Freezing from the Heat: Building Overcooling in Qatar

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Qatar has the unfortunate reputation of the country with the highest per-capita carbon emissions in the world, 15% of which is due to space cooling demand. We investigate the extent to which this demand is driven by ‘overcooling’ in non-domestic buildings, i.e. low indoor set-points resulting in wasted energy and cold thermal discomfort. Using a recently developed overcooling metric, ISO 7730 compliant sensors and occupant survey data comprising 2,472 responses from eight morphologically diverse office buildings, we find that 32% of occupants can be classed as uncomfortably cold. Our analysis implicates the application of the ‘international’ ASHRAE 55 thermal comfort standard in the observed overcooling. Using computer models of the studied buildings, we find that this overcooling is responsible for 27% of their cooling energy demand, translating to 4% of national cooling energy demand and 2% of carbon for all non-domestic buildings. Thus, a simple upward adjustment of set-point temperatures by ~2 °C in non-domestic buildings would greatly improve comfort and reduce energy consumption and carbon emissions without changing the building or its systems. This suggests an urgent need for a new localised thermal comfort standard, with wider regional applicability due to similar culture and climates.

Keywords: Building Energy; Thermal Comfort; Building Overcooling; Cold Thermal Discomfort; Warm and Hot Climates.

Practical Application

Eliminating building overcooling yields in a notable reduction of 8.5% of cooling energy demand for every 1°C increase in the indoor setpoint temperature. This reduction results in an average of 32.3 kW·h/m2/yr in a typical office building in Qatar. A comfort temperature of 24.9 °C is suggested which is on average of 1.5 °C warmer than the currently applied indoor temperature setpoint, resulting in substantial cooling reductions and increased thermal comfort. In practice, raising the indoor setpoint temperature by 2 °C could prevent building overcooling, improving indoor thermal comfort and reducing cooling energy demand across in warm climates.

1 Introduction

Qatar is a fossil fuel rich country situated in the Middle East and part of the Gulf Cooperation Council (GCC). The abundance of energy sources and economic opportunities has led to the rapid modernization and urbanization of the country resulting in a significant expansion of the built environment. Electricity consumption in Qatar is increasing at a rapid rate. For example, it doubled (22.6 TW·h to 47.1 TW·h) between 2009 to 2019 which, in 2019, was roughly five times greater than the global average per capita (1). The low cost of electricity, often free at the point of consumption, has exacerbated demand for HVAC cooling, contributing in turn to the highest per capita carbon emissions in the world at 30.7 tCO_2/capita in 2019 (1).

Qatar experiences a hot desert climate (BWh) according to Köppen and Geiger (2). Summer peak temperatures often reach 43°C, with continued high temperatures averaging over 30°C for 8 months in the year. Thus, active space cooling is unavoidable for many months. While data disaggregated by end-use is hard to come by, recent studies estimates that 36% of all energy use goes towards cooling, split 14% non-domestic consumers to 22% domestic consumers (3–7).

There are two main mechanisms for reducing energy demand for any given service: reducing or eliminating wasteful use (e.g. turning off the service when it is not needed) and improving the efficiency with which the service is delivered (e.g. improving system coefficient of performance). In this paper, we are interested in investigating the former. That is, whether a proportion of Qatar's demand for air-conditioning is wasteful; specifically, whether it is *designed* in a manner that results in wasteful energy expenditure through unduly low indoor temperature setpoints.

Although no nationally prescribed thermal comfort standard exists, there is some evidence to suggest (8) that buildings in Qatar, and more widely in the region, rely on the American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) Standard 55 (9) which is based on the Predicted Mean Vote (10) enshrined in BS EN ISO 7730 (11). It is also the standard prescribed by the leading green building rating system the Global Sustainability Assessment System (GSAS) (12) in Qatar and is hence seen as "good practice".

Whilst claiming global validity, BS EN ISO 7730 and the standards that adopt it, such as ASHRAE Standard 55 and the European Standard EN 16798-1:2019 (13), were developed in the cooler latitudes of North America, Europe and Australia. The application of these standards in warm climates is based on a belief of universal applicability, which has not always stood the test of field data (10,14). The model's Predicted Mean Vote (PMV) has been examined in several studies for its applicability to air-conditioned buildings in warm climates and significant deviations between the mean Thermal Sensation Vote (TSV) and the PMV have been frequently observed in field studies (15–22). In these data, $\Delta_{\overline{TSV}-PMV}$ ranges between -0.2 and -0.5 points on the seven-point sensation scale (-3 = cold, 0 = neutral, +3 = hot). These are substantial given the clear cold bias and the fact that most buildings will be designed to a tolerance of ±0.5 points either side of neutral (i.e. 0) on the same scale and in the case of sealed buildings to within ±0.2. Indeed, this is not the first instance of the PMV model's poor predictive power in specific settings. The development of the adaptive comfort models for naturally ventilated buildings and their eventual enshrinement in standards such as ASHRAE is a result of the discrepancies in comfort between the steady-state model and field observations in naturally ventilated buildings (9,16,23,24).

Hence, the international community is becoming ever more aware of the limitations of applying a universal interpretation of thermal comfort standards around the world leading to, for example, India recently developing its own thermal comfort standard (25). The cold bias noted above, coupled with the peculiar energy and carbon circumstances of Qatar prompt us to investigate this issue from the standpoint of overcooling, discussed further below.

2 Overcooling

The phenomenon of building overcooling is understood to be the excessive cooling of a building which necessitates the purposeful, but ultimately wasteful, expenditure of energy resulting in occupant cold discomfort. In Qatar and across other warm climates, overcooling is ever more prevalent in air-conditioned buildings during the warm seasons (17,26–31). Anecdotally, overcooling and occupant complaint of being cold inside buildings during warm seasons has been observed across different building types such as offices and shopping centres (32–34). Most common accounts of overcooling in buildings are that of occupants feeling "too cold" or "freezing" while outdoor temperatures are much warmer (32–34). In addition to the increase in occupant discomfort, building overcooling results in the unnecessary use of energy. This has the two-fold implication of increased energy expenditure on the one hand with reduced income from decreased worker productivity on the other (35,36).

In Qatar, across several studies investigating thermal comfort, an apparent disconnect between standard-predicted comfort and occupant responses has been observed (8,17,31,37). In the Middle East and North Africa (MENA), the adoption of global standards has been observed through occupant responses to be a source of overcooling in warm climates (8). To assess occupant discomfort, subjective metrics such as the thermal sensation vote (TSV, on the same scale as PMV above) and the thermal preference vote (TPV, on a n-point scale, where n is 3, 5, or 7) are used. The TSV and TPV are used to directly indicate the occupants' response to the thermal condition for both their sensation and preference and can represent whether an occupant is experiencing discomfort or not (37,38). Occupant discomfort due to being cold is observed and recorded across numerous field visits conducted within different thermal comfort assessment studies of buildings in Qatar (17,37). Crucially, no significant complaint was reported by occupants from being discomfited by the heat across these studies (17,37). Using thermal comfort models such as the Predicted Mean Vote (PMV), discomfort is described as a PMV occurring outside the comfortable range [-0.5, +0.5] (10,39,40). The PMV within the studies in Qatar was observed to overestimate the occupants' responses to the actual conditions, i.e., in each case mean TSV was observed to be cooler than PMV (17,37), underlining PMV's unsuitability. Additionally, in the studies which sampled building occupant responses across a range of indoor temperatures from nearly 20°C to 26°C, mean comfort temperatures were determined using Griffiths well-known method (41) to be between 23°C to 27°C, i.e. on the warmer side of the studied range (37). It is noteworthy that green building guidelines in Qatar such as GSAS, following ASHRAE-55, usually suggest a set-point temperature range of 22°C - 25°C, the midpoint of this range being 1.5°C below the midpoint of the observed comfort temperature range in studies discussed above (12,42).

In previous work, we have shown that combining TSV with TPV is the safest means of measuring overcooling (38,43). Using the ASHRAE Global Thermal Comfort Database II (ATCD-II), we demonstrated that in the global south, on average, 17% of building occupants were overcooled (38). Decreasing over-cooling and cold discomfort for occupants in warm climate buildings, will reduce building cooling loads and negate additional energy expenditure (43). Building performance simulations have shown that an average reduction in cooling energy demand of 15% can be observed across several cities in the Global South, by recalculating comfort temperature setpoints (38).

The definition of overcooling in earlier research was appropriately approached directly from the standpoint of thermal comfort to provide a measure of overcooling in buildings. This paper aims to further this discussion by considering:

- How does this definition perform in actual conditions with a history of overcooling complaints?
- What locally derived indoor conditions can be proposed to deliver the greatest level of comfort for occupants?
- How does the design of major building elements affect the energy demand within the proposed comfort conditions?
- What setpoints provide the best balance between maximising thermal comfort and minimising energy consumption in Qatar offices?

3 Methods

Qatar's climate is mostly hot and humid in the summer, warm in the shoulder seasons, with a moderate winter. The summer period in Qatar is from May to September with a mean monthly temperature ranging from 33°C to 37°C; the winter period is between December to February with a mean monthly temperature ranging from 20°C to 24°C, the rest being shoulder months. The summer season in Qatar is hence the period with the greatest reliance on active cooling systems, with some cooling continuing into the shoulder months.

Establishing the comfort and energy impact of overcooling on occupants and office buildings in Qatar involves: (1) collecting thermal comfort data within buildings during the summer season in Qatar, (2) evaluating the collected building occupant responses to overcooling observed in Qatar, (3) evaluating comfort across the range of indoor temperatures recorded in the field (4) simulate the energy demand for cooling across the recorded building operation range combined with varying building design characteristics, and (5) explore the balance between comfort and energy in typical office buildings in Qatar (Figure 1).

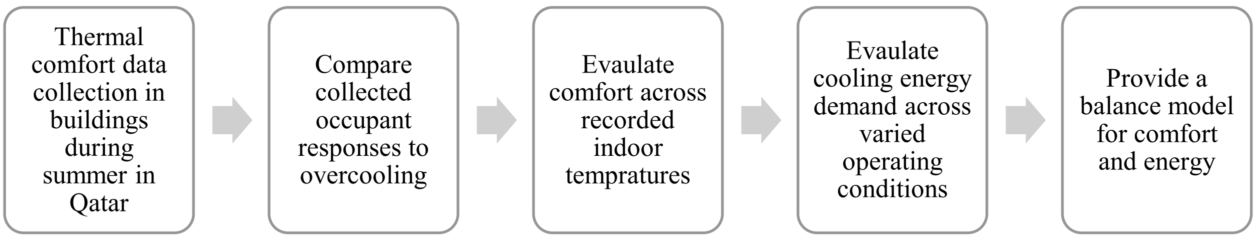


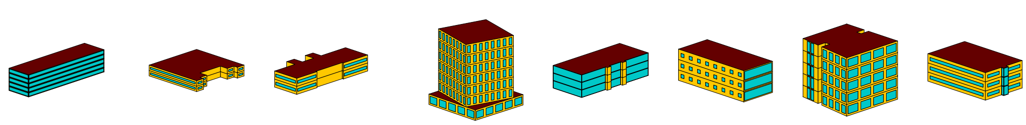
Figure 1 Summarized research steps flowchart highlighting the key stages in the collection, analysis, and evaluation of the research.

3.1 Building Data Collection

Targeting the season with the highest demand for cooling in Qatar, a data collection campaign commenced in June and ended in late August during the summer season of 2019. A total of eight buildings, five private and three public, were visited during this period. A total of 423 occupants were sampled over the collection period resulting in 2,472 responses.

The studied buildings were all office buildings with multiple stories and an open planned office layout holding multiple occupants in the office areas during working hours. A few mixed-use spaces were included in several of the buildings. The construction of the buildings studied resemble a typical International Style in architecture. The building facades are a combination of glass as a transparent component and a variety of cementitious materials (e.g. cement blocks, gypsum board panels) for opaque components in varying degrees. The average façade glazing ratio (FGR) is approximately 55% with the highest observed FGR being 75% and the lowest 35%. The buildings are located in various urban contexts ranging from low density (2 floors or less), medium density (3 to 5 floor), to high density (6 floors for more). These buildings hence represent a diversity of morphologies and constructions within Qatar. A summary of the building characteristics is provided in Table 1.

Table 1 Building Characteristics Summary

Ownership	**Public (A)**			**Private (B)**				
Building	A1	A2	A3	B1	B2	B3	B4	B5
Image								

Single Floor Area (m^2)	4,700	4,350	1,800	1,200	2,100	2,000	1,100	1,600
Total Floor Area (m^2)	23,500	8,700	3,600	8,400	6,300	6,000	5,500	4,800
Number of Floors	5	2	2	7	3	3	5	3
FGR	75%	35%	60%	40%	70%	65%	50%	40%
Façade Wall Construction	Aluminium cladding over built up gypsum wall	Plastered cement block wall		Plastered cement block wall		Aluminium cladding over cement block wall		
Façade Glass Construction	Aluminium frame double glazed windows			Aluminium frame double glazed windows				
Urban Density	High	Low	Low	High	Low	Medium	Medium	Medium
Average Daily Outdoor Temperature ★ (°C)	39	42	47	43	38	41	41	39

★ Qatar Meteorology Department

The data collection was focused within the office spaces of the selected buildings, which were typically open-plan in nature and centrally air-conditioned and hence with little occupant control. The three public buildings (A1-A3) are managed by governmental entities which includes the operation costs of the buildings such as electricity costs – i.e. the user is not directly responsible for the bills. The five private buildings (B1-B5) were tenant-occupied. The tenants were hence responsible for the operation costs of the spaces they utilized in the building. All buildings were visited during the workweek in typical institutional work hours in Qatar, between 8:00–14:00. None of the buildings visited used operable windows for cooling as external temperatures far exceeded comfortable ranges with a daily average of 41°C during the study period.

Four environmental parameters were collected for each building occupant using calibrated thermal environment measurement sensors that conform to ISO 7730 (11). The air temperature (T_a) and the relative humidity (RH) were taken using the Swema HC2A-S air humidity probe, the mean radiant temperature (T_{mrt}) was taken using the Swema 05 767370 globe temperature sensor, and the air velocity (A_v) was taken using the Swema 03 767360 anemometer. All sensors were calibrated before the field visits which conform to ISO 7730. Spot readings of the environmental parameters were taken at the desk of each building occupants' workplace. This was conducted for every participating building occupant in the entire study to connect occupant responses to their immediate thermal conditions.

3.2 Occupant Data Collection

Using the standardized questions for thermal comfort found in ISO 7730 (11), an anonymous questionnaire in both English and Arabic was used for the data collection. An explanation for the data collection procedures was given to all participating building occupants. In addition, consent was taken from all participating occupants for the collection of the required data for the thermal comfort assessment.

The questionnaires were used for the collection of occupant-specific subjective thermal comfort metrics. The TSV and TPV on a continuous seven-point thermal scale were recorded directly from the building occupants (37,38,43), and is summarized in Table 2. The TSV scale includes -3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, and +3 hot which would indicate the thermal sensation the occupant experience in the spaces they occupy. The TPV scale includes -3 much warmer, -2 warmer, -1 slightly warmer cool, 0 no change, +1 slightly cooler, +2 cooler, and +3 much cooler which indicate the users' preference of the thermal environment they occupy. Questions indicating if the occupants are "thermally comfortable" and if they feel "too cold" under the current indoor thermal condition were employed. Additionally, a question comparing the current office temperature to the typical home temperature for the occupants on a continuous seven-point thermal scale (warmer to cooler) was collected.

Given the context of Qatar and the internationally diverse workforce, it was expected to have varying clothing combinations ranging from western to non-western ensembles. The clothing insulation values (CLO) were evaluated from selections made by the occupant using a visual clothing aid depicting the ASHRAE index for non-western clothing ensembles (44) which represents what clothing combination best resembles what they were wearing during their participation. A question asking about how their level of clothing in the office is adjusted having anticipated the office temperature conditions was utilized. The building occupants were in open plan offices and seated for most of their time at work. The normative metabolic rate of work (70 W/m^2) corresponding to seating was ensured by distributing the questionnaire to building occupants that have been in a prolonged seated position, i.e. for twenty minutes or more.

The cold discomfort percentage (CD) and hot discomfort percentage (HD) is calculated by combining aligned votes (e.g., TSV cold discomfort and TPV cold discomfort) for the range of indoor temperatures observed during the field visit. Hot discomfort is considered with a TSV of (+1, +3] and a "cooler" TPV and cold discomfort being considered with a TSV of [-3, -1) and "warmer" TPV. Both CD and HD are normalized against all temperatures and compared to illustrate the discomfort type and intensity observed throughout varying thermal conditions during the study as demonstrated in earlier research (37,38,43). We use the well-known Griffiths method to determine the comfort or 'neutral' temperature (Tn (°C), Equation 1) which depends on the indoor globe temperature Tr (°C), TSV and the Griffiths constant G (°C). G is derived from thermal comfort studies conducted in both field and laboratory settings and varies widely from 0.25 to 0.513, with 0.5 being the most commonly selected value. However, in previous work, a value of 0.32 is suggested for occupants in warm climates and is hence used here (43).

Equation 1 Griffiths Method Equation

$$T_n = T_r + (0 - TSV)/G$$

The results to all questions are examined alongside the recorded indoor temperatures to examine the buildings occupants' attitudes and voting patterns towards thermal comfort in office buildings in Qatar.

Table 2 Summary of occupant data variables across all buildings

Source	Variable / Question	Measured (M) or Derived (D)
ISO 28802-2012	TSV, TPV	M
(43)	• $CD = \frac{\{(TSV,TPV): TSV < -1, TPV > +1\}}{total\ occupant\ votes}\%$ • $HD = \frac{\{(TSV,TPV): TSV > +1, TPV < -1\}}{total\ occupant\ votes}\%$	D
This paper	1. How does the temperature here and now compare to where you live now? (cooler (-3), warmer (+3)).	M

2. Based upon how you feel now, please specify how you feel the temperature. (cold (-3), hot (+3)).

3. Based upon how you feel now, please specify how you would prefer the temperature. (much warmer (-3), much cooler (+3)).

4. Do you feel that the air conditioning here and now is creating a condition that can be called “too cold”? (yes, no).

5. From your previous thermal experience of this space, are you wearing more or less clothes in responses to the conditions here and now? (less clothes (-3), more clothes (+3)).

6. Do you find the temperature to be comfortable? (yes, no).

3.3 Energy Analysis

In this paper we use the EnergyPlus dynamic thermal simulation engine (45) to estimate the cooling energy demand of typical offices in Qatar, over the range of observed indoor temperatures from the field study. As the intention is to evaluate the difference in cooling energy demand between various building cooling conditions and building design settings, notional building thermal models are used, rather than real buildings. The ANSI (American National Standards Institute)/ASHRAE/IES (Illuminating Engineering Society) Standard 90.1 provides such pre-calibrated thermal models which have been used successfully in similar comparative simulation studies (45,46). The use of the ANSI/ASHRAE/IES Standard 90.1 model which can be consistently simulated, allows the evaluation of different cooling and design permutations. The medium office prototype building model is initially selected based upon its similar function and floor area to the buildings studied and building model geometry and construction are edited to exhibit the actual envelope of the eight selected buildings simulated in (Table 1). The recorded indoor temperature range at 1 °C intervals (20 °C – 26 °C) observed during the field visit determine the eight indoor setpoint temperature conditions for the eight selected building simulations which is used to estimate the amount of energy they are using. Across all these simulations, a setback temperature of +2 °C outside building occupancy hours is used, based upon standard building recommendations (ASHRAE 90.1-2020) with an initial setpoint temperature simulation of 24 °C (46,47). Within the eight setpoint temperature simulations, we explore the varying impact of three building design characteristics (Table 1.): heat loss parameter (HLP), façade glazing ratio (FGR), and building obstruction angle (BOA).

The Latin Hypercube Sampling (LHS) approach is used to randomly sample the HLP, FGR, BOA values for evaluating the building cooling energy demand (48–51). LHS generates balanced random sampling of variables and is valuable in simulation studies for sampling in terms of uncertainty and sensitivity (48–51). The HLP is the sum of building fabric and ventilation losses and is sampled using LHS between ASHRAE 90.1-2022 code minimum levels (46,47) and Passivhaus design recommendations (52). The FGR is sampled from a minimal level that offers acceptable daylighting to a fully glazed building with a ratio between 0.30 and 0.90 (53–55). The BOA indicates the angle surrounding buildings obstruct the solar radiation and are sampled between 20° and 80° altitude from the base of the simulated building with a fixed azimuth of 0°, 90°, 180°, and 270° (i.e. we vary the height of the obstruction and not its length, the latter being treated as "infinite" and parallel to the wall surface for each orientation). Each building is sampled with eight variations of each of the three building design characteristics across the recorded indoor temperature range amounting 96 simulations for each building and a total of 768 simulations.

The simulations evaluate annual building cooling energy demand across several indoor conditions and design characteristics in a typical climate for Qatar. The average cooling energy demand reduction for the simulation is compared to cold and hot discomfort across the selected temperature range. This comparison suggests a possible model for the balance of comfort and energy in typical office buildings in Qatar. The optimal balance between comfort and energy consumption can be achieved by raising indoor temperatures to, initially, a level that just beyond the threshold for cold discomfort, as determined by the CD metric based on occupant votes, and subsequently, to raise indoor temperatures as high as possible without the introduction of hot thermal comfort, as determined by the HD metric based on occupant votes This approach allows for a reduction in energy usage that corresponds to the aforementioned increase in indoor temperatures.

4 Results

Throughout the five private and three public buildings visited during this period, a total of 423 questionnaires were completed and gathered which correspond to roughly 40% of the total building occupants across the eight buildings. As not all of the 423 participating building occupants answered each of the questions in the distributed questionnaire, the occupant responses consisted of a total of 2,472 responses to 6 questions from 432 occupants recorded directly from the building occupants. Appendix A provides the response rate against each question. Roughly 40% of the data collected was from the public buildings while the remaining 60% was collected from the private buildings. While only about 20% of the respondents were female overall, their percentage in public buildings is about 35%. This is broadly reflective of women participation in the workforce in Qatar (56). The building occupants' ages ranged from 20 years to 62 years with an average of 40 years which represents the occupational age in Qatar as 70% the economically active population (15 years and above) as represented by the Planning and Statistics Authority (PSA) of the State of Qatar are between 25-44 years (57).

The four key environmental parameters needed to compute PMV, T_a, T_{mrt}, RH, and A_v, were collected for all buildings in the study. Throughout the study period, the average indoor operative temperatures recorded for every participating building occupant observed was 25.7 °C at the highest and 19.7 °C at the lowest with an average of 23.7 °C across all buildings. The daily average outdoor temperatures observed during the study period was 47 °C at the warmest and 38 °C at the coolest. The average outdoor temperature for the entire study period was roughly 41.3 °C which is about 17.6 °C warmer than average indoor operative temperatures recorded (Figure 2), clearly suggesting the need for mechanical cooling and resulting in a mean indoor operative temperature of 23.4 °C across all buildings. However, public buildings produced a significantly lower mean indoor operative temperature of 22.7 °C compared to the private offices 24.1°C (22.7 °C - 24.1 °C, (paired t-test = $p < 0.05$)).

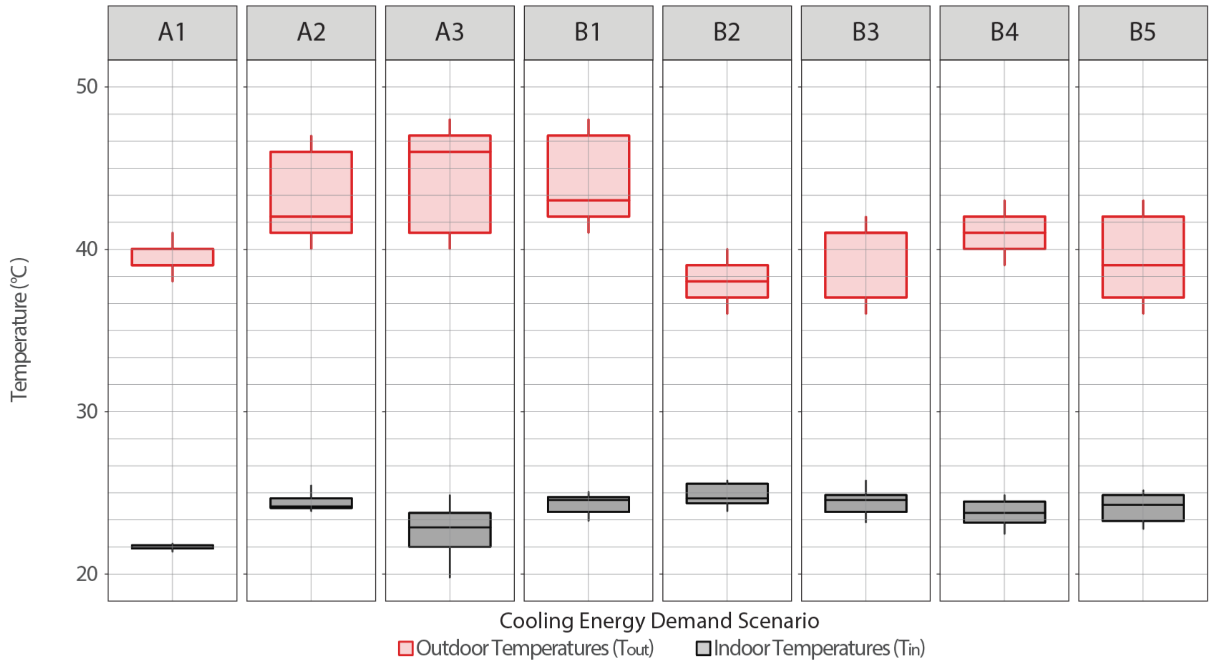


Figure 2 Outdoor (red) and indoor (black) temperatures observed during the entire study (15th June to 30th August 2019) for each building studied. The box and whisker plot shows the maximum, minimum, median, and upper and lower quartiles.

Examining the basic metrics for thermal comfort assessment identifies that the typical building occupant's sensation is slightly cool, and their preference is to have no change. The mean TSV is -0.39 averaged across all occupants' responses depicting a possible discomfort due to being slightly cool (Table 3). Examining the volume of votes on either end illustrates a greater sensation to being colder with roughly 40% of occupants voting between slightly cool to cold [-1, -3) compared to 17% voting from slight warm to hot [+1, +3). The mean TPV across all occupants' responses is closer to no change with a slight preference to be cooler at +0.16. The mean PMV is +0.69 warmer than TSV in this instance which is observed at +0.30 averaged across all occupants' responses on a seven-point scale (-3 to +3) (Figure 3).

Table 3 Occupant Thermal Comfort Data Summary

Ownership	**Public (A)**			**Private (B)**				
Building	A1	A2	A3	B1	B2	B3	B4	B5
N	47	42	59	32	79	73	52	39
Mean PMV	0.15	0.38	0.23	0.20	0.52	0.36	0.23	0.19
Mean TSV	-1.10	-0.09	-0.35	-0.08	-0.05	-0.51	-0.60	-0.33
Paired t-test (PMV-TSV)	t= (5.97), p = 0.000	t= (1.82), p = 0.076	t= (2.78), p = 0.007	t= (1.36), p = 0.181	t= (3.05), p = 0.003	t= (5.71), p = 0.000	t= (5.42), p = 0.000	t= (2.37), p = 0.024
Mean TPV	-0.09	0.35	0.03	0.28	0.18	0.11	0.09	0.49
Mean CD	26%	2%	20%	9%	9%	12%	12%	3%
Mean HD	2%	10%	8%	6%	10%	3%	0%	5%

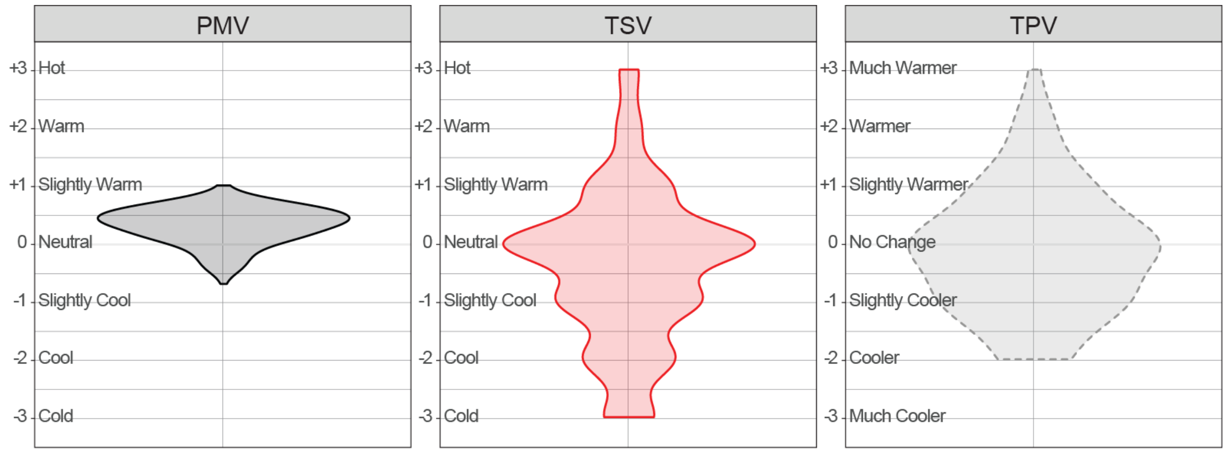


Figure 3 Building occupant PMV (black), TSV (red), and TPV (grey) observed during the entire study. The violin plot illustrates the voting density of the occupant data across the seven-point scale for PMV, TSV, and TPVs.

Examining the mean TSV and TPV in Figure 4 for the building occupants for the indoor temperatures observed during the field study, we find that TSV remains a negative value throughout the observed indoor operative temperatures. In cooler indoor temperatures, discomfort is substantial in contrast to warmer temperatures. In the indoor operative temperature range 20 °C to 22 °C, mean TSV between ranges from -1.59 to -0.83 and the occupant response weighted average is -0.94. Within these temperatures, occupant discomfort is evident and mean TSV is substantially lower than -0.50. However, between 23 °C to 26 °C, mean TSV ranges from -0.28 to -0.20 with an occupant response weighted average of -0.24. Mean TPV between 20 °C to 21°C is a negative value indicating a preference to be slightly warmer with a weighted average of -0.37 (Figure 4). Between 22 °C to 26 °C mean TPV is positive indicating a preference to be slightly cooler however at a lesser magnitude, compared to 20 °C and 21 °C, as observed by the lower occupant response weighted average of +0.21 of these bins from Figure 4. The mean PMV is negative at -0.43 only in the 20 °C bin, but can be considered comfortable given that it lies in [-0.5, +0.5] (Figure 4). In fact, the entire range of observed operative temperatures is seen as comfortable by PMV, except at 26 °C where it slightly exceeds the upper threshold of +0.5.

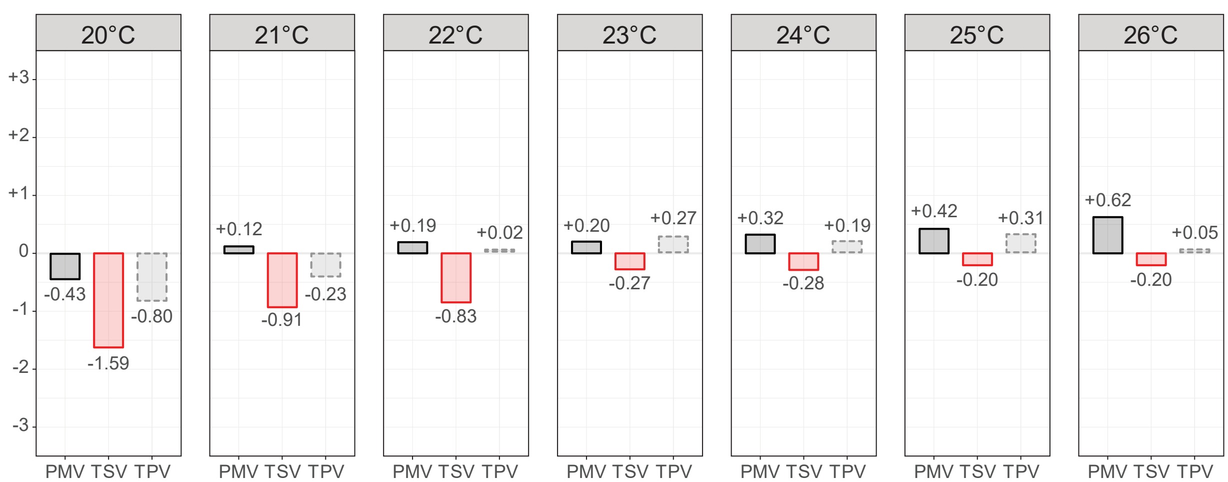


Figure 4: Building occupant PMV, TSV, and TPV binned by 1℃ indoor operative temperature (20℃ - 26 ℃) recorded during the study. Negative PMV values indicate that the given conditions are predicted to be cool, negative TSV values indicate the average surveyed occupant reports feeling cool and negative TPV values indicate a desire to feel warmer.

It is noteworthy that the only discomfort prediction by PMV across the range of observed indoor temperatures during the study, is that of being warm at 26 °C. The TSV and TPV all indicate a likely discomfort from being cool within the same indoor temperature ranges observed which represents the difference between occupant voting and the PMV across the temperature range. In addition, as TSV and TPV are communicated directly from the sensation and thus preference of the occupants, if occupants felt either comfortable or cold, adjustments in the occupants' clothing could result in a distortion of these metrics. Further, we explore the occupants' stance in the same indoor thermal conditions towards their comfort and if they feel too cold. Evaluating occupant comfort based upon the responses to the question examining whether the occupants are "thermally comfortable" and if they feel "too cold" under the current indoor thermal conditions identifies the occupant mindset to comfort in typical Qatari office buildings.

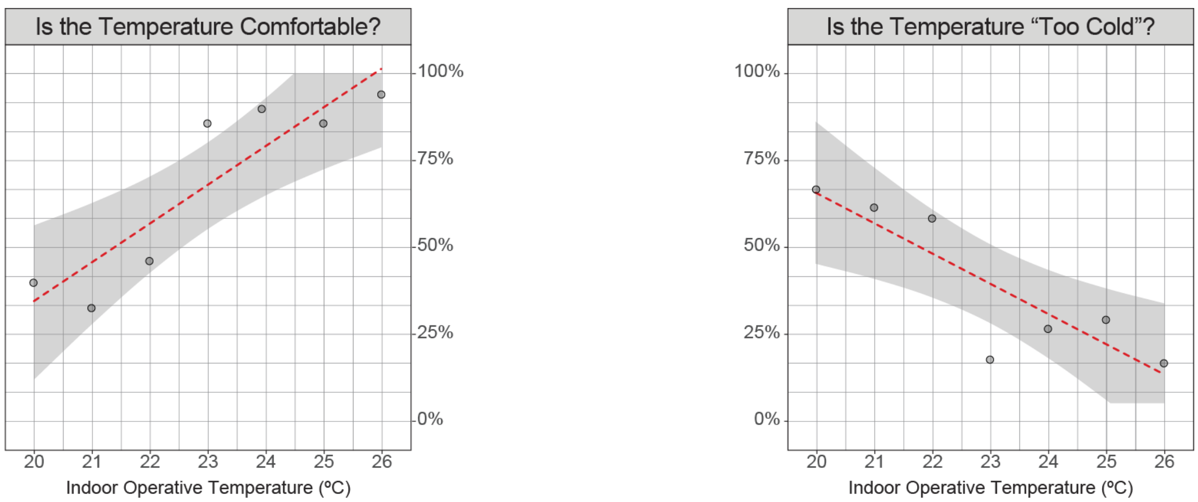


Figure 5 Proportion of occupants voting "yes" (y-axis) across a range of indoor operative temperatures for the following two questions. Left panel: Do you find temperature to be comfortable here and now? Right panel: Do you feel that the air conditioning here and now is creating a condition that can be called "too cold"? The red dashed line is linear regression across the votes and the 95% confidence intervals is shown in grey.

Figure 5 shows the percentage of occupants responding "yes" to 'right here right now' questions around whether the experienced thermal conditions are perceived to be comfortable and whether they associate the air-conditioning with excessive coolth. This produces the mutually consistent result of greater cold discomfort at lower temperatures associated with excessive air-conditioning.

Evaluating occupant responses for home temperature compared to office temperature and alterations to clothing based upon the anticipated office temperature, we find substantial increase in cooler office temperatures and office clothing.

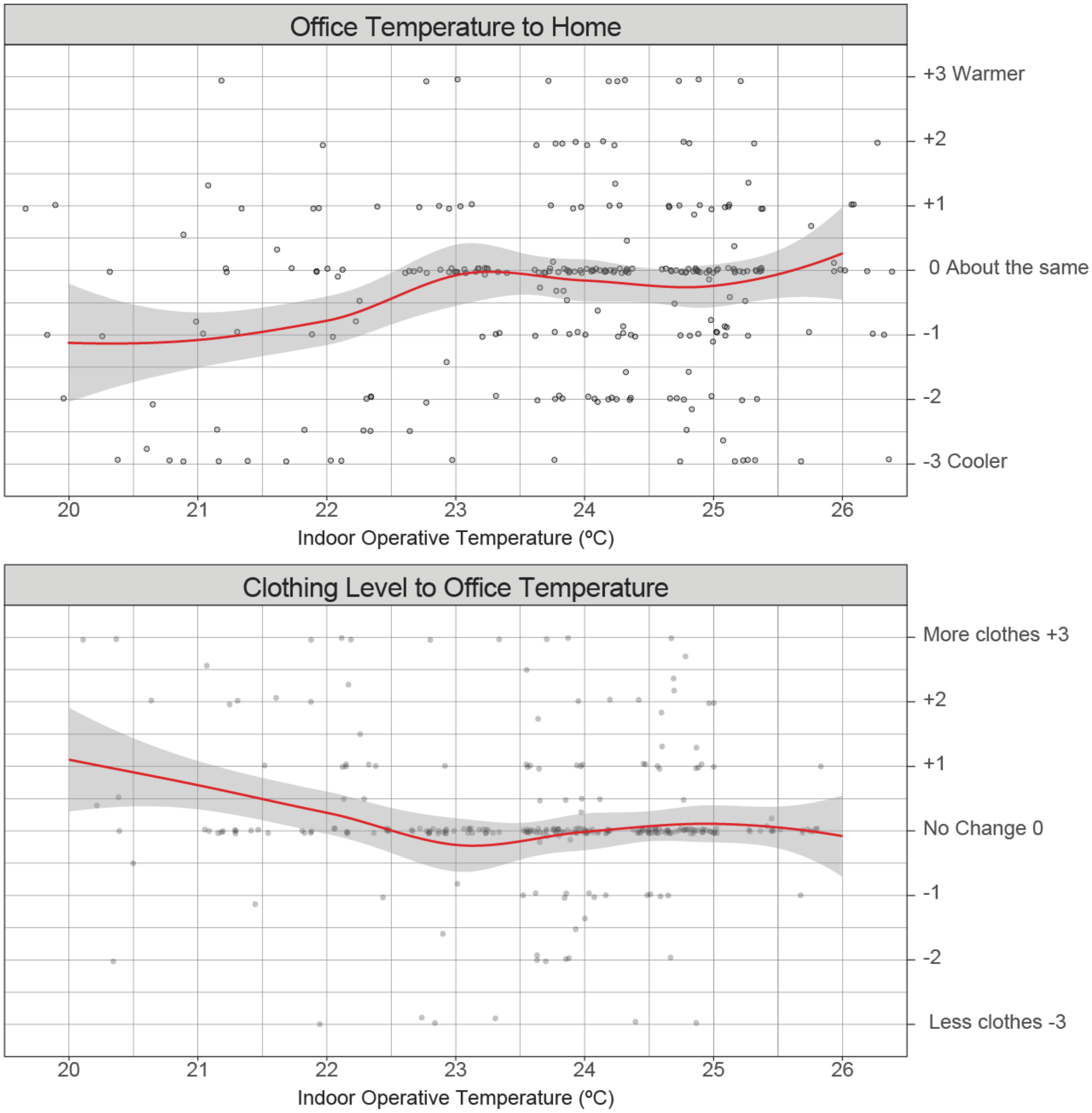


Figure 6 Occupant responses against the prevailing recorded indoor operative temperature during the field visit for, up, office temperature in relation to home temperature and, down, office clothing level in anticipation to office temperature. Data $\in [-1, +1]$ on the ordinate are 58% for up panel and 37% for the down panel. Data $\in [-2, +2]$ on the ordinate are 34% for up panel and 19% for the down panel. The red line corresponds to the average of the voting across the temperature range, while the grey band denotes the 95% confidence interval for predictions derived from the average line.

Figure 6 indicates that of the participants who think their office temperature is similar to the one they select at home (42%) the majority only do so when their office temperature lies between 22.5 °C and 25.5 °C. Of the remaining, 62% find their office to be cooler than their home, compared to 38 %.

The impact of the cooler than desired office temperatures can be seen when comparing those stating office temperatures are cooler than home and wearing warmer clothing, either as additional layers or warmer layers. The value for office clothing compared to anticipated office temperature (C_{off}) reveals that the occupants on average wear more clothing in the offices in the cooler temperature ranges. Average C_{off}

is positive indicating more clothing with an average of +0.28 across all temperatures. Notably, C_{off} at the coolest temperature of 20℃ is observed at +0.64 and at the warmest of 26℃ at 0.01 (Figure 6), suggesting that warmer office setpoint temperatures are more in line to what the occupant would set their home temperatures at. In cooler temperature ranges (20 °C to 22 °C), occupants who perceive that office temperatures are cooler are, on average, wearing additional clothing, suggesting that this is due to their discomfort with the colder indoor temperature than they are accustomed to Figure 7.

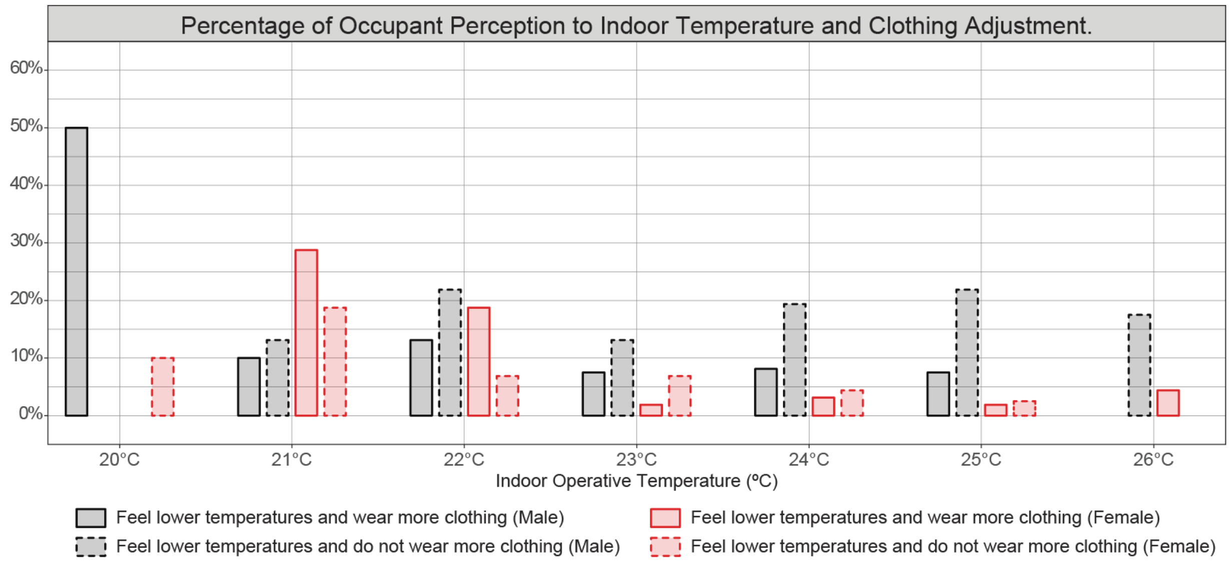


Figure 7 Percentage of occupants stating cooler office temperatures compared to home and percentage of occupants wearing more clothing, either as additional layers or warmer layers, in anticipation of office temperatures from the entire study binned by 1℃ indoor operative temperature for both male and female occupants.

In Figure 8, we now examine both the cold discomfort (CD) and hot discomfort (HD) percentages through the combination of aligned votes for TSV and TPV based on the work in (37,43). That is, hot discomfort is defined only when a TSV of (+1, +3] is associated with a vote for cooler conditions on TPV and cold discomfort where a TSV of [-3, -1) and "warmer" TPV are associated. When using these definitions, average CD is about 18% while HD is substantially lower at about 4% across all the temperatures. Considering that ISO 7730 requires the Predicted Percentage Dissatisfied (PPD) does not exceed 10%, a CD of 18% can be seen as representing serious discomfort. In fact, CD is often substantially higher at lower temperatures and at 20 ℃, stands at 50%. In contrast, maximum observed HD across the entire range of indoor temperatures is 8.1% (Figure 8). HD values across 20℃ to 26℃ are barely visible with an average of 4% across the range of indoor temperatures. This is likely a fluctuation in occupant responses as serious hot discomfort (i.e. HD > 10%) is not observed across 20 ℃ to 26 ℃.

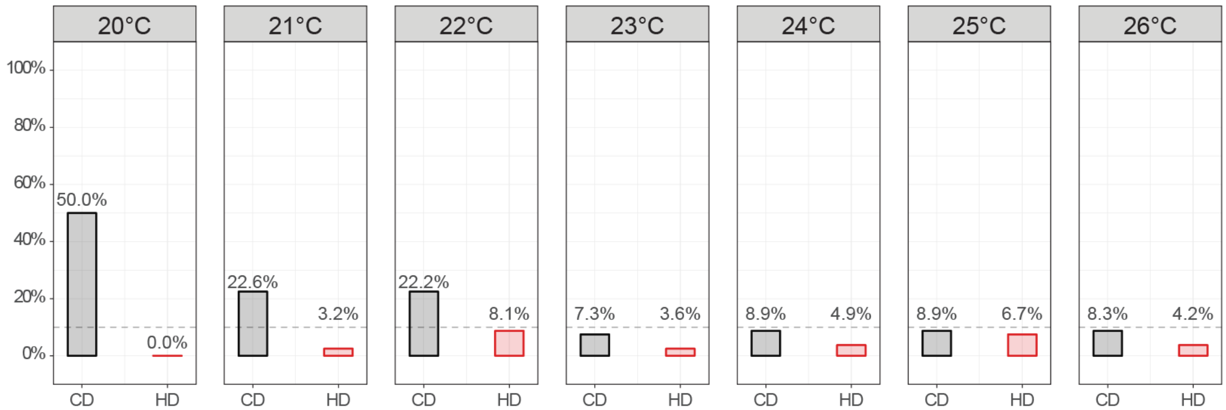


Figure 8: Percentage of occupants experiencing cold discomfort in black (CD) and hot discomfort in red (HD) from the entire study by 1 ℃ indoor operative temperature bins. The dashed line shows the maximum 10% PPD standard from ISO 7730 transposed on these data as an indication of the severity of cold discomfort.

Across all metrics and questions gauging comfort deployed in this study, substantial indications of discomfort are observed for the TSV, TPV, comfort question, too cold question, T_{off} question, C_{off} question, and CD in cooler temperatures. Temperatures between 20℃ and 22℃ seem to indicate the highest level of cold discomfort. However, at 23℃ and warmer, all metrics and questions examined indicate an increased acceptability for this temperature and warmer. This suggests that 23℃ might be where cold discomfort ends and comfort begins. However, to what extent does this local comfort range in Qatar influence the comfort and energy impact is further explored through energy simulation.

4.1 Energy Evaluation

Benchmarking against existing data is carried out as a sanity-check as we do not have time series data for our buildings. Qatar's Global Sustainability Assessment System (GSAS) recommends an energy performance coefficient (EPC) between $0.8 < EPC \leq 1.0$ for minimum energy compliance. The EPC is evaluated for a given building in kW·h/m²/yr by a ratio of the building energy demand to a reference energy of a notional building of 125 kW·h/m²/yr(12).

The simulated average annual energy demand across our eight buildings is 134.6 kW·h/m²/yr, i.e., an EPC of 1.07, which illustrates that in general these building consume more than the GSAS reference energy of a notional building. No data appear to exist in the literature on in-use performance data on energy consumption. One study using simulations produced by researchers at the Gulf Organisation for Research and Development (GORD), which is the body responsible for GSAS, found that mean energy demand for ten highly-glazed buildings in Qatar to be 181 kW·h/m²/yr (58). The highest FGR in our set is 75% for which we obtain mean a demand of 170 kW·h/m²/yr, close to the data from the above study. This suggests that our simulations are consistent with expectations for this type of building in Qatar.

Results in Figure 9 are from the simulation of the building design variables in EnergyPlus, representing a total of 96 cases per building: (4 FGR + 4 BOA + 4 HLP) × 8 Setpoints (20 °C to 27 °C) in one-degree intervals, resulting in a total of 768 simulations. We observe that the first quartile for BOA (i.e. an estimate of how low the cooling energy consumption might be for a well-shaded building) is approximately at the same position as the third quartile for BOA when the set-point temperature is increased by 2 °C (e.g. both are at a little over 100 kWh/m² for setpoints 20 °C and 22 °C). Thus, a 2 °C uplift in setpoint is equivalent to the savings accruing from a well-shaded building. The equivalent reduction for HLP is also 2 °C. FGR clearly has the largest effect amongst the studied building design variables such that the scale of savings accruing from selecting small windows (and hence lower solar gain) only achievable by an uplift in set points of nearly 4 °C.

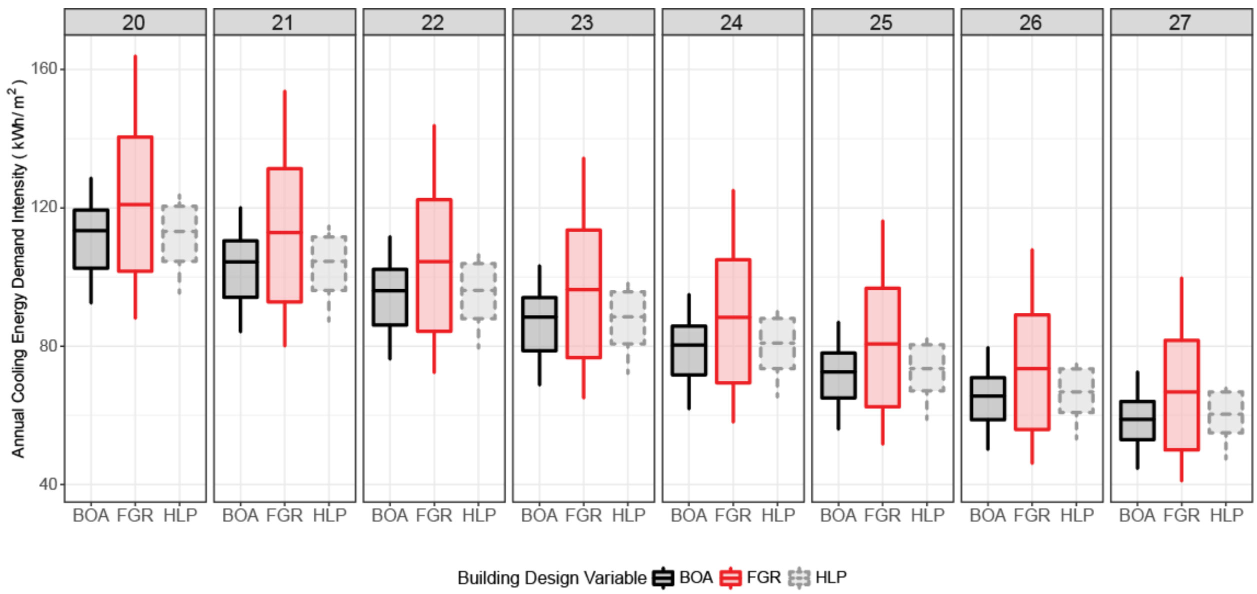


Figure 9 Annual cooling energy demand for the different building design variations for building obstruction angle, façade glass ratio, and heat loss parameter split by the different indoor setpoint conditions from 20°C to 27°C. The box and whisker plot shows the maximum, minimum, median, and upper and lower quartiles.

Evaluating comfort across the indoor temperature conditions, however, establishes instances where reducing cooling energy demand is rational. Considering both the CD and HD documented during the study across the range of indoor temperatures observed, a basic discomfort model is established. Considering the model, we can illustrate the occupant's experience towards comfort in typical office buildings in Qatar (Figure 10).

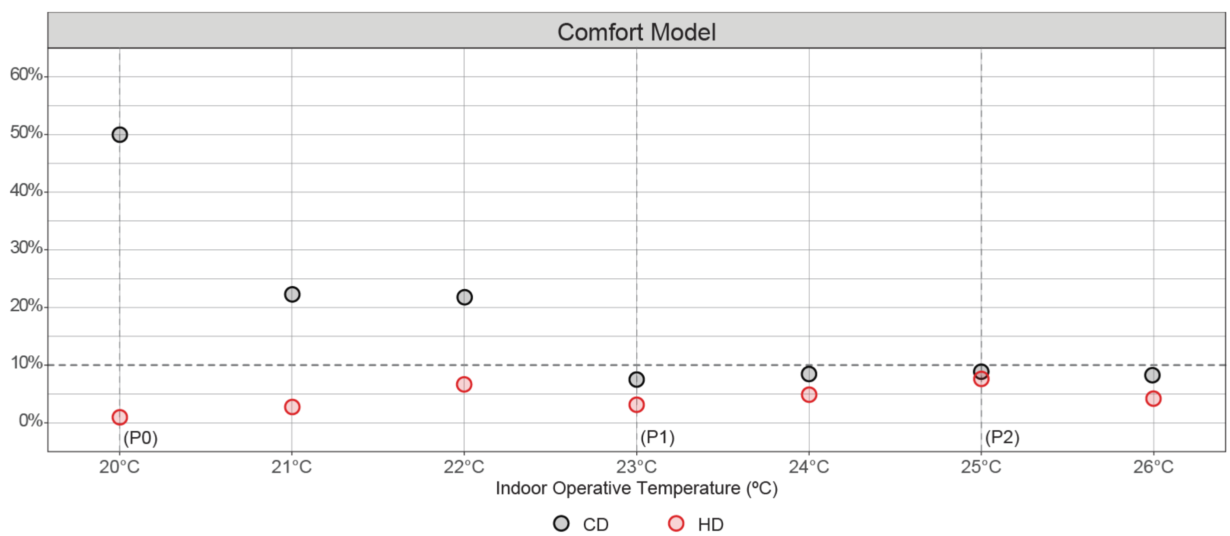


Figure 10 Comfort model for hot and cold discomfort based upon both CD and HD calculated as a percentage from total occupants from the entire study binned by 1°C indoor operative temperature. The study's coldest indoor temperature setting recorded is marked as P0, P1 is the first point at which CD drops below a nominal acceptance of 10%, and P2 represents where HD may be problematic as it approaches 10%. Note that little data exist at 26 °C (5 % of the sample) so the observed reduction in HD is unreliable, but included for completeness.

As expected, CD decreases as indoor operative temperatures rise (Figure 10). The CD range across the recorded indoor temperatures sufficiently extends from high CD at 20°C to almost not existent CD at 26°C. The CD data collected suggests that the temperature point where CD is no longer an issue to the occupants is within the sampled temperatures. A further occupant response in a greater range of warmer indoor temperatures is needed to have an effective assessment for HD. To understand where comfort is achievable it is crucial to examine where both cold and hot discomfort occur within the proposed model. Starting at the coolest indoor temperature observed during the study (20 °C), marked as P0, the highest CD is observed in the model occurs at roughly 50% (Figure 10). CD drops to under 10% only at 23 °C and continues to decrease with warmer indoor temperatures (Figure 10). If we consider the threshold for comfort at a maximum of 10% for CD alone (i.e. cold discomfort at ≤ 10%), 23 °C and warmer is noted to be temperatures where CD is not significant. HD as is, is not representative of occupant experience and suggests a need for the expansion of HD points in warmer temperatures.

Based upon the considered model, three possible cooling scenarios are presented. P1 is where CD is at the minimum point of acceptance and indoor temperature conditions should not cool past this point as it would result in greater that 10% from cold discomfort alone. Maintaining an indoor temperature condition at P1 is associated with a 22% reduction in cooling energy demand from the coolest observed indoor temperature condition (P0) in this study. At P2, where HD would possibly be problematic as it approaches 10%, a 35% reduction in cooling energy demand on average from P0 is observed going from an average of 143.7 $kW{\cdot}h/m^2/y$ to 93.7 $kW{\cdot}h/m^2/yr$.

P1 is the point of maximum cooling supply, it is unjustifiable to expend further cooling energy when occupants are at the maximum allowable threshold for cold discomfort as any additional cooling past this point will result in more than 10% cold discomfort. P2 is where decreasing the cooling supply is balanced by the need to supply cooling. Anything past P2 would provide the risk of a larger group of occupants feeling too warm rather than too cool. In theory, cooling supply can be decrease further past P2 to the point where HD is considerable, however to what extent necessitates an expansion of the model to accurately depict where HD exceeds 10%. Thus, it is imperative to reach P1 at a minimum, where both comfort and energy benefits are expected, with P2 being the maximum possible benefit to energy without an expected negative comfort impact. An optimal suggestion would be to aim for a setpoint temperature ranging from P1 to P2, specifically at 24 °C indoors. This choice is considered reasonable since it is slightly lower than the average Griffiths comfort temperature of 24.9 °C, hence reducing the likelihood of experiencing discomfort due to overheating. Considering an optimal indoor temperature setpoint of 24 °C, this analysis reveals that the overcooling observed within this study accounts for 27% of the cooling energy consumption of the buildings in this study. This suggests that the overall cooling energy demand associated with overcooling corresponds to roughly 4% of at the national level, i.e. 27% of the present contribution of 14% from non-domestic consumers to national demand in Qatar (3–7). Given that Qatar's mean carbon emissions intensity from electricity generation between 2011-2020 was 0.49 $kgCO_2/kWh$ (s.d. 0.0001 $kgCO_2/kWh$ (59)), we estimate that overcooling is responsible for ~2% of the carbon emissions associated with non-domestic buildings in Qatar.

5 Discussion

Since there is no local thermal comfort standard in Qatar, ASHRAE Standard-55 (10) is routinely adopted as "best practice". In Qatar, public and government-funded buildings must typically adhere to regulated building standards, and this likely includes thermal comfort criteria. Since the operational costs of public buildings are subsidised, there is less appreciation of the possibilities of reducing cooling energy demand.

This is illustrated through the statistically significant difference in indoor operative temperatures between building types with public buildings operating at 1.4 °C below private, on average.

The idea embedded in the thermal comfort literature that the ideal indoor temperature is one that provokes a "neutral" response needed to be tested as a feeling of being cool in a hot climate is not necessarily an indication of cold discomfort but rather a statement of how people like to feel. This is illustrated by the disjunction between those providing a negative TSV vote but not desiring conditions to get warmer in the TPV question – at 17% in the public buildings and 16% in the private buildings (16.5% overall).

Hence, measuring true cold discomfort not only requires estimating the TSV and TPV composite 'cold discomfort' (CD) metric but also a direct question measuring whether residents felt the need to alter clothing due to the air-conditioning indoors. CD has been determined to be strongly connected to this question across the buildings as 32% of occupants who identified with more clothing in the office compared to home exhibit CD, against roughly 5% CD with occupant who stated less clothing in the office compared to home. This provides strong assurance that, in future research, the percentage of cold discomfort is a useful metric for quantifying cold thermal discomfort in buildings and that this definition using both CD and HD is appropriate to gauge discomfort conditions due to overcooling.

In contrast to a mean TSV of -0.39, mean PMV is +0.30, i.e. a prediction that people would feel *warm* under the same conditions. This clearly implicates the use of (±0.5) PMV via global thermal comfort standards in producing the many concerns with excessive cooling in hot and suggesting that a local alternative would substantially improve service in these climates. What should this local alternative look like? When the percentages of cold and hot discomfort were calculated across all buildings in our study, a substantial drop in cold discomfort was observed when temperatures are raised and crucially, this is not followed by an increase in hot discomfort. This would imply that, at the simplest level, a Qatar-localised thermal comfort standard would involve raising the indoor setpoint temperatures arrived via a prediction from ISO 7730 or ASHRAE 55, with the combined effect of reducing both cooling energy demand and cold discomfort while not increasing hot discomfort for building occupants. This supports observations in earlier research (17,26–31). Computed comfort temperatures for all eight buildings are found to be between 23.8 °C and 25.8 °C using both CD and the well-known Griffiths method (41).

The study provides essential fundamental insights into the cooling requirements and comfort levels of buildings in the warm climate of Qatar. To improve the applicability of the results, future research should encompass a wider variety of building typologies, such as residential, hospital, and educational establishments, among others. An expanded and varied selection of buildings and inhabitants, along with a prolonged research duration encompassing many seasons, would facilitate a more intricate comprehension of energy consumption patterns and comfort levels.

It is obvious that an overcooled building in a hot climate will consume more energy than is needed to produce comfort. Our eight studied buildings were carefully selected to be typical of the region and comprising a variety of form factors and glazing ratios. Our simulation data, obtained by sampling across a wide range of parameters for each of these buildings, enable extrapolation of our results to a wide range of buildings. These data suggest that a substantial drop in cooling energy demand of around 8.5% for every 1°C increase in set point temperatures is possible and can assist buildings in achieving the recommended energy performance coefficient for minimum energy compliance as suggested by GSAS (12). Not only this, occupants have been frequently observed to resort to active heating in overcooled rooms, further increasing energy consumption. Thus, maintaining overcooled areas not only wastes energy and causes discomfort for inhabitants, but it can also create a feedback loop in which people expend more energy to counteract the overcooling of the spaces they occupy.

Since most developed countries are located in warmth-demanding colder regions, coolth-demanding warmer climes have generally been overlooked in thermal comfort studies and eventually standard development. Current urbanisation patterns in expanding warm climatic regions are expected to increase reliance on active cooling systems in the built environment, perhaps leading to noteworthy overcooling given that space cooling is a fast-expanding industry in these climates. Future cooling demand is expected to increase dramatically as the population grows, the built environment expands, and space cooling technologies become more available and affordable. It is hence impractical to try to reduce overcooling without a reliable understanding of overcooling in the built environment and, if not addressed, will increase thermal discomfort, energy consumption, and carbon emissions in developing regions.

6 Conclusion

In this paper we collect, analyze, and evaluate field data to determine the effect of building overcooling on comfort and energy in a warm climate. Data for eight buildings in Qatar, as an example of a warm climate, are examined using developed definitions and measures for overcooling. During the 2019 summer season in Qatar, five private and three public buildings were visited, yielding 2,472 individual thermal comfort responses from building occupants. The average TSV is -0.39, indicating the possibility of cold thermal discomfort. The mean PMV is +0.30, which is substantially higher than the TSV.

To answer our first research question on whether the recently developed overcooling definition performs well in real buildings, a series of questions were added to the ISO 28802:2012 compliant thermal comfort survey to tease out occupant response to potential overcooling. These include questions around whether the occupants are thermally comfortable at the exact moment of survey, if they felt the air conditioning is creating a condition that can be called “too cold”, whether their workplace temperature is colder than those they set at home and whether they modified their clothing based on workplace temperature. Responses to all these questions clearly demonstrate the presence of significant overcooling across all buildings. The new definition of overcooling which suggests overcooling occurs when cold discomfort (CD) is greater than hot discomfort (HD) in warm weather clearly matches the subjective observations given mean CD was 18% compared to a mean HD of only 4%. This provides strong evidence for the effectiveness of the overcooling definition allowing for detailed analysis of discomfort and further research into overcooling.

In response to the second research question on what indoor conditions our data might suggest, analysis of the CD and HD data suggest a comfort range between 23 °C and 25 °C which is independently confirmed through the well-established Griffiths method which suggested a neutral comfort temperature of 24.9 °C, which is 1.5 °C higher than mean observed indoor temperatures (23.4) and 1.7 °C above PMV 0. Given the range above and the computed neutral temperature, we conclude that overcooling can be substantially eliminated in Qatari office buildings by raising the indoor setpoint temperature by around 2 °C from current norms is proposed to provide the greatest level of comfort for the local occupants in Qatar.

Our next question is on the impact of the design of major building elements on energy demand within the proposed comfort conditions. In the study we consider the Façade Glazing Ratio (FGR) which determines the balance of energy flows through the transparent and opaque elements of vertical facades, the Heat Loss Parameter (HLP) which combines the conductive and ventilative losses across all surfaces and the Building Obstruction Angle (BOA) which determines the effect of the surrounding obstructions on building energy performance. We state the best performance for each of these three parameters in terms of the implied equivalent uplift in indoor setpoint temperatures. We hence find that FGR has the most significant impact on building energy consumption as the lowest consumption at 30% FGR equates to a raising of indoor setpoint of 4 °C. The lowest consumption for both BOA (80° shading angle) and HLP (Passivhaus recommended) equate to a 2 °C raising of the indoor setpoint.

Our final question was to determine which setpoint/s provide the best balance between maximising thermal comfort and minimising energy consumption in Qatar offices. Indoor setpoints between 23 °C and 25 °C are found to lower cold discomfort without increasing hot discomfort. Using calibrated thermal simulations of the eight studied buildings, we estimate a potential to lower cooling energy demand by 11.3% overall by eliminating overcooling at an indoor setpoint temperature of 25 °C. The average reduction in cooling energy demand is 8.5% for every 1°C increase in the indoor setpoint temperature amounting to an average of 32.3 kW·h/m^2/yr. These estimates are conservative as they do not account for the savings accruing from the elimination of unnecessary heating systems that were observed to use during our survey.

Overall, we suggest the urgent need to adopt indoor setpoint temperatures for Qatar that maximize thermal comfort, eliminate overcooling and minimize wasteful energy demand by careful consideration of the data in this paper.

7 Acknowledgement

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8 Data access statement

The data used in this paper are available at the address below. When using these data, please cite as follows:

Alnuaimi, A., Natarajan, S., Kershaw, T., in press. *Freezing from the Heat, Building Overcooling in Qatar.* Bath: University of Bath Research Data Archive. https://doi.org/10.15125/BATH-01315.

9 References

1. IEA. Data and Statistics [Internet]. 2022 [cited 2022 Apr 6]. Available from: https://www.iea.org/data-and-statistics

2. Köppen W. Classification of climates according to temperature, precipitation and seasonal cycle. Petermanns Geogr Mitt. 1918;64(1918):193–203.

3. Budaiwi IM, Al-homoud MS. Envelope retrofit and air-conditioning operational strategies for reduced energy consumption in mosques in hot climates. 2013;33–50.

4. Ayoub N, Musharavati F, Pokharel S, Gabbar HA. Energy consumption and conservation practices in Qatar - A case study of a hotel building. Energy Build. 2014 Dec 1;84:55–69.

5. Dabaieh M, Wanas O, Hegazy MA, Johansson E. Reducing cooling demands in a hot dry climate: A simulation study for non-insulated passive cool roof thermal performance in residential buildings. Energy Build. 2015;89:142–52.

6. Saffouri F, Bayram IS, Koc M. Quantifying the cost of cooling in qatar. In: 2017 9th IEEE-GCC Conference and Exhibition (GCCCE). IEEE; 2017. p. 1–9.

7. Andric I, Al-Ghamdi SG. Climate change implications for environmental performance of residential building energy use: The case of Qatar. Energy Reports. 2020;6:587–92.

8. Elnaklah R, Alnuaimi A, Alotaibi BS, Topriska E, Walker I, Natarajan S. Thermal comfort standards in the Middle East: Current and future challenges. Build Environ. 2021;200:107899.

9. ASHRAE. Standard 55-2020, Thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating and Air Conditioning Engineers. 2020;

10. Fanger P. Thermal Comfort: Analysis and Applications in Environmental Engineering. New York, : McGraw-Hill; 1970.

11. ISO. BS EN ISO 7730: 2005: Ergonomics of the Thermal Environment. Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria. International Standards Organization Geneva; 2005.

12. GORD. GSAS 2019 Design & Build Guidelines Manual. 2019;

13. EN EUS. 16798-1: 2019. Energy Performance of Buildings—Ventilation for Buildings—Part. 2019;1.

14. Toftum J, Fanger P. Extension of the PMV model to non-air-conditioned buildings in warm climates. Energy Build. 2002;34(6):533–6.

15. Humphreys MA, Nicol JF. The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. Energy Build. 2002;34(6):667–84.

16. de Dear R, Brager GS. Developing an adaptive model of thermal comfort and preference. 1998;

17. Indraganti M, Boussaa D. Comfort temperature and occupant adaptive behavior in offices in Qatar during summer. Energy Build. 2017;150:23–36.

18. Nicol F. Adaptive thermal comfort standards in the hot–humid tropics. Energy Build. 2004;36(7):628–37.

19. Cena K, de Dear RJ. Field study of occupant comfort and office thermal environments in a hot, arid climate. ASHRAE Trans. 1999;105:204.

20. Donnini G, Molina J, Martello C, Lai DHC, Kit LH, Chang CY, et al. Field study of occupant comfort and office thermal environments in a cold climate: Final report on ASHRAE RP-821. Montreal, Quevec, Canada: AND Inc. 1996;

21. de Dear R, Fountain M. Field experiments on occupant comfort and office thermal environments in a hot-humid climate. 1994;

22. Schiller G, Arens EA, Bauman F, Benton C, Fountain M, Doherty T. A field study of thermal environments and comfort in office buildings. 1988;

23. Nicol JF, Humphreys MA. Thermal Comfort As Part of a Self-Regulating System. Build Res Pract. 1973;1(3):174–9.

24. Nicol JF, Humphreys MA. Adaptive thermal comfort and sustainable thermal standards for buildings. Energy Build. 2002;34(6):563–72.

25. Sanyogita M, Yash S, Rawal R, deDear R, Thomas L. Developing an India Model for Adaptive (Thermal) Comfort: IMAC 2014. 2014;

26. Zhou X, Yan D, Jiang Y, Shi X. Influence of asynchronous demand behavior on overcooling in multiple zone AC systems. Build Environ. 2016;110:65–75.

27. Paliaga G, Zhang H, Hoyt T, Arens E. Eliminating overcooling discomfort while saving energy. ASHRAE J. 2019;61(4):14–28.

28. Yang W, Wong NH, Zhou J. Overcooling and thermal comfort in air conditioned university buildings in Singapore. Indoor Air 2014 - 13th International Conference on Indoor Air Quality and Climate. 2014;554:546–53.

29. Mendell MJ, Mirer AG. Indoor thermal factors and symptoms in office workers: findings from the us epa base study. Indoor Air. 2009;19(4):291–302.

30. Cena K, de Dear R. Thermal comfort and behavioural strategies in office buildings located in a hot-arid climate. J Therm Biol. 2001;26(4–5):409–14.

31. Indraganti M, Boussaa D. An adaptive relationship of thermal comfort for the Gulf Cooperation Council (GCC) Countries: The case of offices in Qatar. Energy Build. 2018;159:201–12.

32. Williams E. The Conversation. 2016 [cited 2019 Feb 2]. Overcooling and Overheating Buildings Emits as Much Carbon as Four Million Cars. Available from: www.theconversation.com/overcooling-and-overheating-buildings-emits-as-much-carbon-as-four-million-cars-64950.

33. Green P. New York Times. 2019 [cited 2019 Feb 2]. Do Americans Need Air-Conditioning? Available from: www.nytimes.com/2019/07/03/style/air-conditioning-obsession.html.

34. Murphy K. New York Times. 2015 [cited 2019 Feb 2]. Enduring Summer's Deep Freeze. Available from: www.nytimes.com/2015/07/05/sunday-review/enduring-summers-deep-freeze.html.%0A

35. Kershaw T, Lash D. Investigating the productivity of office workers to quantify the effectiveness of climate change adaptation measures. Build Environ. 2013;69:35–43.

36. Roelofsen P. The impact of office environments on employee performance: The design of the workplace as a strategy for productivity enhancement. Journal of facilities Management. 2002;

37. Alnuaimi A, Natarajan S. Extreme Cold Discomfort in Extreme Hot Climates, A Study of Building Overcooling in Office Buildings in Qatar. The Journal of Engineering Research [TJER]. 2021;18(2):101–13.

38. Alnuaimi AN, Natarajan S. The Energy Cost of Cold Thermal Discomfort in the Global South. Buildings. 2020;10(5):93.

39. Samiuddin S, Budaiwi IM. Assessment of thermal comfort in high-occupancy spaces with relevance to air distribution schemes: A case study of mosques. Building Services Engineering Research and Technology. 2018;39(5):572–89.

40. Palme M, Isalgué A, Coch H, Serra R. Dynamic sensation of comfort in buildings: the temperature changes effects. … 28 th Conference and 2 nd …. 2007;2(September):746–50.

41. Griffiths I. Thermal Comfort in Buildings with Passive Solar Features: Field Studies [Internet]. Commission of the European Communities; 1991. (Euratom publications - EUR). Available from: https://books.google.com.qa/books?id=tGO5HAAACAAJ

42. GORD. GSAS 2019 OPERATIONS ASSESSMENT & GUIDELINES MANUAL. 2019.

43. Alnuaimi A, Natarajan S, Kershaw T. The comfort and energy impact of overcooled buildings in warm climates. Energy Build. 2022;260:111938.

44. Havenith G, Ouzzahra Y, Kuklane K, Lundgren K, Fan J, Au Y, et al. A Database of Static Clothing Thermal Insulation and Vapor Permeability Values of Non-Western Ensembles for Use in ASHRAE Standard 55, ISO 7730, and ISO 9920. ASHRAE Trans. 2015;121:197–215.

45. DOE. EnergyPlus [Internet]. 2021 [cited 2019 Dec 2]. Available from: https://energyplus.net/

46. DOE. 90.1 Prototype Building Models -- Complete Package | Building Energy Codes Program [Internet]. 2018 [cited 2019 Dec 2]. Available from: https://www.energycodes.gov/901-prototype-building-models-complete-package

47. ASHRAE. STANDARD 90.1-2019 — ENERGY STANDARD FOR SITES AND BUILDINGS EXCEPT LOW-RISE RESIDENTIAL BUILDINGS. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 2019;

48. Hopfe CJ, Hensen JLM. Uncertainty analysis in building performance simulation for design support. Energy Build. 2011;43(10):2798–805.

49. Breesch H, Janssens A. Performance evaluation of passive cooling in office buildings based on uncertainty and sensitivity analysis. Solar energy. 2010;84(8):1453–67.

50. De Wilde P, Tian W. Predicting the performance of an office under climate change: A study of metrics, sensitivity and zonal resolution. Energy Build. 2010;42(10):1674–84.

51. De Wit S, Augenbroe G. Analysis of uncertainty in building design evaluations and its implications. Energy Build. 2002;34(9):951–8.

52. Passive House Institute. Passive House Planning Package. 2019.

53. Alghoul SK, Rijabo HG, Mashena ME. Energy consumption in buildings: A correlation for the influence of window to wall ratio and window orientation in Tripoli, Libya. Journal of Building Engineering. 2017;11:82–6.

54. Ashrafian T, Moazzen N. The impact of glazing ratio and window configuration on occupants' comfort and energy demand: The case study of a school building in Eskisehir, Turkey. Sustain Cities Soc. 2019;47:101483.

55. Alwetaishi M. Impact of glazing to wall ratio in various climatic regions: A case study. Journal of King Saud University-Engineering Sciences. 2019;31(1):6–18.

56. General Secretariat for Development Planning. Qatar National Vision 2030. Doha; 2008.

57. Planning and Statistics Authority. Economically Active Population (15 Years and Above) by Nationality, Gender and Age Groups. Doha, Qatar; 2022.

58. Alhorr Y, Elsarrag E. Climate change mitigation through energy benchmarking in the GCC green buildings codes. Buildings. 2015;5(2):700–14.

59. Statista. Emissions intensity from electricity generation in Qatar from 2011 to 2020. 2024.

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Appendix A

Table 4 Thermal Comfort Questions Response Rate Summary

Question	Response Rate
Question on thermal sensation.	100.0%
Question on thermal preference.	99.5%
Question on thermal conditions here and now if "comfortable".	97.2%
Question on thermal conditions here and now if "too cold".	94.6%
Question on comparing home and office thermal conditions.	97.9%
Question on comparing home and office clothing patterns.	95.7%