The Impact of Different Thermal Comfort Models on Zero Energy Residential Buildings in the Hot Climates

Abstract

The selection of a thermal comfort model for establishing optimal indoor hygrothermal conditions during the hot period has a major impact on energy consumption of Net Zero Energy Buildings in hot climates. The objective of this paper is to compare the influence of using different thermal comfort models for zero energy buildings in hot climates. The paper compares the impact of applying Fanger’s model, Givoni’s model, the ASHRAE 55 adaptive comfort model and the EN 15251 adaptive comfort model about in terms of energy consumption and comfort performance. Using both the building performance simulation tools ZEBO and EnergyPlus for energy simulation, an existing prototype of a residential apartment module is used to evaluate the energy performance and thermal comfort in two parametric series. The first one is the result of coupling natural ventilation and mechanical cooling, and the second one is the result of guided coupling natural ventilation, mechanical cooling, and ceiling fans. This study shows that the difference in percentage of energy consumption for meeting the comfort criteria according to the ISO 7730 in comparison to the EN 15251, ASHRAE 55 or Givoni’s model, varied up to 16%, 21%, and 24.7% respectively for the presented case study. More energy savings can be expected for buildings in hot climates with greater cooling demands.

1 Introduction

Net Zero Energy Buildings (NZEBs) aim to reduce at a minimum the energy required for space cooling, space heating, (humidification and dehumidification if required), ventilation, lighting, and also, according to some definitions, also appliances. By default, NZEBs are grid connected and they benefit from renewable energy sources, such as direct solar radiation, wind, and the earth’s thermal storage capacity to balance their energy consumption annually. However, using the words of the European standard EN 15251: “An energy declaration without a declaration related to the indoor environment makes no sense. There is, therefore, a need for specifying criteria for the indoor environment for design, energy calculations, performance and operation of buildings.” Thus, the specification about of thermal comfort objectives that a building must achieve is a prerequisite for its design. Such objectives shall be explicitly included as an integral part of the definition of a zero energy building in a hot climate and needs to be quantitatively defined through reliable and explicit methods for assessing the thermal comfort performance of a building. However, most energy efficiency research is conducted with the cold climates in mind, and so the impact of the selection of different thermal comfort models for NZEBs in hot climates has been scarcely studied.

To date, a variety of thermal comfort models are available in the literature, and along with methods of standardization for moderate indoor environments, such as the Fanger comfort model (also called rational or...
static model), the European adaptive comfort model, the American adaptive comfort model, the Building Bioclimatic Chart. They provide the most likely thermal or hygrothermal conditions as individual objective values or zones on a psychrometric chart. These models deliver those conditions that should “statistically” minimize thermal discomfort perceived by typical occupants in a moderate environment and can be used for assessing how a given thermal or hygrothermal indoor condition is far from an optimal one.

Thermal comfort models have developed in the last four decades and have included added in standards, but their inclusion of standards happened arrived in different periods: the Fanger comfort model was first included in the ANSI/ASHRAE 55 in 1982, then in the ISO 7730 in 1984, the American adaptive model was added to a revision of the ANSI/ASHRAE 55 in 2004, and the European adaptive model has been included in the EN 15251 in 2007. Furthermore, the adoption of standards on thermal comfort is globally voluntary. In fact, national legislations do not impose the adoption of a thermal comfort model to set objective conditions or to the set the points of buildings; energy systems, rather they indicate a reference temperature to be maintained during the winter (and sometimes summer), and possibly an acceptability band around the reference value.

All standards on thermal comfort basically agree with suggesting the adoption of the Fanger model for mechanically heated and/or cooled buildings, while the ANSI/ASHRAE 55 offers the possibility to use the American adaptive model in a “naturally ventilated building,” whether or not the “mean monthly outdoor air temperature” falls into a given temperature domain (10 ÷ 33.5°C), and the EN 15251 allows the use of the European adaptive model in “buildings without mechanical cooling,” whether or not the “exponentially weighted running mean of the daily outdoor air temperature” falls into a given temperature domain (10 ÷ 30°C). The Givoni’s Building Bioclimatic Chart is not included in any standard, but it is often used in hot and tropical climates, where the applicability of adaptive models is limited.

In this paper, an extended study is performed on the effects of different thermal models on the energy performance of NZEB based on a previous study. A brief description of the main comfort models is proposed and their adoption in standardization is presented; then the impact of adopting different thermal comfort models on the design and energy consumption of a net zero energy residential apartment module in a hot climate is investigated by comparing optimal comfort temperatures drawn for a given hot climate and by assessing the energy needed for space cooling and heating.

The methodology used consists of screening the existing comfort models’ suitability for hot climates. The study includes an inventory of suitable comfort models that can be used as solutions for NZEBs. Then a typical base case building is selected for simulation analysis in order to examine the impact on thermal comfort and energy performance. The building energy use analysis is performed using the software ZEB, an optimization engine, which guides EnergyPlus, a simulation engine, aiming to conduct global parametric analysis where the parameters are varied. Finally, analysis of the results provides guidance on the strategic design decision making for designing comfortable NZEBs in at least one hot climate.

This paper is organized into five sections. The first section identifies the research problem, objective, and significance. The second section provides a review of the principles of thermal comfort, followed by a literature review section on thermal comfort models. The third section summarizes how the thermal comfort models have been introduced in standards. The fourth section reports the results of a case study that investigates the impact of different thermal comfort models on energy consumption. The final section discusses and concludes the study's outcomes, implications, and limitations.
2 Review of thermal comfort in buildings

Fathy wrote: “People living in the hot, climates, are faced with a different problem: amplified ultraviolet rays that hit our concrete structures and rebound onto us in hot and humid weather conditions.” In hot climates, it is always necessary to avoid sensible and latent heat gains in every possible way and to achieve thermal comfort conditions while minimizing energy consumption. This section reviews the thermal comfort model for NZEBs in hot climates and lists multiple model and systems solutions.

Thermal comfort is usually used to indicate whether an individual does not feel too hot or too cold with respect to a given thermal environment. It is a concept that has attracted the attention of a number of scientists and doctors and it has been defined according to three main approaches: a physiological, a psychological, and a rational (also called heat-balance-based) approach. According to the physiological approach, the thermal perception of an individual is due to the entity of nervous impulses that start from thermal receptors in the skin and reach the hypothalamus. According to the psychological approach, thermal comfort is “that condition of mind which expresses satisfaction with the thermal environment.”. This definition is reported in the international standard ISO 7730, and a similar definition is also reported in the American standard ASHRAE 55, although the ASHRAE definition highlights the subjective character of such a concept by adding to the previous definition the sentence “[…] and is assessed by subjective evaluation.”. According to the last approach, thermal sensation is related to the heat balance of the human body, and thermal comfort is that the condition when heat flows leaving the human body balance balancing those incoming and the skin temperature and the sweat rate are to be within specified ranges depending on the metabolic activity.

Therefore, the term thermal comfort is, in general, used to provide information about the thermal state of an individual within a given thermal environment.

2.1 Thermal comfort nomenclature, parameters and evaluation scales

Thermal comfort is viewed as a state of mind where occupants are satisfied with their surrounding thermal environment and they do not desire neither a warmer nor a cooler condition. According to the Fanger approach, there are six primary factors that affect thermal sensation that are either environmental or personal parameters; these factors are: air temperature, mean radiant temperature, air velocity, humidity, metabolic rate, and clothing. All these six factors are time dependent, but thermal comfort is just assessed by assuming steady-state conditions. Since previous exposure or activity can affect thermal comfort perception for about one hour, thermal comfort requirements are not addressed to for temporary visitors to a space. Moreover, thermal comfort models do not typically apply to sleeping or bed rest, even if though Lin and Deng proposed a modified version of the Fanger comfort model extended to sleeping thermal environments.

Researchers have shown that other contributing parameters include climate change with time, the building and its services, and occupants’ perception. Due to biological variance beyond occupants and psychological phenomena, neither perfect conditions nor well defined thermal comfort boundary settings exist, but rather a thermal comfort zone with a band of operative temperatures that satisfy the highest percentage of occupants. Humphreys found that the best representation to predict occupants’ thermal comfort, had to be derived from field studies. Using a field survey, questionnaires with synchronized records of parameters was done while measuring personal thermal states or changes. According to the literature, the evaluation of the personal thermal state is suggested through a series of guidelines with three scales:

1. A scale of perception of the personal thermal state with seven degrees and two poles: from ‘Cold’ to ‘Hot’ with a central point of neutrality that corresponds to the absence of hot and cold.
2. An evaluative scale with four degrees and one pole: present affective assessment from ‘Comfort’ to ‘Discomfort’.

3. A future thermal preference scale with seven degrees and two poles; from ‘Cooler’ to ‘Warmer’ with a central point of indecision that corresponds to the absence of change.

The evaluation of thermal surroundings or local climate can be made through two additional scales:

1. Scale of personal acceptability of local climate with two degrees: from ‘Generally acceptable’ to ‘Generally unacceptable’.

2. Scale of tolerance of local climate with two degrees: from ‘Tolerable’ to ‘Intolerable’.

On the other side, the strict reliance on laboratory-based comfort standards, such as ASHRAE, ignores important cultural and social differences in the need or desire for air-conditioning. A special issue of Energy and Buildings focused on these non-thermal issues, with a variety of papers examining how individuals and cultures vary in their perceived need for and expectations of air-conditioning.

The relationship between human thermal comfort and indoor temperature passes through the thermal sensation of occupants and it is not a linear function. In the words of Fanger, “human thermal discomfort” can be translated with into “predicted percentage of dissatisfied” (PPD) and “thermal sensation” with a “predicted mean vote” (PMV). The relationship between PPD and PMV is an exponential curve. De Dear, Brager, and Cooper [37] also used the Fanger relationship in order to relate “thermal sensation votes” and “percentage of dissatisfied.”

2.2 Fanger rational comfort model

Following since the development of air-conditioning, the business community has been more inclined towards artificial indoor environments and sealed buildings. In 1970, based on climate chamber experiments, Fanger introduced the so-called PMV/PPD model of thermal comfort, which first established a relationship between six primary factors based on a thermal balance equation developed under steady-state conditions. Figure 1 is an example representing that represents PPD as a function of PMV. This model has been incorporated into a number of standards and design codes (e.g., ISO 7730). The model is intended for application to situations similar to those of sealed air-conditioned buildings. In these types of buildings, the envelope is completely sealed with non-operable windows and occupants interact with an artificial indoor environment totally disconnected from the outside one. Recent field measurements have highlighted some inaccuracies when the model is applied to either air-conditioned or non-air-conditioned buildings. The model was found to overestimate and underestimate occupants’ responses in warm climates. Givoni suggests that one cause is that, in the heat balance equation, air velocity is only considered when computing the convective heat exchange coefficient and not for the calculation of sweat evaporation. Researchers have suggested that the PMV/PPD model should only be used for sealed air-conditioned buildings. Nevertheless, the PMV/PPD model is commonly applied during the design of air-conditioned office buildings in hot climate zones. Since there are no other models for net zero energy residential buildings, it has been applied in the analysis of fully air-conditioned NZEBs in this study.

2.3 Request for and rising of adaptive comfort models

In order to find an alternative to the PPD model, in 1995, ASHRAE sponsored a field survey project (RP-884), which focused on statistical analysis of high quality data from existing buildings, rather than the heat balance...
approach derived from climate chamber data. The data were collected from 160 naturally ventilated, air-
conditioned and mixed-mode office buildings in a number of climate zones; including those considered hot
humid and hot dry. Occupants in naturally ventilated buildings were found to accept wider temperature
variation and higher indoor temperatures than those in air-conditioned buildings [28, 43]. De Dear and Brager
observed that occupants of office buildings showed a low sensitivity to indoor temperature changes. The
gradient of their thermal sensation votes with respect to indoor operative temperature turned out to be 1 vote
for every 3 ºC to 5 ºC change in temperature. Values in the same range were encountered in the work
of Oseland and of Van Der Linden et al. The apparent acceptance of warmer temperatures is thought to be
due to different psychological perceptions and adaptations. This finding has changed the idea that occupants
can be considered as passive users, in contrast, occupants either adapt to the surrounding environment to
suit their expectations—using windows, blinds, (ceiling) fans, and doors—or changing metabolic rate (activity
level and cold drinks), rate of heat loss (clothing) and thermal environment (controls).
Across a number of adaptive comfort studies, outdoor temperature was proven to have the dominant effect on
defining thermal comfort conditions.
A number of adaptive models seek to correlate perceived thermal comfort with some measure of recent
external temperatures and the current internal temperature [49].
The adaptive comfort models are derived from a black-box approach and relate the indoor optimal operative
temperature ($T_o$) to an elaboration of the outdoor air temperature ($T_o$), by linear regression analysis and the
optimal indoor operative temperature as $T_o = a T_o + b$. Several adaptive comfort models have been developed
over the decades, and they differ in the function used to elaborate the outdoor air temperature ($T_o$) and for in the
different values of the coefficients ‘$a$’ and ‘$b$’ (Table 1). These remarks indicate a lack of
universally accepted parameter values (‘$a$’ and ‘$b$’) and functions to expressing the evolution of outdoor air
temperature.

2.4 American adaptive comfort model

The ASHRAE adaptive comfort model, presented in the American standards ASHRAE 55:2004, is applicable
for monthly mean outdoor air temperatures included in the range of 10 ÷ 33.5 ºC (50 ÷ 91.4 ºF) and is
delivered together with an indication of comfort boundaries, as shown in Figure 2. Two acceptable ranges are proposed for an acceptability (considered as complementary to the predicted percentage of
dissatisfaction) of 80 % and 90 %, which correspond to a deviation of ±3.5 ºC and ±2.5 ºC, respectively from
the optimal comfort temperature (Figure 2).

This comfort model presented in the ASHRAE 55 derives from the previous work of De Dear, Brager and
Cooper. According to this study, the optimal comfort temperature was computed by using the monthly mean
new effective temperature (ET*), calculated on a calendar monthly basis, and ranges ranging in the interval of
[5, 33]ºC. In 1998, the ASHRAE committee SSPC 55 decided to include an adaptive comfort model in the next revision of the ASHRAE Standard 55. However, a
number of modifications were carried out on the original adaptive model during the revision process. They
were mainly aimed at finding a balance between “scientific evidence with expert judgment, practical experience, pragmatism, added assumptions, and compromises to compensate for the gaps in our knowledge.”. The first modification consisted of changing the independent variable for the calculation of the optimal comfort temperature: the original new effective temperature was substituted with the monthly mean of the outdoor dry-bulb air temperature for the month in question.

The original new effective temperature accounts for radiative, convective and latent heat transfers\(^1\) and is calculated using the two-code-node model, which aims at computing the heat flow exchanged by the human body’s core towards the environment, passing through the skin. Instead, the monthly mean of the outdoor dry-bulb air temperature is much simpler, more accessible and can be calculated directly from typical meteorological data. The choice of a monthly average for a given (calendar) month implies that the profile of the optimal comfort temperature is a step function. Brager and De Dear accepted the request of simplification of the ASHRAE committee SSPC 55 and adapted their original comfort model to have the outdoor operative temperature as an independent variable

\[
T_{c}^{\text{ASHRAE 55}} = 0.31 T_o + 17.8
\]

where \(T_o\) is the monthly mean of the outdoor dry-bulb air temperature of the month in question. Moreover, the lines are extended horizontally for values of the monthly mean outdoor air temperature outside the range of [5, 33] °C (Figure 3).

Finally, the ASHRAE committee SSPC 55 considered the lower values too low and did not reach an agreement on how to deal with the temperature outside the range of measured data, so instead they and decided (i) to truncate the lines of the graph at the end-points of the range regardless of what the data actually showed, and the range was stopped at 10°C instead of 5°C. “An awkward consequence of this decision, however, is an unrealistic step change in allowable indoor temperatures as soon as the mean outdoor air temperature rises above 33°C.”.

Many researchers, however, have challenged this assumption of universal applicability, arguing that it ignores important contextual differences that can attenuate responses to a given set of thermal conditions. Fanger disagrees with the adaptive approach in concept, since it only deals with outdoor air temperature and neglects the other five primary factors they have identified. Indeed, they proposed and extended a version of the original PMV model, which also takes into consideration all of the six parameters.

Givoni, while revising his already notable work on the building bioclimatic chart, suggested that at least air temperature, surface temperature, and air velocity should be taken into consideration in hot climates. He expanded the boundaries of the comfort zone based on the expected indoor temperatures achievable with different passive design strategies, applying a “common sense” notion that people living in un-air-conditioned buildings become accustomed to, and grow to accept higher temperatures or humidity. However, a proposed addendum in September 2008 suggested the use of the PMV model to air speed below 0.20 m/s. Air speed greater than this value may be used to increase the upper operative temperature limits of the comfort zone in certain circumstances. This increase can effectively be achieved by using ceiling fans to elevate air temperature.

\(^1\) The new effective temperature is defined as: “the temperature (DBT) of a uniform enclosure at 50% relative humidity, which would produce the same net heat exchange by radiation, convection and evaporation as the environment in question.”.

Comment [MrP2]: Who is they? Should it say he in reference to Fanger?
speed to offset increased air and radiant temperatures. As shown in Figure 4, elevated air velocity is effective at increasing heat loss when the mean radiant temperature is high, and the air temperature is low. However, if the mean radiant temperature is low or humidity is high, elevated air speed is less effective. The required air speed for light, primarily sedentary activities may not be higher than 0.8 m/s. But the ceiling fan’s effect cannot control humidity and depends on clothing and activity. Figure 5 shows the acceptable range of operative temperature and air speed for a given clothing level.

2.5 European adaptive comfort model

According to the European standard EN 15251, acceptable comfort temperatures actually depend on the type of system used to provide summer comfort. If cooling is provided by an active system, an active system provides cooling, then indoor temperatures must respect those defined by the Fanger model, plus a certain assumption of acceptability for different categories of buildings. Instead, if summer comfort is provided by passive cooling strategies, then the upper temperature limit is set by an adaptive model, plus a certain assumption of acceptability for different categories of buildings. Generally, the implementation of the adaptive model indicates that indoor thermal comfort is achieved with a wider range of temperatures than does with the implementation of the ISO 7730 model (see Figure 6). Both models use statistical analysis of survey data to back up their claims in their respective areas of applicability. In some situations it proves possible to maintain a building’s interior conditions within the EN 15251 adaptive comfort limits entirely by natural means. In these cases, there is no energy use associated with achieving indoor summer comfort.

The optimal operative comfort temperature can be calculated by knowing the daily mean outdoor dry-bulb air temperature of previous days

\[
T^\text{EN(15251)}_m = 0.33T_e + 18.8
\]

with \( T_e = (1-\alpha)\sum_{i=0}^{n} (\alpha^i T_i) \)

where \( T_m \) is the exponential weighted running mean of the daily outdoor dry-bulb air temperature, \( T_{e(i)} \) is the daily mean outdoor dry-bulb air temperature of the previous \((1 + i)\) day, and \( \alpha \) is a constant included in the range \([0, 1]\), but a recommended value is 0.8 in order to simplify the calculations to the standards that the EN 15251 suggests as a simplified equation to calculate the exponential weighted running mean of the daily outdoor dry-bulb air temperature:

\[
T_m = \frac{T_1 + 0.8T_2 + 0.6T_3 + 0.5T_4 + 0.4T_5 + 0.3T_6 + 0.2T_7}{3.8}
\]

The assumptions of acceptability are expressed for different categories of buildings of occupants inside a building and are expressed as symmetrical ranges around the optimal comfort temperature. Table 2 reports the optimal comfort temperature and the upper and lower limits of the comfort categories.
The upper comfort boundary is defined available for a running mean indoor air temperature from 10 °C to 30 °C and the lower comfort boundary from 15 °C to 30 °C (Figure 6).

In order to understand this difference in the temperature boundaries, we refer to the category ranges proposed by Seppanen et al. (Figure 7). Although they used the mean monthly outdoor air temperature as an independent variable instead of the running mean of the outdoor air temperature, and also in Figure 7, the upper and the lower boundaries of the comfort ranges are different in order to match the summer boundaries of the range (correlated to the outdoor temperature) with the winter boundaries (independent from the outdoor temperature). According to this interpretation, the warm period (or summer) might be interpreted as beginning when the lower boundary starts to be correlated to the outdoor temperature, i.e. for a mean monthly outdoor air temperature higher than 18°C and in winter when it is lower than 18°C.

Applying this interpretation to the EN 15251 graph, the running mean of the outdoor air temperature of 15°C might be considered the “switching temperature” between summer and the rest of the year.

2.6 Givoni’s Building Bioclimatic Chart

In 1963, Baruch Givoni introduced the Building Bioclimatic Chart (BBCC), developed by Milne and Givoni 1979, based on expected indoor temperatures rather than the outdoor conditions. The BBCC, represented in Figure 8, presents boundaries of the comfort zone and of zones where specified passive strategies are effective.

Those zones have been drawn thanks to experiments carried out in residential buildings. The psychrometric chart presented in Figure 8, is considered as to be the best representation of climatic variables. In 1992, Givoni proposed two sets of boundaries for developed and hot developing countries with a suggested elevation of 2K. Recent researches based on dynamic thermal simulation have has indicated the inaccuracy of these boundaries, and highlighted the lack of diurnal and seasonal variations that may impact the pattern use of the passive strategies. At early stages of the design, indoor temperatures can hardly be identified, since the design is still immature.

2.7 Thermal Comfort and Zero Energy Buildings

As part of the IEA’s work on zero energy buildings, The joint project SHC Task 40/ECBCS Annex 52 on Net Zero Energy Buildings developed an extensive body of literature on the relation between energy performance and thermal comfort of NZEBs. Most of the research work was conducted in the context of temperate and cold climates, including the work of Athienitis and O’Brien on the modeling, design, and optimization NZEBs and Doiron on energy performance and comfort. However, only a few publications have addressed thermal comfort for NZEB’s in the hot climates. This includes the work of PIMENT Laboratory at the University of La Reunion that focused on the assessment of occupant comfort using post-occupancy evaluation for two low-tech naturally ventilated NZEBs in the tropical climate. Also, Beccali et al. and Cellura et al. investigated the
importance of thermal inertia and the radiative nature of thermal exchanges of massive envelopes in relation
to thermal comfort in the Southern Italian climate. In a recent work, they investigated the energy performance
of a NZEB in an Italian climate. In 2014, Causone et al. published a paper on the design of an NZEB for the
Mediterranean climate. The paper aimed to present monitored data on the optimal energy balance and
thermal comfort using automated control for a case study in Catania, Italy. The Most of the aforementioned
publications were developed during or after the IEA SHC Task 40/ECBCS Annex 52 entitled "Towards Net
Zero Energy Solar Building" and are considered as valuable contributions, however, they are dispersed. They
did not address comfort in a systematic way, mapping different available standards and analyzing its
application for NZEBs in hot climates. Therefore, this review proposes a fundamental and detailed insight on
into the indoor comfort literature as a contribution to the state-of-the-art on the topic.

3 Synthesis of thermal comfort review

Following the extended review in Section 2, we can state that thermal comfort standards help
designers to establish indoor conditions that suit occupants’ expectations. Historically, the first comfort model
integrated into a standard was Fanger’s static model. It was firstly introduced by the American Society of
Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) in the standard ANSI/ASHRAE 55 in 1982,
then by the International Organization for Standardization (ISO) in the international standard ISO 7730 in 1984.
Some revisions of both of these standards were presented in 1992 and in 1994. In 1995, Parsons and Nicol
found that Western world standards were not appropriate for many countries, especially hot climate
countries, and an updated international standard for thermal comfort would have been required. In 2004,
ASHRAE 55 was revised and introduced the adaptive comfort model developed by de Dear and Brager was
introduced. This standard suggested the adoption of Fanger’s PMV/PPD model for sealed air-conditioned
buildings and De Dear and Brager’s adaptive model for naturally ventilated buildings. In 2007, the European
Committee for Standardization (CEN) introduced the European standards EN 15251, which suggested the
adoption of the Fanger’s PMV/PPD model for mechanically heated and/or cooled buildings, and Humphreys
and Nicol’s adaptive model for buildings without mechanical cooling systems.
The available models worldwide are mainly focused on office buildings, partly because of the limited number
of surveys in the area of residential buildings and the scope of these standards is extended to "other buildings
of similar types used mainly for human occupancy with mainly sedentary activities and dwelling." Therefore,
the largest issue in this discussion remains the applicability of those standards and models of non-air-
conditioned residential buildings in the hot climates.

4 Implication of the choice of a thermal comfort model

In order to test the previously mentioned models and standards, this section applies the four comfort models to
a case study. The case study is described in detail, and the simulation program helped in generating the
different energy requirements to satisfy the thermal objectives of the four models. In this paper, we have used
the adaptive comfort models to set reference conditions in a hybrid residential building, although it would be, in
theory, outside the scope of ASHRAE 55 and EN 15251.
4.1 Case study

A reference multi-residential building (Figure 9) was selected to assess the impact of the different thermal models. The typical meteorological year (TMY2) for Cairo was selected for this case study. Cairo is part of the mid-latitude global desert zone, and its climate is considered extremely hot and dry according to the Köppen climate classification (Group B). According to ASHRAE climate classification, Cairo is hot and humid (2b). The selected benchmark represents Egyptian flat apartments in narrow front housing blocks. For this study, we selected a benchmark based on recent research, to develop a benchmark models for the Egyptian residential buildings sector. It was assumed to represent apartments (Typology 1) in high urban densities of Egyptian cities, incorporating surrounding buildings and streets. The benchmark was developed to describe the energy needed for space heating and cooling, lighting, production of domestic hot water and electric appliances in respect to the building’s layout and constructions (Table 3).

Table 3

Table 3 lists the base-case and code compliance characteristics, in addition to the measures for achieving maximum energy efficiency. These include: energy efficient lighting, appliances in order to reduce electricity use as well as internal gain and high-efficiency HVAC system; a well-insulated, airtight building envelope; high-performance windows with a diurnal and nocturnal operational schedules; and finally, most favorable window distribution (window-to-wall ratio) and overhang depth in order to utilize passive solar gain.

Figure 9 shows the impact of the combined application of these measures to the annual delivered energy required by the building.

Figure 9

Further reduction in delivered energy for space heating and cooling could be achieved by sizing the HVAC system for reduced heating and cooling energy needs.

The building performance simulation (BPS) programs ZEBO and EnergyPlus were used to perform the analysis and assess the impact of using different thermal models. The tasks performed for simulation included: simulation of the benchmark apartment, analysis of on-site availability of renewable energy, minimization of building energy use with passive design and energy efficiency measures, and the sizing of systems for the collection and storage of renewable energy to meet the reduced building needs. TMY2 weather data were used for analyzing the building energy performance and sizing solar systems, respectively. The research started by determining the annual average energy use for space heating and cooling to determine the user’s electric consumption patterns and spikes. By this, the research acquired a starting point for comparing the energy output of various systems in relation to seasonal summer discomfort hours. Then, passive and active design strategies were implemented in order to achieve a zero energy performance without compromising thermal comfort. The passive and active design strategies included the installation of thermal insulation, shading devices, energy-efficient lighting systems and appliances, double glazing, flat plate collectors and photovoltaic panels. Finally, the thermal objectives and set point values variations were investigated to identify the impact and variation in reaching the NZEB performance objective, as which is presented in the following section.
4.2 Thermal objectives, set-point values, and results

To put the available comfort models into perspective, Figure 10 and Table 4 compare the impact of the application of the four comfort models, namely the Fanger model as implemented in ISO 7730, the American adaptive comfort model as reported in ASHRAE 55, the European adaptive comfort model as stated in EN 15251 and the Givoni model, using the climate data of from Cairo.

In order to calculate the optimal comfort condition according to the Fanger comfort model, we assumed that the dry-bulb air temperature is equal to the mean radiant temperature (hence equal to the operative temperature), the indoor air relative humidity is equal to 50%, the air velocity amounts to 0.1 m/s, the metabolic activity is 1.2 met, the external work is zero met, and clothing resistance is 0.5 clo in summer and 1.0 clo in winter.

Figure 10
Table 4

Figure 11 shows the monthly energy use for space heating and cooling due to the adoption of the several comfort models, which resulted in four varying patterns.

Figure 11

In Figure 11, we refer to the ‘equivalent’ energy need for cooling. The adjective ‘equivalent’ is used to mean that these quantities of energy are calculated according to a reference set-point conditions obtained by adopting the two adaptive comfort models, which, according to the standards ASHRAE 55 and EN 15251, should not be used in case the building is conditioned by a mechanical cooling system. However, the rule about the application of comfort models proposed by standards is weak when applied to hybrid buildings or to buildings where the occupants have the complete control of the building systems (e.g., residential buildings). In fact, the standards suggest referring to the Fanger model, since the building is expected to be in steady-state conditions, but hybrid buildings and residential buildings are often far from steady-state conditions.

5 Discussion

The variation in the comfort model was so very huge and summarized the previous discussion. For example, the Fanger model indicates that indoor thermal comfort (operative temperature) is achieved with a very narrow (red line) temperature range. On the other range of the spectrum, the Givoni Model (black line) has a very wide temperature range of the temperature reaching 30 °C. Generally, the application of the adaptive models (both in the two versions included in ASHRAE 55 and EN 15251) can be achieved with a wider range of temperatures than the Fanger model. In consequence, in some situations it is possible to maintain building interior conditions within the adaptive comfort limits entirely by natural means. In these cases, there is no need for energy cooling associated with achieving indoor summer comfort. Therefore, the adaptive comfort model is thought to be more appropriate for mixed-mode non-air-conditioned buildings in hot climates.
The second objective of this paper was to investigate the effect on energy need for space cooling due to the choice and selection of one of the four thermal comfort approaches in designing a non-fully or mixed-mode air-conditioned building.

The case study demonstrated a difference in the annual delivered energy varying from 2526 kWh/year (the Fanger case) to 2114 kWh/year (-16% with respect to the Fanger case) to 1995 kWh/year (-21% with respect to the Fanger case) to 1900 kWh/year (-25% with respect to the Fanger case). Energy savings using an adaptive comfort model were estimated as 10 ÷ 18% of the overall cooling load. The research outcome would have had a stronger impact if we used an additional dataset of case studies (combining multiple orientations or using conventional baseline models of ASHRAE, for example) and in-depth data analysis in terms of energy performance. However, addressing this limitation is outside the scope of the current research.

It should be mentioned that ASHRAE 55 and EN 15251 simply propose to use the Fanger comfort model in those buildings with a mechanical cooling system, and the adaptive comfort model in those buildings without a mechanical cooling system2 (EN 15251), or in a (occupant-controlled) naturally ventilated building3 (ASHRAE 55). Even if applying this classification can seem simple, a number of other cases exist, e.g., in the U.S., the term ‘mixed-mode buildings’ is used for those buildings that are mainly mechanically-conditioned, but use free natural ventilation during those periods with a favorable outdoor air temperature. Accordingly, Kalz and Pfafferott propose five building categories: (i) air-conditioned buildings, (ii) mixed-mode air-conditioned buildings, (iii) low-energy buildings with mechanical cooling, (iv) low-energy buildings with passive cooling, and (v) buildings without cooling. Moreover, they suggest limiting the scope of the Fanger static model to only fully and mixed-mode air-conditioned buildings; conversely this implies that the scope of adaptive models is extended to the last three building typologies of the aforementioned list, which are typically referred to as mixed-mode non-air-conditioned buildings. Moreover, there is evidence in the scientific literature that mixed mode buildings are considered to be more similar in their operation to naturally ventilated buildings than to fully air-conditioned ones. Rijal, Humphreys and Nicol and Humphreys and Nicol observed that the operation of windows and fans in naturally ventilated and mixed mode buildings was almost identical. Furthermore, across a database of 370 mixed-mode and air-conditioned buildings, mixed-mode non-air-conditioned buildings were found to provide higher occupant satisfaction. The EN 15251 adaptive comfort model, with its wider range of acceptable conditions, could promote a longer operation of natural ventilation; reduce the dependence on mechanical cooling, and consequently save ventilation and cooling energy. The thresholds that regulate the alteration between active and passive modes have to respect the adaptive comfort criteria, especially when sizing equipment.

Finally, we believe that there is an urgent and concrete need to investigate the topic further. This could possibly be done through a technical committee exploring the possibility of adopting adaptive models, at least in hybrid NZEB or high performance buildings (creating different dataset), where the occupant still has a direct control of a few control opportunities, or in residential buildings where the occupant usually wants to maintain the control of the operation of the building’s thermal systems, for example, to reduce operational costs.

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2 that "are buildings that do not have any mechanical cooling and rely on other techniques to reduce high indoor temperature during the warm season like moderately-sized windows, adequate sun shielding, use of building mass, natural ventilation, night time ventilation etc. for preventing overheating."

3 those buildings where the thermal conditions of the space are regulated primarily by the opening and closing of windows by the occupants.
The objective of the present paper is to show that the adoption of an available thermal comfort model is of paramount importance, since reference conditions for the indoor environment are significantly different and this causes a high, big, different, difference in the energy performance, at least in this case study. However, we did not want to predict the percentile differences due to different case studies. For this reason, we used the case study only to show an order of magnitude of the phenomenon and a following request to study more in-depth the application rule of thermal comfort models, since some dark areas have not yet been clarified. For example, the rule about the application of comfort models proposed by standards is weak when applied to hybrid buildings or in buildings where the occupant has the complete control of the building systems (e.g., residential buildings). In fact, the Fanger model should be used in steady-state conditions, but hybrid buildings and residential buildings are often far from being in steady-state conditions. Furthermore, the adoption of adaptive comfort models is only limited to the summer period (as specifically stated in EN 15251), but this condition does not derive from the statistical analysis, which used datasets collected during summer and winter. Also, the domain of the adaptive comfort model (ASHRAE 55) has been reduced without any scientific reason. Therefore, future research is heading towards creating additional datasets of case studies in order to come up with initial or guiding generalizations, and finally allowing us to suggest the hybrid use of different comfort models. We will have included this paragraph to extend our discussion and study limitations.

6 Conclusion

The review presented in this paper covers different thermal comfort models and standards for sealed and non-sealed residential buildings. This review is fundamental because it has a direct impact on defining NZEB in hot climates and the implications and requirements that influence the design. This study shows, that the difference in percentage of energy consumption meeting the comfort criteria according to ISO 7730 respectively. This contradicts the strict comfort limits as defined in ISO 7730, which suggests a very high level of precision in terms of thermal comfort predictability. The introduction of a certain level of comfort negotiability in adaptive thermal comfort standards might be helpful, to take advantage of the individual range of adaptive possibilities in a specific building. This could support the application of natural ventilation in buildings as well as the adoption of occupant-controlled strategies in order to maximize occupants’ satisfaction. When predicting adaptive thermal comfort by using building simulation, the results should refer to the weather data set and the occupant behavior that the study has been based on, and provides information concerning their likelihood for variability due to different influences.