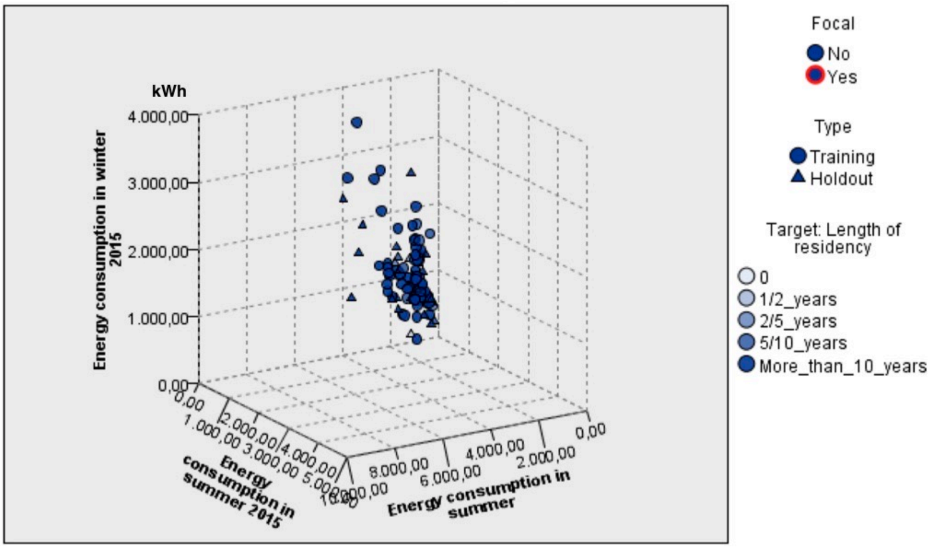


Fig.25. (f): Distribution of energy consumption by length of residency.

According to Figure 25 (f), which shows the effect of length-of-residency on energy use, energy consumption of households who had lived in their flats for more than 10 years ranged between 400–3.800 kWh; this wide variance was due to the number of household members in each flat and the age bands of the participants. Of the sampling population, 47% were 55–65 and 65-year-of-age and older; this age group was primarily retirees in the high-income group (i.e., more than 10.000 TL) who spent most of their time at home. Notably, the energy consumption of residents who had lived in their units for 5–10 years, who comprised 10% of the sampling size, ranged between 900–1.600 kWh; even though these flat owners were younger, they had children living in their home, and their high energy consumption was due to attempts to acclimatise their indoor-air environments. These results suggest that when EPCs are being developed, length-of-residency should be considered in addition to other socio-demographic factors to properly understand and address the building-energy-performance gap and to foresee and avoid discrepancies between predicted and actual energy use.

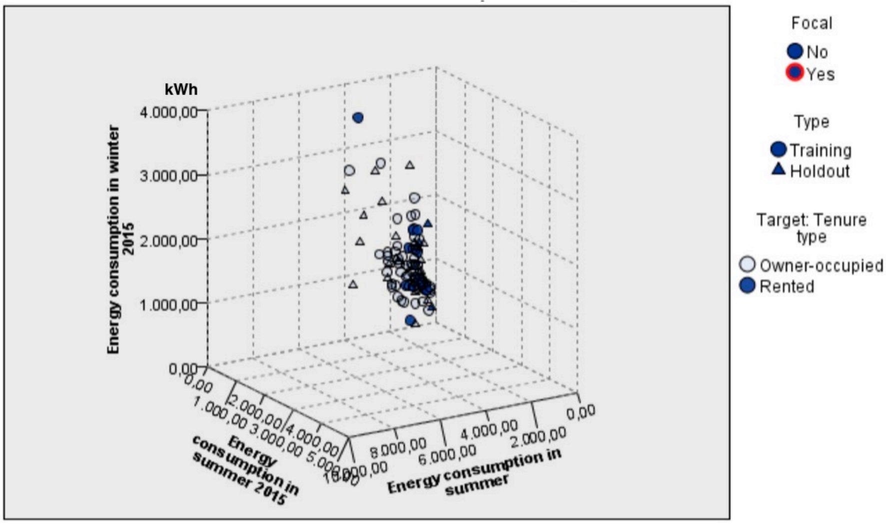


Fig.25. (g): Distribution of energy consumption by tenure type.

To avoid research bias and reduce discrepancies in predicted energy use, the present study examined associations between household energy consumption and type of tenancy; the findings of this analysis are presented in Figure 25 (g). With the exception of one unit that used 3.800 kWh of energy, most renters consumed between 100–800 kWh of energy, and the energy consumption of owner-occupiers ranged between 200–2.800 kWh; these results indicate that a household's socio-economic status is a more important factor for energy consumption than their type of tenancy. This contradicts the traditional manner in which EU member states have verified energy consumption according to tenancy type, and confirms that other factors, such as socio-economic status, the physical properties of the building elements, local climate conditions and most importantly, cultural assets of the case-study locations. Figure 26 demonstrates the main research outputs and its contribution to energy for sustainable development which also corresponds the objectives of the Sustainable Development Goals (SDG).

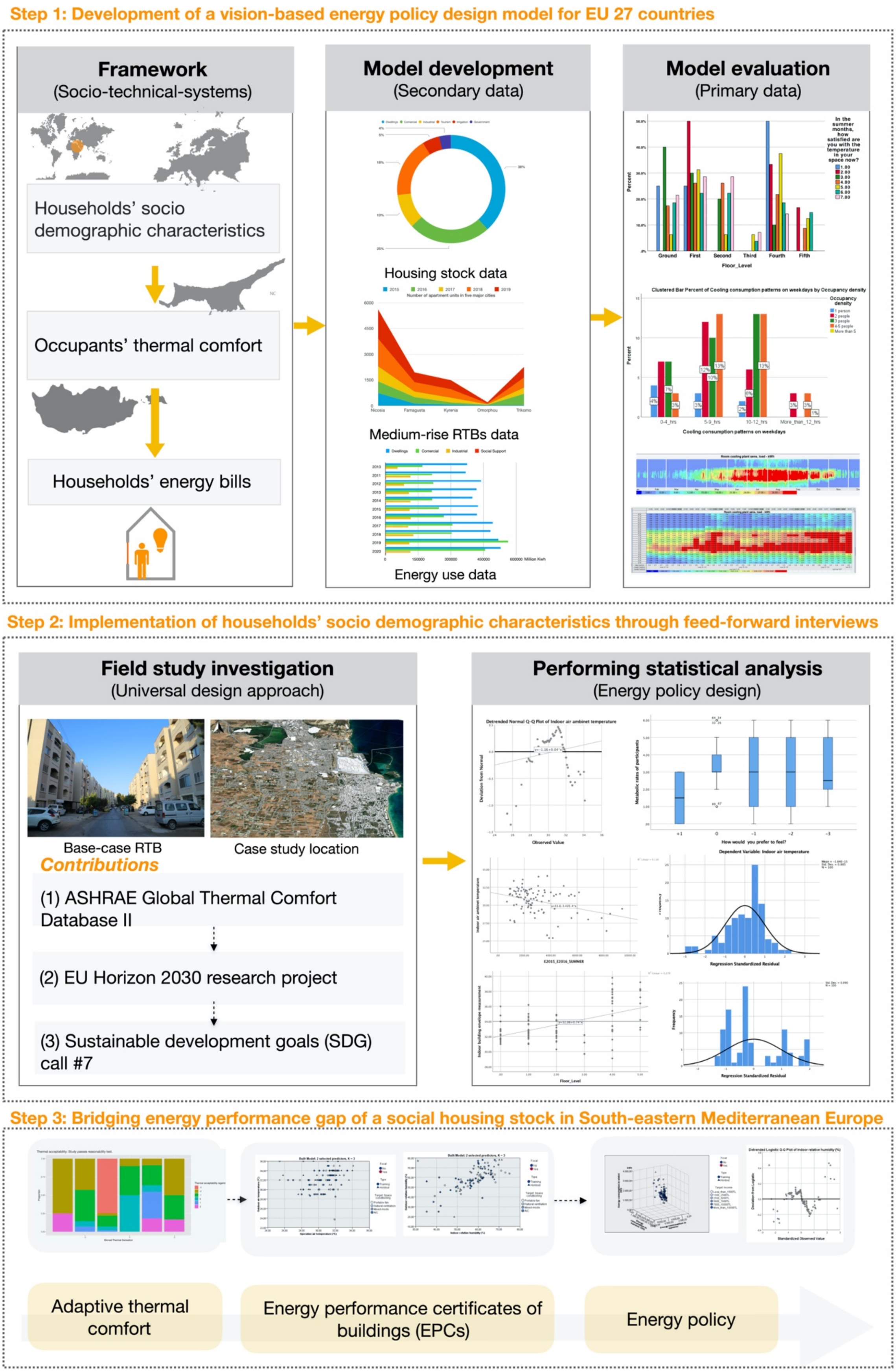


Fig.26. Step-by-step research impact factor and its contributions to knowledge in developing evidence-based energy policy framework, considering households' adaptive thermal comfort.

Limitations of the study

The goal of the study was to provide effective responses to the RQs with the use of available data and resources, even though this resulted in certain limitations that should be considered. A new STS conceptual framework could provide contributions that would consider real-life occupant energy-use experiences in the decision-making process for future retrofitting interventions. An analytical approach with a high level of abstraction was therefore chosen for energy policy. Table 15 demonstrates the summary of research limitations to delineate the technical constraints that are related to key concepts, which should be addressed by future scholars.

Table 15
List of limitations.

Key Concepts	Limitations
Sampling Size	- A large sample is required to conduct TSVs and evaluate the collected data, which could affect the generalisation of the results to provide an overall understanding of home-energy performance. - A call-back survey was carried out to increase the response rate, but due to time constraints, only five households were successfully recruited; as such, the sampling size was not considered in the statistical analysis.
Statistical Analysis	- The ranking system of subject participant responses were estimated from self-reported behaviours and were expected to vary; this lack of integration prevailed, despite evidence that some errors were detected in the parametric (*P*-test) analysis. This is because the respondents did not provide an accurate vote of the thermal-comfort assessment criteria.
Questionnaire Survey	- No direct question was asked about household income, mostly to increase response rates. The researcher identified the respondents' income levels by considering their age and employability.

Additional research is required to better understand the possible link between occupant behaviour and energy consumption. Significantly more work still needs to be done to investigate specific climate conditions and different housing typologies, as well as relevant subjective measures, such as the socio-demographic characteristics, backgrounds and social structures of different households. Moreover, other novel methodologies that include advanced modelling features related to occupant behaviour when evaluating the energy performance of buildings (i.e., stochastic and deterministic models) should be developed.

Conclusion

This study reveals a number of significant advances that provide a comprehensive understanding of the thermal performance of archetype residential buildings and occupants' thermal comfort levels; the findings allow direct comparison, where applicable, against the objectives of this empirical study.

A systematic literature review was conducted to fill the existing knowledge gap in four key areas: building overheating risks, thermal comfort, occupant behaviour and energy modelling.

Occupancy patterns and habitual household adaptive behaviour were already known to be significant determinant factors related to home energy performance, but occupant thermal comfort in relation to the development of a socio-technical-systems (STS) conceptual framework had not been addressed, and available data on the neutral adaptive thermal comfort of social-housing residents were not found in the ASHRAE Global Thermal Comfort Database II.

An analysis of the questionnaire results revealed that a moderate negative correlation ($r = -0{,}329$, $p < 0{,}01$) was found between household income and type of tenancy. A moderate positive correlation ($r = 0{,}252$, $p < 0{,}05$) was found between household income and length of residency, because 23% of the respondent households reported below-average annual incomes. The highest peak in the length of residency shows that occupants who were 45–55 years of age were at $f > 4{,}0$, and occupants who were 65 years of age and older were at $f = 4{,}0$; the members of the latter age group were the first legal owners of these flats, and as their ages and lengths of residency increased, their income also increased, between $f = 2{,}80$ and $f = 4{,}0$.

The present study also revealed a number of diverse methods for occupants in the southeastern Mediterranean climate to develop optimum thermal conditions in the summer. It was determined that a total of 48% of the households were 55–65 or 65 years of age and older; therefore, it is important to consider the impact of age on thermal comfort in these flats. A moderate negative correlation ($r = -0{,}229$, $p < 0{,}05$) was found between the occupants' age and their complaints related to thermal discomfort. Even though the correlation analysis did not discover a relationship between gender and age, a moderate positive correlation ($r = 0{,}218$, $p < 0{,}01$) was confirmed between age and the different floor levels of the flats when the reasons for thermal comfort were included as a dependent variable. At the time of the survey, the occupants' socio-demographic factors were shown to have an impact on their thermal comfort preferences.

Insights from this study will enhance the national energy network for Cyprus and improve subsidisation schemes throughout Europe. Moreover, energy policies and regulations will benefit from a conceptual-level analysis of the climate characteristics of each EU member state, as this will allow more accurate planning.

Declaration of Competing interest

The authors declare 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 the designing of flow diagrams; and **Bertug Ozarisoy** provided sources (e.g. illustrations, tables and datasets), comments, and major edits to the paper. **Prof. Hasim Altan** provided necessary supervision to check the accuracy of the statistical information included into the article and he supported the author during the writing-up process of the Methodology, Results and Discussions. **Prof. Hasim Altan** wrote the Conclusions. Additionally, **Prof. Hasim Altan** wrote the cover letter to explain the novelty of study to the Editor-in-Chief at the time of submission.

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Graphical Abstract – The flow diagram demonstrates the novelty of the socio-technical-systems conceptual framework developed for this study.

Supplementary material
Supplementary data to this article can be found online at –
Supplementary Material – The questionnaire survey proforma - An investigation of cooling energy consumption patterns of households and Thermal comfort.

Data set in Mendeley
Data set to this article can be found online at –
Data set 1: 3D rendering model of a base-case RTB in rvt. file for other scholars' further research work.
Data set 2: The raw data of statistical data set was designed in the Statistical Analysis in Social Science (SPSS) version 25.0, including spv. file for other scholars' further research work.

Appendix A.1

Fig.A.1. Mapping of building deteriorations in base-case RTBs.

Appendix A.2

Table A.1
Tests of associations between age band and gender factors with energy efficiency awareness.

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	**Age band**	77.424[a]	11	7.039	6.113	0.001
	Gender	2.995[b]	11	0.272	1.253	0.265
Intercept	**Age band**	0.150	1	0.150	0.130	0.719
	Gender	1.765	1	1.765	8.127	0.005
Occupation	**Age band**	15.348	1	15.348	13.33	0.001
	Gender	0.336	1	0.336	1.547	0.217
Tenure type	**Age band**	0.338	1	0.338	0.293	0.590
	Gender	0.020	1	0.020	0.091	0.763
Energy consumption	**Age band**	4.333	1	4.333	3.763	0.056
	Gender	0.078	1	0.078	0.359	0.551
Energy advises	**Age band**	0.003	1	0.003	0.003	0.957
	Gender	0.005	1	0.005	0.023	0.879
Energy conservation	**Age band**	0.908	1	0.908	0.788	0.377
	Gender	0.013	1	0.013	0.058	0.810
Energy efficiency awareness	**Age band**	0.749	1	0.749	0.650	0.422
	Gender	0.764	1	0.764	3.515	0.064
Income	**Age band**	1.917	5	0.383	0.333	0.892
	Gender	1.740	5	0.348	1.603	0.168
Error	**Age band**	101.326	88	1.151		
	Gender	19.115	88	0.217		
Total	**Age band**	1171.000	100			
	Gender	67.000	100			
Corrected Total	**Age band**	178.750	99			
	Gender	22.110	99			

a. R Squared = .433 (Adjusted R Squared = 0.0362)
b. R Squared = .135 (Adjusted R Squared = 0.027)

Appendix A.3

Table A.2
Multivariate analysis of households' socio-demographic characteristics to develop evidence-based energy policy design.

Effect		Value	F	Error df	Sig.
Intercept	Pillai's Trace	0.088	4.201[b]	87.000	0.018
	Wilks' Lambda	0.912	4.201[b]	87.000	0.018
	Roy's Largest Root	0.097	4.201[b]	87.000	0.018
Occupation	Pillai's Trace	0.152	7.799[b]	87.000	0.001
	Wilks' Lambda	0.848	7.799[b]	87.000	0.001
	Roy's Largest Root	0.179	7.799[b]	87.000	0.001
Tenure type	Pillai's Trace	0.005	0.206[b]	87.000	0.815
	Wilks' Lambda	0.995	0.206[b]	87.000	0.815
	Roy's Largest Root	0.005	0.206[b]	87.000	0.815
Energy use	Pillai's Trace	0.043	1.953[b]	87.000	0.148
	Wilks' Lambda	0.957	1.953[b]	87.000	0.148
	Roy's Largest Root	0.045	1.953[b]	87.000	0.148
Energy advises	Pillai's Trace	0.000	0.012[b]	87.000	0.988
	Wilks' Lambda	1.000	0.012[b]	87.000	0.988
	Roy's Largest Root	0.000	0.012[b]	87.000	0.988
Energy conservation	Pillai's Trace	0.010	0.440[b]	87.000	0.645
	Wilks' Lambda	0.990	0.440[b]	87.000	0.645
	Roy's Largest Root	0.010	0.440[b]	87.000	0.645
Energy efficiency awareness	Pillai's Trace	0.043	1.945[b]	87.000	0.149
	Wilks' Lambda	0.957	1.945[b]	87.000	0.149
	Roy's Largest Root	0.045	1.945[b]	87.000	0.149
Income	Pillai's Trace	0.097	0.901	176.00	0.534
	Wilks' Lambda	0.903	0.906[b]	174.00	0.529
	Roy's Largest Root	0.096	1.693[c]	88.000	0.145

a. Design: Intercept + Occupation + Tenure type + Energy use + Energy advises + Energy conservation + Energy efficiency awareness + Income
b. Exact statistic
c. The statistic is an upper bound on F that yields a lower bound on the significance level.

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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 PhD research project undertaken at the University of East London, United Kingdom. The paper is devised after the completion of the research project. 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 author has provided additional financial flow from his own budget to complete this project successfully. **Dt. Serife Gurkan** fully funded this PhD research project undertaken at the Graduate School, School of Architecture, Computing & Engineering, University of East London between 26/09/2016 – 29/09/2020. She also supported the researcher (**Bertug Ozarisoy**) financially at the time of developing this research paper proposal, conceptualising, data collection and writing up processes. She provided substantial amount of financial investment throughout the research progress. Additionally, **Dt. Serife Gurkan** paid the researcher's travel expenses to enable him to conduct the field survey in Cyprus.

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