Co-Alignment of Comfort and Energy Saving Objectives for U.S. Office Buildings and Restaurants

Lourdes Gutierrez^{ab}, Eric Williams^a

^a Golisano Institute for Sustainability, Rochester Institute of Technology, USA. 111 Lomb Memorial Drive, Rochester, NY 14623, USA.

^b Corresponding author. Tel.: +1 585-475-7363; Fax: +1 585-475-5455; lmg4630@rit.edu.

ABSTRACT

Post-occupancy research shows that only 11% of commercial buildings met the ASHRAE thermal comfort standard. Many buildings are too warm in winter and/or too cool in summer, wasting energy and not providing comfort. We investigate potential energy savings in U.S. offices and restaurants if thermostat settings are changed according the updated ASHRAE 55-2013 comfort model that accounts for outdoor temperature and clothing choice for different climate zones. We develop eQUEST building models calibrated to reproduce energy consumption statistics. Changes in energy consumption due to the new settings are analyzed for 14 cities, results are extrapolated to estimate potential national savings. We find that, depending on the climate zone, each degree increase in the summer saves 0.6 to 1.0% of total building electricity consumption. Each degree the winter setting is lowered saves 1.2% to 8.7% of total building natural gas consumption. With new thermostat settings, national savings are 2.5% of the total consumed in all office buildings and restaurants, summing up to national savings of 69.6 million GJ annually, comparable to all 2015 total solar PV generation in U.S. The goals of improved comfort and energy/economic savings are thus co-aligned, raising the importance of thermostat management as an energy efficiency strategy.

Keywords: Energy efficient buildings, Commercial building stocks, dynamic clothing insulation model, Operation-focused interventions, Energy management, Thermal comfort, Thermostat settings.

1. Introduction

Commercial buildings represent 19% of United States primary energy consumption [1] with a total of 8,116 million square meters of floor space [2], and an annual primary energy consumption of 19.26 Billion GJ [3]. 42% of this energy is consumed by heating, ventilation and air-conditioning (HVAC) systems [1]. Energy savings strategies for HVAC systems in commercial buildings are thus important on a national scale. Moreover, between 2003 and 2012 there was a 14% increase in the number of buildings and a 22% increase in floorspace, suggesting the issue is growing in importance [2].

Although HVAC systems should provide thermal comfort, post-occupancy research of over 370 commercial buildings around the world (70% in the U.S.) showed that only 11% of the buildings met the criteria that no more than 20% of building occupants be dissatisfied [4]. In order to improve thermal comfort prediction, the latest version of the Thermal Comfort Standard - ASHRAE 55-2013 [5] introduces a new feature to thermostat settings design: modeling of the comfort experienced by occupants and their choice of clothing [6]. For example, on a cold winter day occupants will wear more clothing, thus they will be more comfortable in a cooler room. This is important because occupants will choose clothing depending on the season/weather conditions, thus to better deliver comfort building thermostat settings should account for clothing choice.

Thermostat settings are not only important for thermal comfort but also for energy consumption. The General Services Administration (GSA) Public Buildings Service recommends thermostat settings in summer from 23.3°C (74°F) to 25.6°C (78°F) [7] to achieve energy savings of 1 to 3% for each degree when the thermostat is set above 22.3°C (72°F). The Consumer Energy Center from the California Energy Commission recommends setting thermostat in winter to 20°C (68°F) [8] to achieve 5-20% energy savings. Although both reports show the relevance of the thermostat settings on energy consumption and the same recommendations are found in other references [9,10], there is as yet little research that links thermal comfort models to energy savings strategies on commercial buildings in U.S.

Given this context we pose the following research question: to what extent are the objectives of comfort and energy-saving co-aligned? If, for example, occupants are actually more comfortable with lower winter thermostat settings, comfort is improved and energy is saved. Conversely, it could be that making occupants more comfortable would require lowering thermostat settings in summer or raising them in winter, increasing energy use. If savings are found, the co-alignment of comfort and energy savings goals could help persuade facility managers to change thermostat-setting practices.

We explore the research question via a case study in which we model the shift in energy use due to changing thermostat settings in U.S. office buildings and restaurants. Current thermostat settings are taken as 21°C (70°F) year-round, we compare this to a new thermostat setting scheme designed to deliver comfort accounting for occupants wearing different clothing depending on the climate. Specifically, we develop winter and summer thermostat settings for different U.S. climate zones by interpreting the ASHRAE comfort model accounting for the role of clothing choice. The macro-level energy implications of changing thermostat settings is done by calibrating a building level energy simulation model (eQUEST) to reproduce aggregate energy consumption as reported in the 2003 Commercial Building Energy

Consumption Survey (CBECS) [11]. Annual energy use for baseline and modified thermostat settings are compared for different U.S. climate zones and then extrapolated to the national level.

Reviewing related literature, Azar and Menassa [12] estimate energy savings for the stock of commercial buildings in different climate zones across the U.S from different strategies, including changing thermostat settings. At the building level, Fernandez et al [13] analyzes several temperature strategies on supply air, chiller water, schedules, and thermostat set points for large office buildings. Their strategy is to set two thermostat settings 20.6°C (69°F) for the heating season to 23.9°C (75°F) for the cooling season. This thermostat schedule is also used in the U.S. Department of Energy's Advanced Energy Retrofit Guide [14], reported to yield an average energy saving of 8% of the total site usage from a baseline of 21.7°C (71°F) for heating and 22.8°C (73°F) for cooling season. Hoyt et al [15] analyze energy consumption and thermostat settings by climate zones for midrise offices with variations on the Variable Air Volume (VAV) system and thermostat settings. Based on this research, Brager et al [16] concluded that from a thermostat baseline between 22°C and 24°C expanding the settings 1°C for cooling or heating could reduce around 10% of HVAC energy consumption. Outside the U.S, Gaglia et al. [17] calculated energy savings for the non-residential building stocks in Greece, they considered that thermostats strategies could increase 5% of HVAC energy consumption. The British Council for Offices [18] recommended a thermostat setpoint of 24°C for UK offices, estimating savings of 0.7% of total energy consumption from a 22°C baseline, Indraganti et al [19] confirmed that the Japanese policy to increase the thermostat to 28°C in summer at offices buildings would still provide thermal comfort for occupants.

The above literature review shows there is a variety of prior work that explores energy savings for different thermostat settings. The contribution of this work is make the connection between comfort and energy use in thermostat settings, in particular considering how climate influences clothing choice and thus comfortable thermostat settings. While our main goal is to understand the linkage between comfort and energy use, note that our thermostat setting scheme accounting that vary by season and climate zone is relevant to the comfort literature. In the energy domain, our calibration eQUEST [20] simulation models for individual buildings to reproduce national aggregate consumption by climate zone is of general use.

2. Method overview

The proposed method combines thermal comfort theory with energy savings calculations for a group of existing commercial buildings. Figure 1 shows the overall flow of the method. First, we find the thermostat settings by climate zone that meet occupants' thermal comfort according to the standard ASHRAE 55-2013[5]. By using the Center for the

Built Environment's (CBE) Thermal Comfort Tool [21] and fixing environmental variables typical in commercial buildings, we build a relationship between outdoor temperature at 06:00 a.m. and the maximum and minimum thermostat settings that will achieve a satisfied building population greater than 80%. We select 14 cities across U.S. and find the average outdoor temperature at 06:00 a.m. by season (summer and winter) using their Typical Meteorological Year weather files (TMY3) [22]. Using these temperature values in the ASHRAE comfort functions, we calculate thermostat settings by city and then aggregate the results to obtain the maximum and minimum thermostat settings by climate zone in the U.S. While thermostat settings could in principle vary day-by-day, in practice this would be such a dramatic shift from current practice, we propose different winter/summer settings in order to be more practicable for facility managers across the U.S. and better reflect typical capacity to manage settings. Also, given the variability in expected hours of occupancy, the settings are applied 24 hours a day, seven days a week.

I. Find thermal comfort settings for U.S. climate zones

II. Find energy savings for commercial buildings

III. Estimate national savings

Fig. 1 Overview of methodology to determine climate-dependent thermostat settings and estimate change in energy use

Next, the change in energy use for the new thermostat settings are calculated for two types of mechanically conditioned (electrical cooling and natural gas heating) commercial buildings: office buildings and full service restaurants. Both types of buildings are simulated using eQUEST 3.65, starting with a default model [20]. As we aim to

estimate potential savings for an aggregate group of existing buildings, rather than an individual building, we alter building characteristics so that the energy consumption of each type of building in each climate zone matches the 2003 Commercial Building Energy Consumption Survey (CBECS). For this step, both types of buildings are simulated for 14 selected cities, setting an average thermostat baseline of 21.1°C (70°F). The results are analyzed by climate zone, so the individual models are calibrated by changing the equipment efficiency to approximate the group results to the CBECS ratios. The calibrated energy models are set as a baseline, we then find the change in energy use from changing winter and summer thermostat settings away from 21.1°C (70°F) for the 14 selected cities. Then we aggregate the city results by climate zone to determine the average savings by climate zone and type of building.

Finally, the national change in energy use due to the new thermostat settings is calculated. The change of energy use in each climate zone is weighted by the total floor space to obtain a national change in electricity and natural gas consumption for mechanically conditioned offices and restaurants. Economic implications of the thermostat change are assessed assuming an average cost of electricity of 0.10 \$/kWh [23] and of natural gas of 7.89 \$/MMBtu [24].

3. Thermal comfort settings for US climate zones

In this section we draw on prior thermal comfort models to develop recommended thermostat settings for the U.S. that depend on season and geographical location.

3.1. Thermal comfort model

Thermostat settings are designed according to the Thermal Comfort Standard - ASHRAE 55, based on the Predicted Mean Vote (PMV) model [5]. PMV is a measure of occupant's comfort, using a scale that ranges from +3 to -3 (+3 = hot, +2 = warm, +1 = slightly warm, 0 = neutral, -1 = slightly cool, -2 = cool, -3 = cold). The model predicts PMV as a function of six variables: metabolic rate (met), clothing insulation (I_{cl}), relative humidity (RH), air temperature (t_a), radiant temperature (t_r) and air speed (V_a). According to the standard, compliance is achieved if $-0.5 < PMV < 0.5$, which also means that thermal satisfaction is obtained inside a threshold with a maximum air temperature related to $PMV = +0.5$ and minimum air temperature related to $PMV = -0.5$. This model, initially proposed by Fanger in 1970 [25, 26], has been widely used to determine thermostat settings. However, post-occupancy research has showed dissatisfaction far higher than the allowed by the standard [4]. From a variety of field studies [27, 28], Humphrey, de Dear and Brager found that any thermal model should reflect a human thermal adaptation based on outdoor temperature as they found a correlation between the indoor comfort temperature and the mean outdoor temperature. Since the PMV model did not include a

variable related to outdoor temperature, a function of clothing insulation to the outdoor temperature has been included in the latest version of the standard, ASHRAE 55-2013.

In the PMV model, clothing insulation (I_{cl}) could vary between 0 to 2 clo, but most designers of building mechanical systems usually select two values 0.5 clo for summer (e.g. short sleeve shirt and trousers) and 1.0 clo for winter (e.g. long sleeve shirt, sweater and long trousers). This assumption neglects geographical differences in climate: in winter an occupant in New York wears heavier clothes than one in Florida. Usually occupants change clothing across season, according to weather conditions, so clothing insulation values should change with outdoor temperature. Therefore, settings in cold climate zones should not be the same as warm climate zones. From the ASHRAE existing building database, Schiavon and Lee [6] found a relationship between outdoor temperature at 06:00 a.m. ($t_{a(out,6)}$) and clothing insulation (I_{cl}) (Eq. 1), which has been included in the ASHRAE 55-2013 [5]

$$\begin{array}{ll} \text{For } t_{a(out,6)} < -5^{\circ}\text{C} & I_{cl} = 1.00 \\ \text{For } -5^{\circ}\text{C} \leq t_{a(out,6)} < 5^{\circ}\text{C} & I_{cl} = 0.818 - 0.0364 t_{a(out,6)} \\ \text{For } 5^{\circ}\text{C} \leq t_{a(out,6)} < 26^{\circ}\text{C} & I_{cl} = 10^{(-0.1635 - 0.0066 t_{a(out,6)})} \\ \text{or } t_{a(out,6)} \geq 26^{\circ}\text{C} & I_{cl} = 0.46 \end{array} \quad (\text{Eq. 1})$$

3.2. Relationship between indoor and outdoor temperature to achieve a satisfied population $\geq 80\%$

To build the relationship, four variables are fixed to represent characteristics of commercial buildings such as offices, restaurants and education facilities. Based on Dear and Brager's [28] analysis of existing mechanical conditioned buildings from the ASHRAE database, we assume: $met = 1.2$ met (metabolic rate for seated person), $V_a = 0.1$ m/s, $RH = 50\%$, $t_a = t_r$. Under these assumptions, the mean radiant temperature is equal to the air temperature, which also represents the thermostat settings (t_h). With these four variables fixed, the two remaining variables, clothing insulation (I_{cl}) and air temperature (t_a) that $-0.5 < PMV < 0.5$, are found using the Center for the Built Environment's (CBE) Thermal Comfort Tool [21]. As each value varies with clothing insulation, from the relationship between outdoor temperature at 06:00 a.m. and the selected clothing by occupants (Eq. 1), two functions are built relating the maximum and minimum thermostat setting (t_h) to the outdoor temperature at 6 a.m. ($t_{a(out,6)}$) with the highest value of $PMV < 0.5$ or $PMV > -0.5$ (equation 2).

$$\begin{array}{l} \text{Maximum Thermostat Setting } ^{\circ}\text{C (Max } t_h) = 0.08 t_{a(out,6)} + 24.4 \\ \text{Minimum Thermostat Setting } ^{\circ}\text{C (Min } t_h) = 0.12 t_{a(out,6)} + 20.9 \end{array} \quad (\text{Eq. 2})$$

With these two functions, the maximum and minimum thermostat settings can be selected according to the outdoor temperature at 06:00 a.m. These thermostat settings are expected to result in a percentage of dissatisfied population less

than 20% and can be applied for any city in any climate zone or building where occupants are mostly seated (e.g. restaurants, office buildings, educational buildings).

3.3. Recommended thermostat settings for 14 cities in different climate zones

The 2003 Commercial Buildings Energy Consumption Survey (2003 CBECS) divides the U.S. into five climate zones. The CBECS climate zones are aggregations of climate divisions as defined by the National Oceanic and Atmospheric Administration (NOAA), which in turn are regions within a state that are as climatically homogeneous as possible. Each NOAA climate division is placed into one of five CBECS climate zones based on its 30-year average heating degree-days (HDD) and cooling degree-days (CDD) for the period 1971 through 2000[29]. Climate Zone 1 has less than 2,000 CDD and greater than 7,000 HDD, Zone 2 has less than 2,000 CDD and 5,500-7,000 HDD, Zone 3 has less than 2,000 CDD and 4,000-5,499 HDD, and Zone 5 has at least 2,000 CDD and less than 4,000 HDD. According to this division, we have selected 14 cities from different climate zones:

- Climate Zone 1: Concord - New Hampshire, Minneapolis - Minnesota, Juneau – Alaska;
- Climate Zone 2: Columbus - Ohio, Boston – Massachusetts;
- Climate Zone 3: Philadelphia - Pennsylvania, Washington DC - District of Columbia, St. Louis – Missouri;
- Climate Zone 4: Tulsa – Oklahoma, Little Rock – Arkansas, Atlanta – Georgia; and
- Climate Zone 5: Houston – Texas, Phoenix - Arizona, Miami – Florida

The outdoor temperature at 06:00 a.m. is calculated from a city's weather file. Crawley [30] compared energy consumption data to simulations using different weather files, concluding that TMY2 weather files provide results that closely represent typical weather patterns. TMY files are based on data from 1976 to 2005 provided by the National Climatic Data Center. For our analysis we use the updated version of the TMY file, the TMY3. Since thermostat settings depends on the facility manager, and not all commercial buildings have automatic controls, a single thermostat setting is proposed for each city. The average outdoor temperature at 06:00 a.m. is determined for the coldest and hottest season: winter (21 December to 21 March) and summer (21 June to 21 September) for each city. Table 1 shows the results, first the average outdoor temperature at 06:00 a.m. is calculated for each city and each season (third column), then these values are used in equation 3 to find the thermostat setting threshold (maximum and minimum thermostat settings) per season for each city that should realize a satisfied population greater than 80% (fourth column). As expected, the results for each city are similar by climate zone, also the warmer climate zone the higher thermostat settings. Finally, we aggregate these results, which are the recommended thermostat settings by climate zone.

A more sophisticated management system could involve adjusting thermostat settings every day according to the weather. As mentioned earlier, to accommodate constraints on building management, we propose for two different

seasonal settings only, the winter settings can be extended to the fall season, and the summer settings can be used in the spring season.

Climate Zone	City, State	Average Outdoor Temperature 06:00 a.m. (°C)		Thermostat Settings (°C) (-0.5<PMV<0.5)				Recommended Thermostat Settings by Climate Zone	
		Winter	Summer	Winter		Summer		Winter	Summer
1	Juneau, Alaska	-3.7	10.6	20	24	22	25	20°C – 24°C (68°F - 75°F)	23°C – 26°C (73°F - 79°F)
	Concord, New Hampshire	-8.2	14.4	20	24	23	26		
	Minneapolis, Minnesota	-7.8	17.0	20	24	23	26		
2	Columbus, Ohio	-3.4	17.4	20	24	23	26	20°C – 24°C (68°F - 75°F)	23°C – 26°C (73°F - 79°F)
	Boston, Massachusetts	-2.1	19.0	21	24	23	26		
3	Philadelphia, Pennsylvania	-1.2	20.1	21	24	23	26	21°C – 24°C (70°F - 75°F)	23°C – 26°C (73°F - 79°F)
	Washington DC, DC	-1.1	18.3	21	24	23	26		
	St. Louis, Missouri	-0.4	20.6	21	24	23	26		
4	Tulsa, Oklahoma	0.4	22.3	21	25	24	26	21°C – 25°C (70°F - 77°F)	24°C – 26°C (75°F - 79°F)
	Little Rock, Arkansas	2.4	22.1	21	25	24	26		
	Atlanta, Georgia	4.2	21.3	21	25	23	26		
5	Miami, Florida	17.3	25.6	23	26	24	27	22°C – 25°C (72°F - 77°F)	24°C – 26°C (75°F - 80°F)
	Houston, Texas	7.9	23.5	22	25	24	26		
	Phoenix, Arizona	9.7	28.1	22	25	24	27		

Table 1 Recommended Thermostat Settings range by Climate Zone for mechanical conditioned buildings (fixed variables: metabolic rate=1.2 met, air velocity =0.1 m/s, relative humidity= 50% and air temperature = mean radiant temperature = thermostat settings). The temperature range corresponds to -0.5<Predicted Mean Vote (PMV) <0.5.

To check the plausibility of the recommended settings in Table 1, one approach would be to compare them with current settings in commercial buildings. Unfortunately, there is insufficient public data on commercial thermostat settings to enable this comparison. Alternatively, we examine the thermostat setting data of the Residential Energy Consumption Survey (RECS). Since individual homeowners choose their own settings, these settings presumably reflect the comfort preferences. The RECS data indicates that U.S. homeowners on average set the thermostat at 21.1°C (70°F) for heating and 22.8°C (73°C) for cooling. Based on this, we suggest to use the minimum recommended temperature for each season from the range in Table 1 is safe to ensure comfort (e.g. Climate Zone 2, Winter at 20°C and Summer at 23°C). Facility managers interested in saving energy can explore raising the summer setting which depending on circumstances, e.g. dress code, can still ensure comfort. Choi et al [31] performed a post-occupancy evaluation of 20 U.S. General Services Administration office buildings and found that female occupants tends to prefer higher summer temperatures, which was attributed to clothing difference. Also, Haghighat and Donnini [32], from an analysis of different indoor air environment correlations for 12 office buildings in Canada, found that clothing insulation values were

much higher (about 0.11 clo) for males than for females in both seasons. Higher thermostat settings in summer, above 23°C (73.4°F), were shown by Mendell and Mirer [33] to be associated with better health outcomes for occupants. Therefore, raising summer thermostat setting to the maximum recommended temperature (eg. Climate Zone 2, Summer at 26°C) with an adjustment on male dress code would achieve higher savings and higher comfort for more occupants.

4. Energy savings from thermostat settings: office buildings and full service restaurants

The goal of this section is to estimate the change in energy use by changing the thermostat settings in two types of commercial buildings in the U.S.: Office Buildings and Full Service Restaurants. After calibrating a model for individual buildings to reproduce aggregate energy use, we find the change in energy use from marginal changes in thermostat settings for the 14 selected cities in different climate zones. Lastly, we estimate the macro-level potential energy savings on heating and cooling by changing the thermostat settings to recommended values by climate zone shown in Table 1.

4.1 Modeling, calibrating and setting the baseline

In order to calculate the potential energy savings for the stock of commercial buildings, we need to find the energy consumption baseline for the stock with an initial thermostat setting. 2003 CBECS microdata [11] provides detailed energy consumption data by type of building, climate zone and energy end use. From this microdata we select two types of Non-Mall buildings: type 2 - Office Buildings and type 15 – Food Service (Full Service Restaurants). We calculate the electricity consumption per square foot for buildings with electrical space cooling and ventilation, and the natural gas consumption per square foot for buildings with natural gas space heating. Since thermostat setting data is not collected in CBECS, a thermostat threshold of 20°C-22°C (69°F-71°F) with an average setting of 21.1°C (70°F) is assumed for occupied and non-occupied schedule, this was also assumed in Hoyt et al [15]. Table 2 shows the energy consumption per square foot calculated by climate zone for the two types of commercial buildings.

2003 CBECS ENERGY CONSUMPTION PER SQUARE FOOT BY CLIMATE ZONE (CZ)	OFFICE BUILDING					FULL SERVICE RESTAURANT				
	CZ1	CZ2	CZ3	CZ4	CZ5	CZ1	CZ2	CZ3	CZ4	CZ5
HVAC Electricity Energy Ratio Consumption kWh/m2										
Space Cooling (kWh/m2)	13.0	20.6	25.4	32.3	73.4	19.2	24.5	50.4	69.3	144.2
Ventilation (kWh/m2)	15.0	18.8	18.4	15.1	17.4	36.2	44.0	58.8	84.8	58.0
HVAC Natural Gas Consumption mBtu/m2										
Space Heating (mBtu/m2)	538.2	547.9	372.4	170.1	241.1	874.0	750.2	902.0	525.3	232.5

Table 2. 2003 CBECS End Use Energy Consumption per square foot for Office Buildings and Full Service Restaurants. Table 2 ratios represent the energy consumption of the selected group or stock of buildings (CZ=Climate Zone).

To analyze the variation of energy consumption by changing thermostat settings, it is required to build individual models by each city that will represent each stock by type of building and climate zone. The individual models are built

from eQUEST 3.65 default settings, where most of the characteristics are similar to the average characteristics from 2003 CBECS. Starting with eQUEST default characteristics, the calibration consists of making plausible modifications to equipment, efficiency and operation hours to best match Table 2 – CBECS 2003 energy consumption ratios. Once this is achieved, running the model with new thermostat settings should reasonably simulate changes in energy use in a typical building in the climate zone.

The office building model could be segregated by pre and after 1980 construction and/or by small, medium and high size, but we prefer to use the midrise individual model to represent the average office stock. DOE reference model characteristics are used [34, 35], implying a three-floor midrise office with an average area of 4,982 m² and one floor restaurant with an average area of 511 m². The equipment selected for both type of buildings are furnace unit for space heating and packaged air conditioning unit for cooling. The air distribution for offices is a Variable Air Volume (VAV) system with a minimum volume set point of 35% except for zone 2 with a value of 30%, and the air distribution for restaurants is a Constant Air Volume (CAV) system.

With these basic building characteristics set, we vary building efficiency parameters in eQUEST within to reproduce average CBECS energy consumption data. Similar work on eQUEST for modeling office buildings to represent CBECS ratios has been done by and Azar & Menasa [36], where furnace efficiency was varied between 80 and 50% to achieve ratios errors within 10% of the CBECS energy ratios. In contrast we decided to keep the efficiency within boundaries given by the Annual Energy Outlook and DOE reference models intended to reflect the current building stock: Furnace Coefficient of Performance from 0.7 – 0.8 and the Packaged air conditioning unit Energy Efficiency Ratio from 8.63 – 9.7. Figure 2 shows the energy consumption ratios of the calibrated Office Building individual models per city and climate zone vs. the CBECS energy ratios. The calibrated building models are the baseline set at 21.1°C (70°F) for cooling, heating and design temperatures for occupied and non-occupied schedules. The supply temperature is set at 12.7°C (55°F) for cooling and 48.9°C (120°F) for heating. Having developed typical building calibrations for each climate zone, the eQUEST model is run for the 14 cities and compared with the CBES average. Results appear in Figure 2.

Fig. 2 Comparison of aggregate CBECS energy use data with calibrated eQUEST model, per climate zone, for office buildings (CCNH: Concord - New Hampshire, MNMN: Minneapolis - Minnesota, JNAL: Juneau - Alaska, CLOH: Columbus - Ohio, BSMC: Boston - Massachusetts, PHPA: Philadelphia - Pennsylvania, WDDC: Washington DC - District of Columbia, SLMS: St. Louis - Missouri, TLOK: Tulsa - Oklahoma, LRAR: Little Rock - Arkansas, ATGA: Atlanta - Georgia, HSTX: Houston - Texas PHAZ: Phoenix - Arizona, MIFL: Miami - Florida)

The characteristics from each calibrated individual models are selected from a range of values presented on the U.S. DOE Commercial Reference Building Models of the National Building Stock Report [34], Winiarski et al [37] and Annual Energy Outlook [38]. Table 3 shows the final values of building envelope and equipment of the calibrated models, by climate zone.

	OFFICE BUILDING					FULL SERVICE RESTAURANT		
	Insulation (R-values)		Furnance (COP)	PACU (EER)	Operation hours	Furnance (COP)	PACU (EER)	Operation hours
	Roof	Wall						
CZ 1	21	12	0.7	9.7	8am - 6pm	0.8	9.7	11am - 10pm
CZ 2	18	7	0.7	9.7	8am - 7pm	0.8	9.7	11am - 11pm
CZ 3	14	17	0.7	9.7	8am - 7pm	0.8	8.63	11am - 12am
CZ 4	14	4	0.8	9.7	8am - 6pm	0.7	8.63	11am - 11pm
CZ 5	12	4	0.7	9.7	8am - 6pm	0.7	8.63	11am - 12am

Table 3. Average characteristics of buildings by Climate Zone (CZ) in calibrated model. PACU =Packaged air-conditioning unit, COP = Coefficient of Performance, EER = Energy Efficiency Ratio. Office building air distribution: Variable Air Volume (30-35%). Restaurant air distribution: Constant Air Volume.

Most of the calibrated models results on an average variability between +-5% CBECS average and individual cities. Exceptions are office building gas consumption in climate zone 4 (+25%), restaurant space heating consumption in

Climate Zone 1 (+30%) and restaurant consumption in Climate Zone 5 (-40%). As concluded by Azar & Menasa high deviations for heating results are expected, and there is not enough CBECS data from Climate zone 5 to calibrate the individual models. We consider that error ratios could be also originated from differences between each city's outdoor temperature and user preferences. However, as Figure 2 shows, the results by climate zone are homogenous for what we conclude that all the calibrated individual models are valid and are set as the baseline for our analysis.

4.2 Marginal savings by climate zone per thermostat change

Starting from the calibrated eQUEST model from the previous section, thermostats settings are modified by increasing and decreasing the temperature by $\pm 0.6^{\circ}\text{C}$ ($\pm 1^{\circ}\text{F}$) degree for both cooling and heating temperature occupied and non-occupied hours from 20°C (68°F) to 26.1°C (79°F). Although savings could be greater if a set-back is defined for non-occupied hours (higher temperatures in summer and lower temperatures in winter), our goal is to propose a simplified thermostat strategy that could be applied year-round by facility managers.

From these variations the marginal savings are calculated to build a relationship between variations of thermostat temperature versus variation on energy consumption. This is calculated for each type of building for each city at different climate zones for cooling (electricity consumption) and for heating (natural gas consumption). Figure 3 shows the average of the 2-3 cities for each climate zone for Full Service Restaurants. As expected, savings on cooling are larger in warmer climate zones, and savings on heating are greater in colder climate zones. With an initial thermostat setting of 21.1°C (70°F), increasing the thermostat setting by 0.6°C (1°F) in summer can reduce 0.6% to 1.0% of the total electricity consumption; meanwhile reducing the thermostat setting by 0.6°C (1°F) in winter can reduce 1.2% to 2.5% of the total natural gas consumption.

Figure 4 shows the average of the 2-3 cities for each climate zone for Office Buildings. From an initial thermostat setting of 21.1°C (70°F), increasing the thermostat setting by 0.6°C (1°F) in summer can reduce 0.4% to 1.0% of the total electricity consumption. Reducing the thermostat setting by 0.6°C (1°F) in winter can reduce 6.5% to 8.7% of the total natural gas consumption. The results are in the range of other references which predicts energy savings in summer of 1 to 3 percent per each degree ($^{\circ}\text{F}$) when the thermostat is set above 22.2°C (72°F) [7], and 5% to 10% percent per each degree ($^{\circ}\text{F}$) when the thermostat is set below 21.1°C (70°F) in winter too [8, 16].

Fig. 3 Restaurant – Potential Electricity and Natural Gas savings for
(a) increasing summer thermostat settings from 21.1°C (70°F) to 21.7 (71°F) and 22.2 (72°F). and
(b) reducing winter thermostat settings from 21.1°C (70°F) to 20.6°C (69°F) and 20°C (68°F).

Fig. 4 Office Building – Potential Electricity and Natural Gas savings for
(a) increasing summer thermostat settings from 21.1°C (70°F) to 21.7 (71°F) and 22.2 (72°F). and
(b) reducing winter thermostat settings from 21.1°C (70°F) to 20.6°C (69°F) and 20°C (68°F).

4.3. Potential national scale energy savings with recommended thermostat settings

With the results from the marginal savings by climate zone analysis, we can extend the analysis to a national scale. We run the calibrated eQUEST models from a thermostat set at a baseline of 21.1°C (70°F) to our recommended thermostat setting values from Table 1. For summer, the cooling setting is 22.8°C (73°F) for climate zones 1, 2, 3 and 23.9°C (75°F) for climate zones 4 and 5. For winter, the heating setting is 20°C (68°F) for climate zones 1 and 2, 21.1°C (70°F) for climate zones 3 and 4, and 22.2°C (72°F) for climate 5. Note that the last setting increases energy use above the 21.1°C/70°F baseline while all the other new settings reduce energy use.

After running eQUEST with the new settings, the changes in energy savings per area are calculated for both building types in five climate zones. The change in national energy use is estimated by multiplying building area per climate zone by the energy saving intensities. The calculations and results appear in Table 4. As expected, potential energy savings for cooling (electricity) are greater for warmer climate zones, as potential energy savings for heating (natural gas) are greater for colder climate zones.

The marginal saving of energy per type of building and climate zone are taken from the simulation results	OFFICE BUILDING					FULL SERVICE RESTAURANT				
	CZ1	CZ2	CZ3	CZ4	CZ5	CZ1	CZ2	CZ3	CZ4	CZ5
Cooling - Potential Electricity Savings										
Recommended thermostat setting °C (°F)	22.8 (73)	22.8 (73)	22.8 (73)	23.9 (75)	23.9 (75)	22.8 (73)	22.8 (73)	22.8 (73)	23.9 (75)	23.9 (75)
Electricity savings (kWh/m2) from assumed thermostat setpoint of 21.1°C	1.74	2.07	2.49	5.38	7.32	4.74	5.92	9.69	12.1	17.4
Building area w/ electrical cooling (10^6 m2)	116.1	220	185.8	179	131	16.3	30.94	12.3	30	30.5
Potential Electricity Savings (million kWh)	202	456	463	968	965	77	184	119	364	533
Subtotal Total Electricity Savings (million kWh)	3,050					1,280				
Total Electricity Savings (million kWh)	4,330									
Heating - Potential Natural Gas Savings										
Recommended thermostat setting °C (°F)	20 (68)	20 (68)	21.1 (70)	21.1 (70)	22.2 (72)	20 (68)	20 (68)	21.1 (70)	21.1 (70)	22.2 (72)
Natural Gas savings (mBtu/m2) from assumed thermostat setpoint of 21.1°C	65.0	68.0	0	0	-39.1	77.7	78.9	0	0	-25.5
Building area w/ gas heating (10^6 m2)	104.1	175	122.6	118	28.99	13.2	26.57	7.15	25.2	13.8
Potential Natural Gas Savings (billion Btu)	6,765	11,882	0	0	-1,133	1,025	2,096	0	0	-351
Subtotal Natural Gas Savings (billion Btu)	17,514					2,771				
Total Natural Gas Savings (billion Btu)	20,285									

Table 4. Potential energy savings on national scale with recommended settings for mechanical conditioned buildings (electrical cooling and ventilation and natural gas heating)

5. Results

From our previous analysis, the results show that thermostat changes to the recommended minimum settings would save: 3,100 GWh in electricity and 17,510 billion Btu in natural gas, in office buildings that represents 1.4% of total office building electricity and 6.5% of natural gas site consumption (CBECS 2003, Table E7A and E5A). Meanwhile, changes to thermostat settings in full service restaurants could achieve savings of 1,300 GWh in electricity and 2,770 billion Btu in natural gas. This represents 2.0% of total full service restaurants electricity and 1.4% of total natural gas

site consumption. Using an annual average retail price in 2013 of 0.10 \$/kWh for electricity and 7.89 \$/MMBtu for natural gas and total potential savings for both types of buildings of 4,400 GWh of electricity and 20,280 billion Btu of gas, the annual savings is \$600 million in utility expenditures and 69.6 million GJ of primary energy. In terms of carbon dioxide, the savings is an annual reduction of about 1% of CO₂-eq emissions from office buildings and restaurants. To provide a reference point, the savings from thermostat settings is comparable to the total energy generation by U.S. solar PV generation in 2015, 83.6 million GJ [39].

Our results are contingent on the modeling elements used: eQUEST, ASHRAE 55-2013 and the CBE Thermal comfort tool. As eQUEST was calibrated to reproduce energy use of average building stock, the functionality required is reasonable simulation of energy use shift associated with thermostat change. Prior work comparing empirical consumption data, eQUEST and EnergyPlus model results suggests the model is robust for our intended use [40]. Our modeling is predicated on the idea that the ASHRAE 55-2013 model appropriately predicts occupant comfort. While there is a good deal of empirical input informing the model, there is a need for additional verification including the clothing and climate issues. There are also calls to move providing comfort away from “dissatisfying the fewest” to achieve more personalized comfort for occupants. For example, Brager et al [16] explore how the winter thermostat setting range could be lowered by installing portable individual heating devices to accommodate variability in preferences.

Using a 21°C (70 °F) baseline thermostat setting is an important input. While this assumption is used in the literature and matches our anecdotal experience, we believe there is a need for future development of datasets that describe usage patterns of commercial buildings, including thermostat settings. Since this research uses 2003 CBECS energy consumption ratios, the projection of potential savings could vary once the analysis is updated using 2012 CBECS.

6. Discussion

Thermal comfort is important for office worker productivity and the customer experience in retail and restaurant spaces. Organizations managing these spaces are thus motivated to be concerned about thermostat settings. While more empirical evidence is needed, there are indications that comfort is often not delivered in commercial spaces and that changing thermostat settings to improve comfort would also reduce energy use. This observation leads to two related questions: 1. How might the intersection of organizational practice, comfort and energy use be better understood? 2. How might the co-alignment of comfort and energy saving goals encourage organizations to pay more attention to the issue?

Focusing first on better characterization of the issues, note there is a lack of data on commercial thermostat settings and the comfort of office workers and customers. For the U.S., the low hanging fruit to improve the data situation is to add questions on thermostat settings to the Commercial Building Energy Consumption Survey (CBECS). As the Residential Energy Consumption Survey (RECS) already includes questions on thermostat settings, extending to CBECS should be straightforward. We do not detail the variety of situations in other countries on how existing survey instruments could be modified to address thermostat settings.

It is not currently clear to what how different organizations think about and implement thermostat settings. While it is important that more information be collected on this issue, we speculate on how the co-alignment of comfort and energy savings might affect organizational behavioral. Organizations have two motivations to be interested in energy use: economics and customer perception of sustainability. For economics, while there is potential to save on utility expenditures for energy reduction, the savings are fairly modest. Potential nationwide savings for office buildings and restaurants for our thermostat settings total \$600 million. Translating this into facility level savings per restaurants yields an average annual saving of \$510 per facility. Thermostat settings must, however, compete for a restaurant manager's attention among many other issues, it is not clear that if \$510 savings is sufficient. Note however that these are average values and that there are buildings (large and/or inefficient ones) with much larger savings. Building energy audits tend to focus on envelope and HVAC improvements, often neglecting to evaluate potential savings from operational changes. Provision of facility specific information to building managers about the potential to save energy from both infrastructure and operational changes would raise awareness of the effect of thermostat settings on energy use.

Recent decades have a rise in the importance of sustainability as a lens through which organizations are evaluated. Paired with concerns over climate change, firms are increasingly measuring, reporting and mitigating their carbon footprints. Changing thermostat settings can mitigate carbon while generating income, so can be an attractive measure. For organizations active in sustainability, carbon benefits may draw attention and action on thermostat settings. This said, carbon mitigation motivated by sustainability reputation is still its infancy and arguably mainly the domain of larger firms in certain sectors.

7. Conclusion

Considering that potential savings by thermostat settings are comparable to all 2015 total solar PV generation in U.S., our results create a motivation for increased government activities to understand thermostat settings and comfort because their energy implications relate to a public good, climate, rather than simply being a private sector affair. Note

that thermostat settings are already being pursued as an energy efficiency strategy in some countries such as Japan and the UK [19, 41].

The last lesson to mention is the importance of seasonal changes in thermostat scheduling. The key issue is that occupant-clothing choice, influenced by climate, allows thermostats to be set closer to the outdoor temperature, and in turn, save energy. There are many possible ways to make thermostat settings differ by season. For management simplicity, we developed two seasonal thermostat settings, one for fall/winter, one for spring/summer. While we did not analyze other types of commercial buildings, we expect similar results. One strategy to make a variable setting easier for a facility manager is to automate the process. If seasonal settings are built into the default of smart thermostats, benefits could be gained with only the initial investment. A smart thermostat could go well beyond the two-season setting studied here and automatically adjust according to weather conditions.

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