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Impact of different thermal comfort models on zero energy residential buildings in hot climate

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ABSTRACT

The selection of a thermal comfort model for establishing indoor optimal 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 on 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 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 guided coupling natural ventilation, mechanical cooling and ceiling fans. This study shows that the percentage of energy consumption difference meeting the comfort criteria according to ISO 7730 in comparison to 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 minimum, energy required for space cooling, space heating, (humidification and dehumidification if required), ventilation, lighting and, according to some definitions also appliances. By default NZEBs are grid connected and 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" [1]. Thus, the specification about 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 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 cold climate in mind and 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 standardization for moderate indoor environment such as Fanger's comfort model (also called rational or static model) [2], the European adaptive comfort model [1,3], the American adaptive comfort model [4], the Givoni's Building Bioclimatic Chart [5]. 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 been developed in the last four decades and have then included in standards, but their inclusion arrived in different periods: Fanger's

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Abbreviations: ASHRAE, American Society of HeatingRefrigerating and Air-Conditioning Engineers; BBCC, Building Bioclimatic Chart; BPS, Building Performance Simulation; CEN, European Committee for Standardization; DBT, Dry Bulb Temperature; DOE, Department of Energy; EPBD, Energy Performance Building Directive; HVAC, HeatingVentilation and Air Conditioning; IEA, International Energy Agency; nZEB, nearly Zero Energy Building; NZEB, net Zero Energy Building; PMV, Predicted Mean Vote; PPD, Predicted Percentage Dissatisfied ;.

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comfort model was first included in ANSI/ASHRAE 55 in 1982 [6] then in ISO 7730 in 1984 [7], the American adaptive model was added to a revision of ANSI/ASHRAE 55 in 2004 [8] and the European adaptive model has been included in EN 15251 in 2007 [1,9]. 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 the set-points of building energy systems, rather indicate reference temperature to be maintained during winter (and sometimes summer) and possibly an acceptability band around the reference value [10–15].

All standards on thermal comfort basically agree with suggesting the adoption of Fanger's model for mechanically heated and/or cooled buildings, while ANSI/ASHRAE 55 offers the possibility to use the American adaptive model in "naturally ventilated building" whether the "mean monthly outdoor air temperature" [1] falls into a given temperature domain ($10 \div 33.5\,^{\circ}\mathrm{C}$), and EN 15251 allows the use of the European adaptive model in "buildings without mechanical cooling" whether the "exponentially weighted running mean of the daily outdoor air temperature" [9] falls into a given temperature domain ($10 \div 30\,^{\circ}\mathrm{C}$). The Givoni's Building Bioclimatic Chart is not included in any standard, but it is often used in hot and tropical climate where applicability of adaptive models is limited [16–19].

In this paper, an extended study is performed on the effect of different thermal models on the energy performance of NZEB based on a previous study [20]. A brief description of main comfort models is proposed and their adoption in standardization is presented; then the impact of adopting different thermal comfort model on the design and energy consumption of net zero energy residential apartment module in hot climates is investigated by comparing optimal comfort temperatures drawn for a given hot climate and by assessing energy need for space cooling and heating.

The methodology used consists of screening the existing comfort models suitable in 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 to examine the impact on thermal comfort and energy performance. The building energy use analysis is performed using the software ZEBO, an optimization engine, which guides EnergyPlus, a simulation engine, aiming to conduct global parametric analysis where the parameters are varied [21,22]. Finally, analysis of result 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 on the principles of thermal comfort followed by a literature review section on thermal comfort models. The third section summaries the thermal models 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 outcomes, implications and limitation.

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" [23]. 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 thermal comfort model for NZEBs in hot climates and list 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 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, 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" [24]. 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 concept by adding to the previous definition the sentence "[. . .] and is assessed by subjective evaluation" [25]. According to the last approach, thermal sensation is related to the heat balance of the human body and thermal comfort is that condition when heat flows leaving the human body balance those incoming and the skin temperature and the sweat rate are within specified ranges depending on metabolic activity [26]. 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 semantic, parameters and evaluation scales

Thermal comfort is viewed as a state of mind where occupants are satisfied with their surrounding thermal environment and desire neither a warmer nor a cooler condition [2]. According to the Fanger's approach, six primary factors affecting thermal sensation are either environmental or personal parameters; these factors are: air temperature, mean radiant temperature, air velocity, humidity, metabolic rate and clothing [27]. 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 1 h [28], thermal comfort requirement are not addressed to temporary visitors of a space. Moreover, thermal comfort models do not typically apply to sleeping or bed rest, even if Lin and Deng [29] proposed a modified version of Fanger's comfort model extended to sleeping thermal environments.

Researchers have shown that other contributing parameters include climate change with time, building and its services, and occupants' perception [3,30,31]. 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 [32,33]. Humphreys found the best representation to predict occupants' thermal comfort, had to be derived from field studies [34]. Using field survey questionnaires with synchronized records of parameters about the thermal indoor and outdoor environments and clothing level and metabolic activity of occupants, researchers also collected and analyzed information about people's thermal satisfaction, preference and attitude to changes [32]. According to the literature, the evaluation of the personal thermal state is suggested through a series of guidelines with three scales [27,35]:

(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 [36] 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 Fanger's words, "human thermal discomfort" can be translated with "predicted percentage of dissatisfied" (PPD) and "thermal sensation" with "predicted mean vote" (PMV). The relationship between PPD and PMV is an exponential curve [2]. de Dear et al. [37] also used the Fanger relationship in order to relate "thermal sensation votes" and "percentage of dissatisfied."

2.2. Fanger's rational comfort model

Following the development of air-conditioning, the business community has been more inclined towards artificial indoor environments and sealed buildings [12]. In 1970, based on climate chamber experiments, Fanger introduced the so-called PMV/PPD model of thermal comfort, which first establishes a relation between six primary factors based on a thermal balance equation developed under steady-state conditions [2]. Fig. 1 is an example representing 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 derived in hot regions (Pakistan and Kalgoorlie-Boulder) highlighted some inaccuracies when the model is applied to either air-conditioned or non-air-conditioned buildings [38–40]. The model was found to overestimate and underestimate occupant response 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 [41]. Researchers have suggested that the PMV/PPD model should only be used for sealed air-conditioned buildings [38,40]. Nevertheless, the PMV/PPD model is commonly applied in 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.

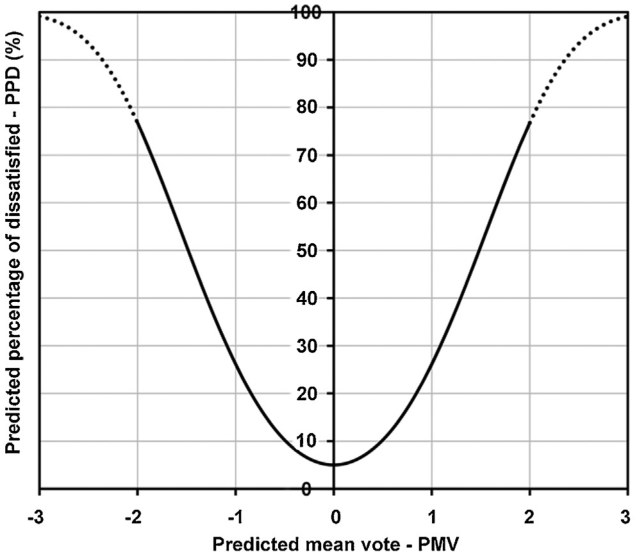

Fig. 1. Predicted percentage of dissatisfied (PPD) as a non-linear function of predicted mean vote (PMV).

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 was collected from 160 naturally ventilated, conditioned and mixed-mode office buildings in a number of climate zones; including those considered hot humid and hot dry [42]. 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 one vote for every 3 °C–5 °C change in temperature. Values in the same range are encountered in work of Oseland [43] and of Van Der Linden et al. [44]. The apparent acceptance of warmer temperatures is thought to be due to different psychological perceptions and adaptations [45]. This finding changed the idea that occupants can be considered as passive users [46], in contrast, occupants either adapt 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) [3,47–49].

Across a number of adaptive comfort studies, outdoor temperature was proven to have the dominant effect on defining thermal comfort conditions [47,50].

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 indoor optimal operative temperature (T_c) to an elaboration of the outdoor air temperature (T_o), by linear regression analysis and the optimal indoor operative temperature as $T_c = aT_o + b$. Several adaptive comfort models have been developed during the decades, and they differ for the function used to elaborate the outdoor air temperature (T_o) and for the different values of the coefficients 'a' and 'b' (Table 1). This indicates the lack of universally accepted parameter values (a and b) and function expressing the evolution of outdoor air temperature [51].

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 temperature included in the range $10 \div 33.5$ °C

Table 1
Terms of the general equation of adaptive models according to several studies.

Source	a	$f(T_{ext})$	b	Range of applicability
[9]	0.33[a]	Exponentially weighted running mean outdoor air temperature	18.8[a]	$f(T_{ext})\in[10, 30]$°C
[26]	0.31[a]	Monthly mean outdoor air temperature	17.8[a]	$f(T_{ext})\in[10, 33.5]$°C
[49]	0.315[c] 0.34[a]	Exponentially weighted running mean outdoor air temperature	17.82[c] 17.63[a]	$f(T_{ext})\in[5, 30]$°C
[50]	0.302[a]	Exponentially weighted running mean outdoor air temperature	19.39[a]	$f(T_{ext}) > 10$ °C
[51]	0.54[a]	Monthly mean outdoor air temperature	13.5[a]	$f(T_{ext})\in[10, 30]$°C
[36]	0.36[c]	Historical monthly mean outdoor temperature	18.5[c]	$f(T_{ext})\in[5, 35]$°C
[4]	0.255[a] 0.04[b]	Monthly mean outdoor effective temperature (ET[a])	18.9[a] 22.6[b]	$f(T_{ext})\in[5, 32]$°C
[52]	0.38[b]	Monthly mean outdoor air temperature of the previous month	17.0[b]	$f(T_{ext})\in(5, 35)$°C
[73]	0.534[b]	Exponentially weighted running mean outdoor air temperature	12.9[b]	Not defined
[74]	0.31[a]	Running mean of the preceding fortnight	17.6[a]	Not defined
[75]	0.534[a]	Monthly mean outdoor air temperature	11.9[a]	Not defined

[a] Model exclusively developed for free-floating and naturally ventilated buildings.
[b] Model exclusively developed for air-conditioned buildings.
[c] Model developed for all type of buildings (free running, mixed mode, conditioned).

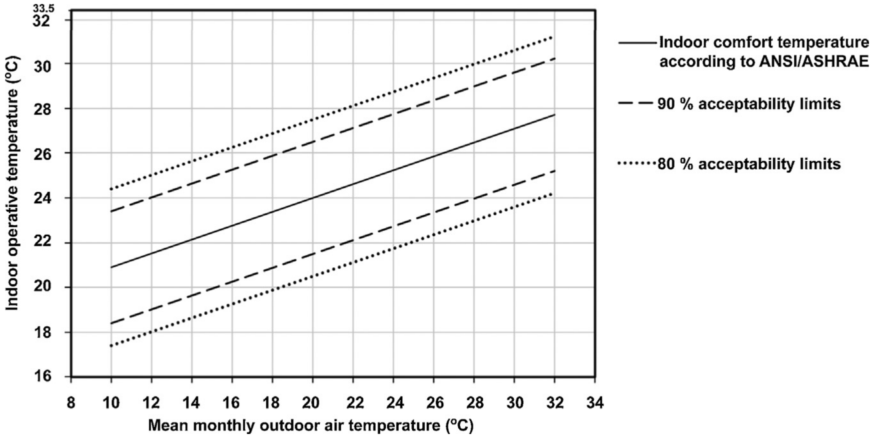

Fig. 2. Indoor comfort operative temperature as a function of the exponentially weighted running mean of outdoor dry-bulb air temperature according to EN 15251.

(50 ÷ 91.4 °F) [47] and is delivered together with and indication about comfort boundaries as shown in Fig. 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 °C and ±2.5 °C, respectively from the optimal comfort temperature (Fig. 2) [45].

This comfort model presented in the ASHRAE 55 derives from a previous work of de Dear et al. [37]. According to this study, the optimal comfort temperature is computed by using the monthly mean new effective temperature (ET*), calculated on a calendar monthly basis, and ranges in the interval °C [5,33]. In this report it is not reported how dealing with monthly mean new effective temperatures that extend outside such interval. In 1998, ASHRAE committee SSPC 55 accepted to include an adaptive comfort model in the next revision of the ASHRAE Standard 55. However, a number of modifications were carried on the original adaptive model during the revision process. They mainly were 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" [45]. The first modification consisted in changing the independent variable for the calculation of the optimal comfort temperature: the original new effective temperature is 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 model which aims at computing the heat flow exchanged by the human body core towards the environment, passing through 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

$$T_C^{ASHRAE\quad 55} = 0.31T_0 + 17.8$$

where, T_0 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 °C [5,33] (Fig. 3) [52].

Finally, the ASHRAE committee SSPC 55 considered the lower values too low and did not reach an agreement on how dealing with the temperature outside the range of measured data and decided (i) to truncate the lines of the graph at the end-points of the range "regardless of what the data actually showed" [45], 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" [45].

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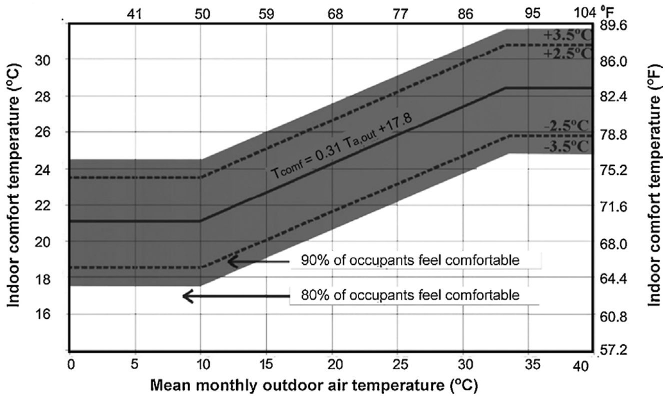
[1] The new effective temperature is defined as: "the temperature (DBT) of a uniform enclosure at 50% relative humidity, which would produce the same net heat exchange by radiation, convection and evaporation as the environment in question" [33].



Tcomf : Optimum comfort temperature for naturally venitlated building
Ta, out: Mean outdoor dry-bulb temperature from minimum and maximum daily air temperature ventilated building

Fig. 3. Acceptable operative temperature ranges for naturally ventilated spaces based on the ASHRAE Adaptive comfort model, reproduced from [45].

Many researchers, however, challenge 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 identified. Indeed they proposed and extended version of the original PMV model, which also take into consideration all 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 in consideration in hot climates [5]. 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 unconditioned buildings become accustomed to, and grow to accept higher temperature or humidity. However, a proposed addendum in September 2008 suggested the use of the PMV model to air speeds below 0.20 m/s. Air speeds greater than this value may be used to increase the upper operative temperature limits of the comfort zone in certain circumstances. This could be achieved by using ceiling fans to elevate air speed to offset increased air and radiant temperatures. As shown in Fig. 4, elevated air speed 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.

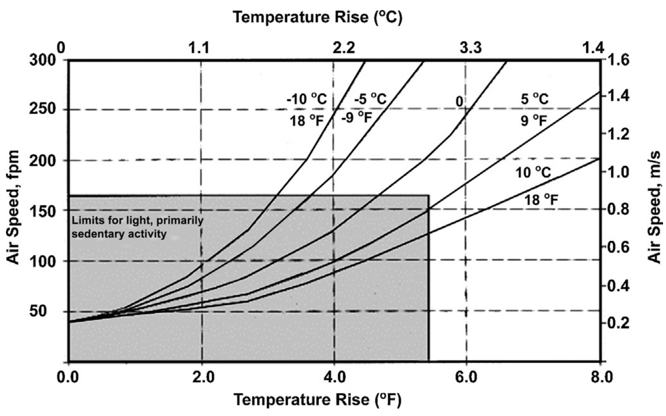


Fig. 4. Air speed required offsetting increased temperature, reproduced from [24].

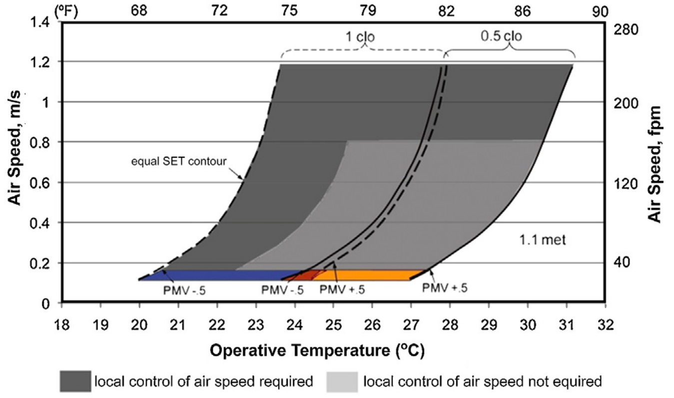


Fig. 5. Acceptable ranges of operative temperature and air speeds, reproduced from [24].

But the ceiling fans effect cannot control humidity and depends on clothing and activity. Fig. 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 then indoor temperatures must respect those defined by the Fanger model plus 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 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 the implementation of the ISO 7730 model (see Fig. 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

$$T_C^{\mathrm{EN\ \ 15251}} = 0.33T_{\mathrm{rm}} + 18.8$$

$$\text{with}\quad T_0 = (1-\alpha)\sum_{i=9}^{n}\left(\alpha^i T_{\mathrm{e}}|_{-(1+i)}\right)$$

where, T_{rm} is the exponential weighted running mean of the daily outdoor dry-bulb air temperature, $T_e \left|\right| - (1+i)$ is the daily mean outdoor dry-bulb air temperature of the previous $(1+i)$ day and α is a constant included in the range [0, 1], but a recommended value is 0.8 in order to simplify calculations the standards EN 15251 suggest a simplified equation to calculate the exponential weighted running mean of the daily outdoor dry-bulb air temperature:

$$T_{\mathrm{rm}} = \frac{T_{\mathrm{e}}|_{-1} + 0.8T_{\mathrm{e}}|_{-2} + 0.6T_{\mathrm{e}}|_{-3} + 0.5T_{\mathrm{e}}|_{-4} + 0.4T_{\mathrm{e}}|_{-5} + 0.3T_{\mathrm{e}}|_{-6} + 0.2T_{\mathrm{e}}|_{-7}}{3.8}$$

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.

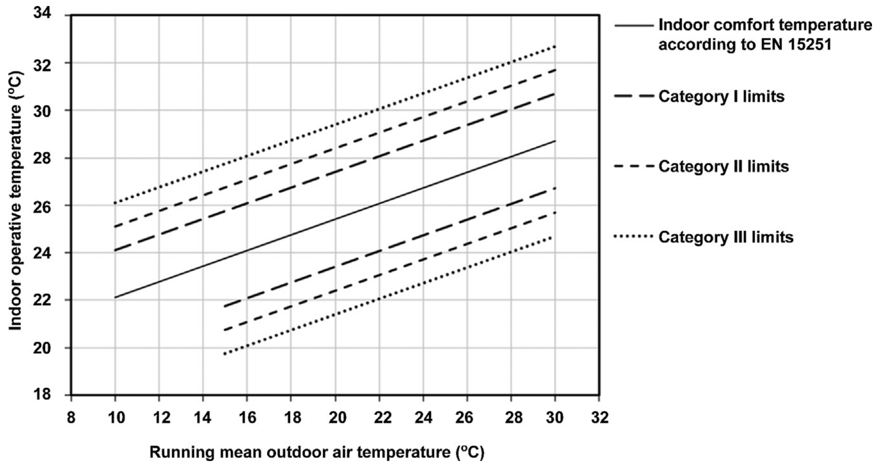


Fig. 6. Indoor comfort operative temperature as a function of the monthly mean outdoor dry-bulb air temperature according to ANSI/ASHRAE 55.

Table 2
optimal comfort temperature and the upper and lower limits of the comfort categories.

EN 15251 category	Description	Fanger model		Adaptive model
		PPD (%)	PMV	DT_{op}(K)
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons	≤6	$-0.2 \le PMV \le +0.2$	±2
II	Normal level of expectation and should be used for new buildings and renovations	≤10	$-0.5 \le PMV \le +0.5$	±3
III	An acceptable, moderate level of expectation and may be used for existing buildings	≤15	$-0.7 \le PMV \le +0.7$	±4
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year	>15	$PMV < -0.7$ OR $PMV > 0.7$	

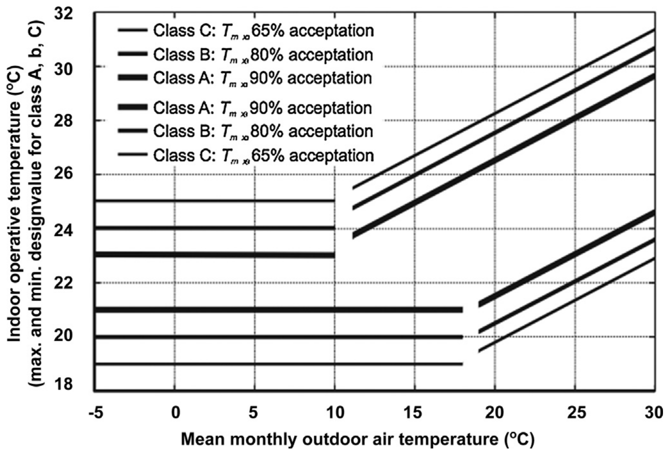


Fig. 7. Design values for the indoor operative temperature as a function of mean monthly outdoor air temperature for buildings without mechanical cooling systems, reproduced from [54].

In Table 2 the upper comfort boundary is defined for a running mean indoor air temperature from 10 °C to 30 °C and the lower comfort boundary from 15 °C to 30 °C (Fig. 6).

In order to understand this difference in the temperature boundaries, we refer to the category ranges proposed by Seppanen et al. [54] (Fig. 7). Although they use the mean monthly outdoor air temperature as independent variable instead of the running mean of outdoor air temperature, also in Fig. 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, 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 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 temperature rather than the outdoor conditions. The BBCC, represented in Fig. 8, presents boundaries of 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 Fig. 8, is considered as the best representation of climatic variables [55]. In 1992, Givoni proposed two sets of boundaries for developed and hot developing countries with a suggested elevation of 2 K [5]. Recent researches based on dynamic thermal simulation have indicated the inaccuracy of the boundaries [56] and highlighted the lack of diurnal and seasonal variations that may impact the pattern use of the passive strategies [57]. At early stages of the design, indoor temperatures can hardly be identified since the design is still immature.

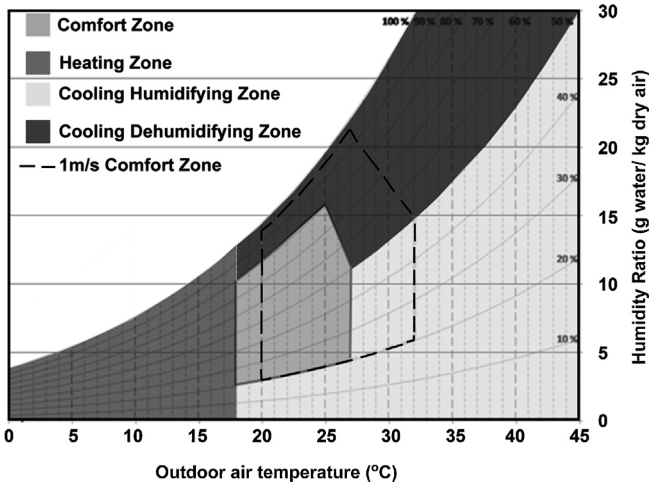


Fig. 8. Givoni's building bioclimatic chart, reproduced from [5,19].

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 [58] on the modeling, design, and optimization NZEBs and Doiron 2011 [59] on energy performance and comfort. However, only few publications addressed thermal comfort for NZEB's in hot climate. This includes the work of PIMENT Laboratory at the University of La Reunion [60–62] that focused on the assessment of occupant comfort using post occupancy evaluation for two low-tech naturally ventilated NZEBs in tropical climate. Also The work of Georgio [63], Cellura et al. [64,65] and who 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. Their most recent work investigated the NZEB energy building performance in the Italian climate [66]. In 2014, Causone et al. [67] published a paper on design of 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 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 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. ~~However,~~ historically, the first comfort model integrated in 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 [68], then by the International Organization for Standardization (ISO) in the international standard ISO 7730 in 1984 [69]. Some revisions of both these standards were presented in 1992 [70] and in 1994 [71]. In 1995, Parsons [72] and Nicol [73] found that western world standards are not appropriate for many countries, especially hot climate countries, and an updated international standard for thermal comfort would have been required [38,69]. In 2004, ASHRAE 55 was revised and introduced for the first time the adaptive comfort model developed by de Dear and Brager [36,45,74]. This standard suggests 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 [28]. In 2007, the European Committee for Standardization (CEN) introduced the European standards EN 15251, which suggests 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 type used mainly for human occupancy with mainly sedentary activities and dwelling" [1]. Therefore, the largest issue in this discussion remains the applicability of those standards and models of non-air-conditioned residential buildings in hot climate.

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 use 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.

5. Case study

A reference multi-residential building (Fig. 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) [75]. 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 a recent research [76], to develop a benchmark models for the Egyptian residential buildings sector. The benchmark model has been calibrated based on the surveyed monthly utility bills of 1500 apartments using two simulation programs. The building performance simulation (BPS) programs ZEBO and EnergyPlus were used to perform the analysis and assess the impact of using different thermal models [22,77]. The dynamic energy simulation of the building was performed using the software EnergyPlus [78], version 8.0.0.23. Each released version of EnergyPlus undergoes two major types of validation tests [79]: analytical tests, according to ASHRAE Research Projects 865 and 1052, and comparative tests, according to ANSI/ASHRAE 140 [80] and IEA SHC Task34/Annex43 BESTest method. Within the capability of EnergyPlus, the building models were set up with a priority to reproduce quite in detail the geometrical features of the building and the physical phenomena that determine the thermal behavior of the building, although this was at the expense of rather large computational times.

It was assumed to represent apartments in high urban densities of Egyptian cities, incorporating surrounding buildings and streets. The benchmark developed to describe the energy need for space

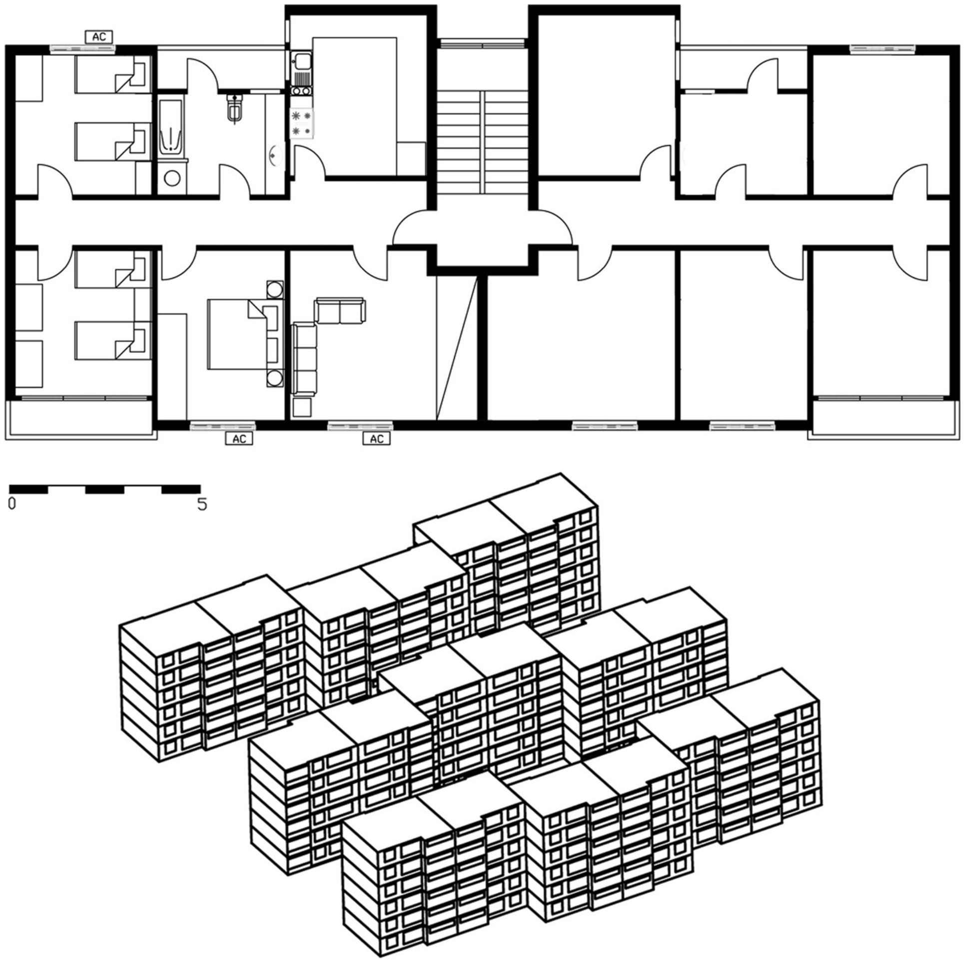


Fig. 9. 3D model representation of the reference case of the apartment and its urban surrounding.

Table 3
Benchmark model and maximum energy efficiency characteristics.

	Properties	Benchmark characteristics	Measures for NZEB
1	Orientation	0°	345°
2	Shape	Rectangular (12 m × 10 m)	Rectangular (12 m × 10 m)
3	Floor height	3 m height	3 m height
4	Roof *U*-value	$U = 1\ \mathrm{W/m^2\ K}$	$U = 0.2\ \mathrm{W/m^2\ K}$ with radiant barrier
5	Wall *U*-value	$U = 2\ \mathrm{W/m^2\ K}$ (no radiant barrier)	$U = 0.4\ \mathrm{W/m^2\ K}$ with radiant barrier
6	WWR	35%	20%
7	Window system	$U = 5.8\ \mathrm{W/m^2\ K}$, SHGC: 0.6 – single pane in aluminum frame, Tv = 0.86	*U*-value: $0.8\ \mathrm{W/m^2\ K}$, SHGC: 0.25, Double pane low-E, argon, fiberglass frame, Tv = 0.6
8	Operable shading	Operable window without exterior shading	Venetian blinds close if sun on window and indoor temp above comfort
9	Overhang	None	1 m overhang and fins (E,W, S)
10	Night insulation	Not considered	50% reduction in glass conductance, insulated roller shutter
11	People density	$0.033\ \mathrm{people/m^2}$	$0.033\ \mathrm{people/m^2}$
12	Infiltration	1.5 ACH	0.6 ACH
13	Internal heat gain[a]	$19\ \mathrm{W/m^2}$ from lighting, $12\ \mathrm{W/m^2}$ from appliances	$5\ \mathrm{W/m^2}$ from lighting, $7\ \mathrm{W/m^2}$ from appliances
13	Natural ventilation	Windows and doors are manually OPENED if cooling is needed	Windows and doors are manually OPENED if cooling is needed
10	Fan forced ventilation	No fans for comfort cooling	Fans for comfort cooling mode variable (Section 4.2)
11	Thermal comfort model cooling set point (°C) Relative humidity (%)	20 °C (68 °F) for heating, 25.5 °C (78 °F) for cooling (RH = 60%)	Variable (Section 4.2)
12	Heating system:	Gas furnace: AFUE 65%	–
13	Cooling system:	Split system: cooling COP 2.5	Split system: cooling COP 3.5
14	Ventilation system	none	Hybrid with Mechanical Ventilation with heat recovery: 85%, fresh air 20 ($\mathrm{m^3/h}$ per person)
15	DHW system	50-gallon electric water heater, 0.86 energy factor	50-gallon gas water heater, 0.86 energy factor
16	PV system	None	$10\ \mathrm{m^2}$ mono-crystalline., 16%

[a] Constant internal gains were obtained from annual equipment and lighting energy use, using conventional vs. energy-efficient appliances, $0.8\ \mathrm{W/m^2}$ (incandescent) vs. $0.17\ \mathrm{W/m^2}$ (CFL) Installed lighting wattage and identical usage profiles for the base-case and maximum efficiency option.

heating and cooling, lighting, production of domestic hot water and electric appliances in respect to buildings layout and constructions (Table 3).

Table 3 lists the base-case and code compliance characteristics in addition to 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. The impact of combined application of these measures on the annual delivered energy required by the building is shown in Table 3.

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 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 with determining the annual average energy use for space heating and cooling to determine user's electric consumption patterns and spikes. By this, the research acquires a starting point for comparing the energy output of various systems in relation to the key available comfort models. 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 include 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 variation were investigated to identify the impact and variation in reaching the NZEB performance objective as presented in the following section.

5.1. Thermal objectives, set-point values and results

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

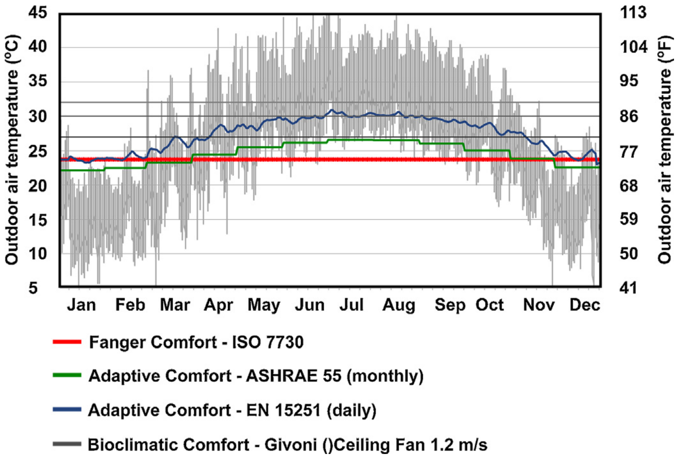


Fig. 10. The application of four models for Cairo in relation to operative temperature.

Table 4
The application of four comfort models for Cairo in relation to annual energy consumption.

Comfort model	Annual energy consumption $kW\,h/m^2$
ISO 7730	58
ASHRAE 55	46
EN 15251	35
Bioclimatic comfort	24

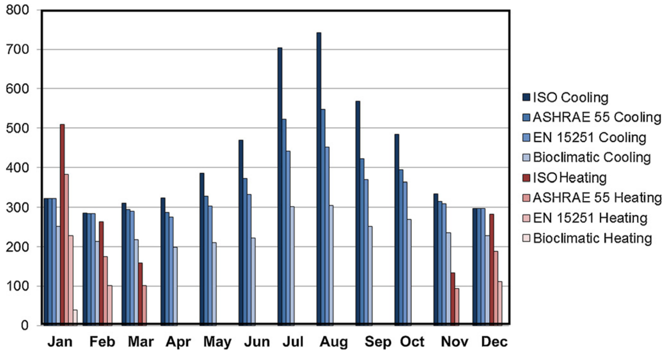


Fig. 11. The monthly energy need for cooling and heating due to the adoption of, ISO 7730, ASHRAE 55 and EN 15251 and Givoni's Bioclimatic Model.

In order to calculate the optimal comfort condition according to the Fanger comfort model, we assume that the dry-bulb air temperature is equal to the mean radiant temperature (hence equal to the operative temperature), indoor air relative humidity is equal to 50%, air velocity amounts to 0.1 m/s, 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.

Fig. 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. In Fig. 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 reference set-point conditions obtained adopting also 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 with 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 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 to be in steady-state conditions.

6. Discussion

The variation in the comfort model is so huge and summarizes 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 temperature reaching 30 °C. Generally the, application of the adaptive models (both 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 [81]. In these cases there is no energy need for 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 [49,50,82].

The second objective of this paper is investigating 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 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 was estimated as $10 \div 18\%$ of the overall cooling load. The research outcome would have a stronger impact if we used 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 or in those buildings without a mechanical cooling system[2] (EN 15251), or in a (occupant-controlled) naturally ventilated building[3] (ASHRAE 55). Even if to apply 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 [83] 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 to limit the scope of the Fanger static model only to 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 [84–87], which are typically referred as mixed-mode non air-conditioned buildings. Moreover, there is evidence in the scientific literature that mixed mode buildings are considered more similar in their operation to naturally ventilated buildings than to fully air-conditioned ones. Rijal et al. [87] and Humphreys and Nicol [85] observed that 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 [88]. The EN 15251 adaptive comfort model, with its wider range of acceptable conditions, could promote longer operation of natural ventilation; reduce the dependence on mechanical cooling and consequently save ventilation and cooling energy [36]. The thresholds that regulate the alteration between active and passive modes have to respect the adaptive comfort criteria especially when sizing equipment [47].

Finally we believe that the urgent and concrete need to investigate the topic further. This could be maybe 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 still the occupant has a direct control on a few control opportunity, or in residential buildings where the occupant usually wants to maintain the control of the operation of building thermal systems for example to reduce operational cost.

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 cause a high different in the energy performance, at least in this case study. We do 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 area have not been clarified yet. 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 to be 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 do not derived 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 dataset of case studies in order to come up with initial or guiding generalization and finally allow us to suggest the hybrid use of different comfort model. We will include this paragraph to extend out discussion and study limitations.

7. 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 direct impact on defining NZEB in hot climates and the implications and requirements that influence the design. This study shows, that the percentage of energy consumption difference meeting the comfort criteria according to ISO 7730 in comparison to EN 15251, ASHRAE 55 or Givoni's model varied up to 16.0%, 21.0% and 24.7%, respectively. This contradicts with 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 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 occupant behavior the study has been based on, and provides information concerning their likelihood for variability due to different influences.

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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" [1].

[3] Those buildings where the thermal conditions of the space are regulated primarily by the opening and closing of windows by the occupants [25].

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Further Reading

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