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Future context for thermal comfort: Impact of a changing climate on energy demand and human thermal comfort

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Abstract
Typical climate conditions for the 20th century may not provide the full range of temperature, precipitation and humidity extremes that likely will be encountered for the built environment of the 21st century. It is important to understand the impact of changing climate on building energy consumption, building design and thermal comfort in existing buildings. Therefore sensitivity studies were conducted for an exemplary location: Mason City Iowa. Based on future scenario climates for the period 2040-2070 produced by eight global/regional climate models, future typical meteorological year (FTMY) data sets were developed for this location and basic energy calculations were conducted in Energy Plus for a typical residence as well as the US DOE commercial reference buildings. Our results show that the increase in energy consumption resulting from projected change in climate over the next 50 year at this location results primarily from responding to an increase in ambient humidity in summer. Therefore, the largest energy cost for maintaining desired levels of health and comfort in the future at this location will be attributed to managing higher ambient humidity levels. Put another way, in order to reduce energy consumption by buildings at this location in the future, priority should be given to finding innovative ways to manage humidity or to adapt.

Keywords: Climate Change, Building Energy Consumption, Future Typical Meteorological Year Data, Adaptation

Introduction

Through collaboration between climate scientists and architects we have studied the impact of changing climate on building energy consumption, building design and thermal comfort in existing and newly constructed buildings. We used eight global/regional climate model combinations in conjunction with the solar radiation analyses method of Wilcox and Marion (2008) to produce scenarios of future typical meteorological years for the middle of the 21st century for a single location: Mason City, IA. Our method goes beyond previous results in that (1) we use dynamical downscaling rather than statistical downscaling of future climate scenarios, (2) our methods are applicable to all locations available in the Typical Meteorological Year (TMY3) database, and (3) we are able to show that impact of climate change on building energy consumption is beyond recent natural variations in climate and beyond the range of differences among the models used in the study.

In the first step presented here sensitivity studies were conducted for various building typologies in a single location: Mason City Iowa. A typical house design with conventional construction of the Midwest was tested to understand its sensitivity to changes in climate. Changes in energy demand between predictions with current TMY data, which are based on past weather data, and our new future TMY data, based on future projections from climate models, were calculated for the variables "temperature" and "relative humidity". Those were used to conduct basic energy consumption calculations in Energy Plus for this typical house and various US DOE commercial reference buildings, which make up about 60% of the US commercial building stock.

The predicted increase of energy consumption resulting from our computed change in climate is seasonal in this location and occurs in summer months mainly as a result of increased humidity. Preventing increases in energy demand in buildings without creating uncomfortable living conditions requires advances in architectural design, or heat/humidity management systems. The sensitivity studies for temperature indicate a direct relationship between changing temperature and the energy consumed: 1°F change in outside temperature creates an increased energy demand of 12,945.4 Btu/day (13,658.1 KJ/day; 3.8 kWh/day) for this home of 2400 ft^2 in summer and a decrease of the same magnitude in winter. The sensitivity studies for relative humidity indicate that a 1% change in saturation vapor pressure changes energy consumption by 0.5% in the same direction.

The climate in the Midwest of the United States is characterized by extreme seasons with very warm and already humid summers and cold dry winters. It is interesting to note that overall annual energy demand for the Mason City Iowa home and the Midwestern commercial reference buildings is predicted to slightly decrease, with a fairly large decrease during the winter heating season that is counteracted by a large increase in cooling load for the summer month, if all internal thermal set points are kept the same. It is therefore apparent that a changing climate will significantly impact energy consumption, if no design alternatives are considered or human understanding of human thermal comfort is challenged to adapt. Our results show that, to maintain current human thermal comfort standards in buildings of the future at this location, managing humidity will be more costly (in terms of energy consumption) than managing temperature.

Understanding of previous research in the field

Currently energy performance predictions are based on climate data of the recent past, for example typical meteorological year data (TMY3). Typical climate conditions for the 20th century may not provide the full range of extreme conditions that will be encountered by the built environment of the 21st century and thus there is growing interest in understanding the impact of future climate models on energy performance predictions for risk management. In previous studies Huang (2006) (as reported by Xu et al., 2009) used results of four global climate model (GCM) future climate scenarios to estimate that net energy use by residential and commercial buildings in Los Angeles will increase by 25 - 28% by 2100 due to increase in atmospheric greenhouse gases. Crawley (2008) used GCMs with statistical downscaling to represent four scenarios of climate change and two cases of urban heat islands for 25 locations worldwide. Overall, the impacts of climate change were projected to reduce energy use for cold climates by around 10% and to increase energy use in tropical climates by more than 20%. In mid-latitudes energy use would change from heating to cooling. The study states that unless significant changes are made to buildings and how they are designed, "building owners will experience substantial operating cost increases and possible disruptions in an already strained energy supply system."

Methodology

In order to understand the impact of a changing climate on building energy consumption, human thermal comfort, and potentially health, sensitivity studies were undertaken in 3 different steps. This was first done for one single location in the Midwestern climate zone.

1. The temperature and humidity levels in the current TMY3 data for Mason City Iowa were altered by discrete amounts and energy consumption was calculated for each of these changes based on current systems.
2. By use of methods described in ASHRAE paper CH12-CO49 (to be published in ASHRAE Transactions Volume 118 Part 1) future typical year data sets were created for each of the eight available climate model combinations available under the North American Regional Climate Change Assessment Program (NARCCAP) (2010). NARCCAP is an international program focused on using regional climate models (RCMs) driven by global climate models (GCMs) to produce high-resolution climate change simulations. The model domain covers the conterminous United States and most of Canada, and the spatial resolution of the RCMs is 50 km. The GCMs are forced with the SRES A2 emissions scenario for the 21st century.
3. Parallel building energy demand calculations were conducted for the same building design first with currently available TMY3 datasets and then with the new FTMY. Annual energy demand, heating demand and cooling demand were also compared and evaluated in the same way for US DOE reference buildings.

Definition of Typical Meteorological Year data

The TMY3 database provides designers and other users with a reasonably sized annual dataset consisting of hourly meteorological values that typify conditions at a specific location over a longer period of time, such as 30 years. For our study, we used the most current version of the typical meteorological year, TMY3, as developed by Wilcox and Marion (2008) and publicly available from the US DOE National Renewable Energy Laboratory (NREL). Although not designed to provide meteorological extreme events, TMY3 data have natural diurnal and seasonal variations for each location and thereby represent a year of site-specific typical climatic conditions.

The TMY3 dataset consists of 12 typical meteorological months (January through December), with individual months selected from different years of the period of record. For example, in the case of the National Solar Radiation Database (NSRDB) that contains 30 years of data, all 30 Januarys are examined, and the one judged most typical is selected to be included in the TMY3. The other months of the year are treated in a like manner, and then the 12 selected typical months are concatenated to form a complete year. These monthly datasets contain actual time series of meteorological measurements and modeled solar values, although some hourly records may contain filled or interpolated data for periods when original observations are missing from the data archive. Also, since adjacent months in the TMY3 may be selected from different years, discontinuities at the month interfaces are smoothed for 6 hours on each side.

TMY3 datasets are derived from the 1991-2005 (NSRDB) update for 1020 locations in the United States and its territories. The TMY3 dataset consists of hourly values of solar radiation and meteorological elements for a 1-year period. The meteorological data used in this dataset are provided by National Climatic Data Center (NCDC) from its Integrated Surface Database (ISD). The 12 selected typical months for each station were chosen using statistics determined by considering five elements: global horizontal radiation, direct normal radiation, dry-bulb temperature, dew-point temperature, and wind speed. These elements are considered the most important for simulating solar energy conversion systems and building systems. Final selection of a month includes consideration of the monthly mean and median and the persistence of weather patterns. (Rabideau et al, 2012)

The TMY 3 data set for Mason City Iowa combined data of the following month into one annual weather file: January 21, 2004; February 21, 1985; March 21, 1976; April 21, 2002; May 21, 1986; June 21, 2001; July 21, 2001; August 21, 2002; Sept 21, 1980; October 21, 1978; November 21, 1977 and Dec 21, 1981. The average monthly values are summarized in Table 1.

Month Avg.	Totcld (tenths)	Dry-bulb (°C)	Dew-point (°C)	Rhum %	Wdir (degrees)	Wspd (m/s)	Lprecip total (mm)
Jan	6.1	-9.9	-14.1	69.9	307.2	5.9	2
Feb	5.5	-8.7	-10.8	85.5	282.7	6.0	N/A
Mar	6.7	1.5	-3.4	71.9	273.6	6.4	N/A
Apr	5.8	8.3	2.0	67.4	237.2	6.4	34
May	6.0	15.2	9.5	72.7	62.9	4.6	N/A
Jun	4.0	20.3	13.8	69.1	191.9	4.8	51
July	3.7	23.2	17.4	72.8	155.5	3.7	69
Aug	4.5	20.4	16.4	79.6	165.3	3.6	129
Sept	4.5	16.7	11.5	73.6	215.5	4.1	N/A
Oct	4.9	8.1	2.6	71.0	241.2	5.1	N/A
Nov	6.3	0.4	-2.8	80.4	221.3	5.9	N/A
Dec	6.3	-8.3	-12.3	72.3	278.0	4.8	N/A
Year Avg	**5.4**	**7.4**	**2.6**	**73.8**	**219.4**	**5.1**	**N/A**

Table 1: TMY 3 Data for Mason City, Iowa: Monthly and Yearly Averages

Future Typical Meteorological Year Data (FTMY)

Building energy consumption is influenced by many design and operational factors, but weather plays a major role. As discussed in detail in Rabideau, Passe and Takle in "Exploring Alternatives to the 'Typical Meteorological Year' for Incorporating Climate Change into Building Design," "future typical meteorological year" (FTMY) data were constructed for the location Mason City Iowa to evaluate the impact of climate change on buildings. The process used in this project involved several steps. First, the "typicalness" of the TMY3 derived by Wilcox and Marion (2008) was evaluated for seven variables - total sky cover, dry-bulb temperature, dew-point temperature, relative humidity, absolute humidity, pressure, and wind speed. The second step was to evaluate the skill of individual RCMs to reproduce TMY3 data. For the final step, data for Mason City, Iowa were extracted from the NARCCAP archive for the eight GCM/RCM model combinations for both the contemporary (1971-2000) and future (2041-2070) time periods. Differences of the monthly averages of these datasets for each variable were then added to the hourly TMY3 data to produce a future typical meteorological year analogous to the TMY3 for the middle of the 21st century. Linear interpolations between the 3-hourly NARCCAP projected changes were made in order to correspond with the hourly TMY3 data. Results presented here represent low-change (WRFG-CGCM3), medium-change (RCM3-CGCM3), and high-change (CRCM-CCSM) scenarios.

The regional climate models used were

WRFG Weather Research & Forecasting Model
RCM3 Regional Climate Model, version 3
CRCM Canadian Regional Climate Model

These models were run for a spatial domain covering North America with lateral boundary conditions provided by the following Global Climate Models:

CGCM3 Third Generation Coupled Global Climate Model
CCSM Community Climate System Model

Typical House Design for Mason City, Iowa

In order to conduct basic thermal energy transfer calculations and to better understand potential impact of a changing climate on building energy demand, a typical house was designed. The house was designed to reflect current residential design and construction practices. The intent was to analyze rising temperature and humidity levels for an average sized home with average insulation value. The typical house designed for this purposes has 2 stories consisting of a total floor plan of 2,380 ft^2 and a volume of 30,582 ft^3 (Figure 2.1 – 2.3).

Building element		**Construction method**		**U-Factor:**
Walls		Wood studs nom. 2x6 in, 24 in o. c.		0.056 BTU/ft^{2}h°F
Window (not shaded)		Double-glazing with 1/8 in. panes: uncoated clear with 1/4 in. air space. SCI =0.5 / SCO =1.0 / CLF=0.7		0.65 BTU/ft^{2}h°F
Roof		standard wood joists, semi-exterior air film, gypsum board, interior air		0.033 BTU/ft^{2}h°F

Table 2: Typical Mason City Iowa Home specifications

For the purposes of the calculations, the air infiltration exchange rate was set at a constant of 25% ACH. Standard construction methods were assumed for walls, windows and roof of the typical house (Table 2), which would be prescribed before ASHRAE 90.1-2004 for this climate zone 6 (ASHRAE 90.2).

As indoor design condition a heating and cooling set point was selected within the range of conventional human comfort zone acceptable according to the ASHRAE Standard 55-1992 (Figure 1), which was inserted into the energy transfer calculation to derive the delta temperature for conduction and convection.
Indoor Temperature: 70°F
Indoor Humidity: 50% relative humidity

To simplify the process the same set point conditions were selected for both summer and winter energy transfer calculations. This methodology does not necessarily reflect actual good practices, but simplified the calculation process (Figure 1).

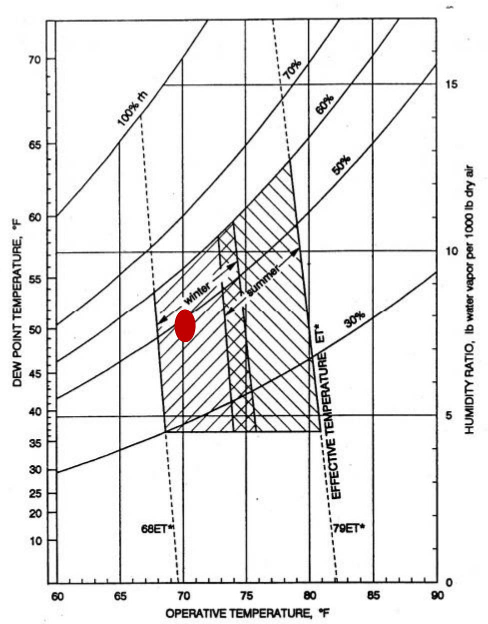

Figure 1: ASHRAE Standard 55-1992
Human Comfort Zone diagrammed onto a Psychometric Chart

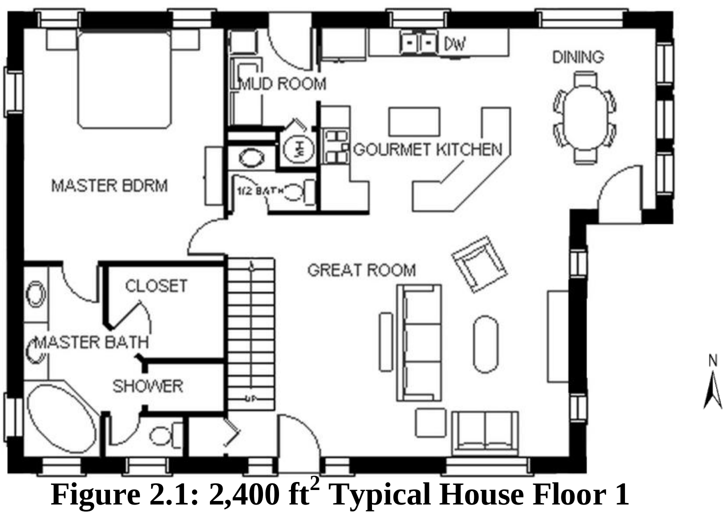

Figure 2.1: 2,400 ft^2 Typical House Floor 1

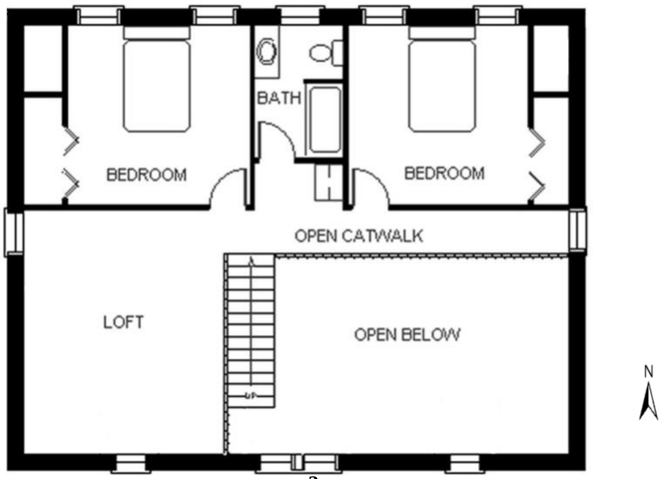

Figure 2.2: 2,400 ft^2 Typical House Floor 2

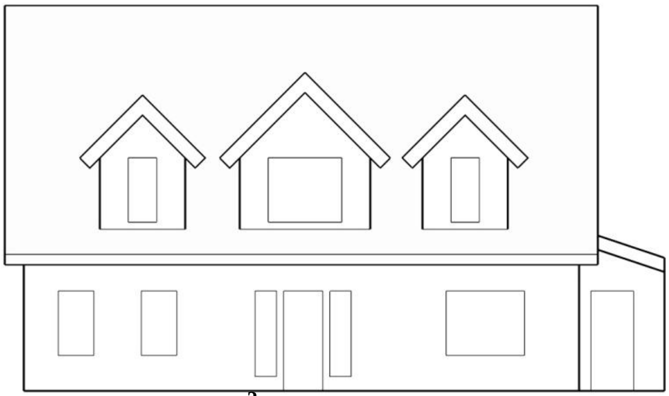

Figure 2.3: 2,400 ft^2 Typical House North Elevation

Simplified evaluation of energy consumption based on Typical Metrological Year (TMY 3) Data

In order to understand the impact rising temperatures and humidity levels due to climate change would have upon building energy consumption, envelope heat transfer was calculated for this hypothetical schematic typical house by using the hourly data of the TMY3 data (Marion 2008) for the 21st day of each month. Additionally the amount of heat transfer was also calculated for daily, monthly and yearly weather data averages. In order to then understand the sensitivity of the Mason City typical house to changes in temperature and humidity values, we ran calculations with altered outside temperature and humidity conditions and increased the temperature within a range of 10°F (+5°F to -5°F range) in 1°F increments. These altered outside design conditions were then applied to the daily low, high and average temperatures for the 21st day in each month given in the TMY dataset and the envelope heat transfer calculations were repeated.

Simplified calculation of heat transfer by conduction and radiation

Heat transfer via the windows of the typical house was calculated as:

$$\boldsymbol{h_t = h_l + h_g}$$

where

h_t = *total energy (BTU)*

h_l = *window energy loss or gain by conduction (BTU)*

h_g = *window energy gain by radiation (BTU)*

Heat loss or gain by conduction via the windows was calculated as:

$$h_l = [(A)(U)(\Delta T)]$$

where

h_l = *energy loss or gain (BTU) depending in season*

A = *area of windows (*ft²)

U = *U-value (*BTU/ft²h°F)

ΔT = *[temperature outside - temperature inside] (°F)*

Heat gain by radiation via the windows was calculated as:

$$h_g = (A)(SHGF)(SCI)(SCO)(CLF)$$

where

h_g = *energy gain (BTU)*

A = *area of windows (ft²)*

SHGF = solar heat gain factor related to building orientation and time of day and year

SCO = outside shading coefficient

SCI = inside shading coefficient (based on glass property)

CLF = cooling load factor (based on internal room properties)

Heat transfer via the opaque envelope of a building was calculated as

$$h_l = [(A)(U)(\Delta T)]$$

where

h_l = *energy loss or gain (BTU) depending in season*

A = *area of windows (*ft²)

U = *U-value (*BTU/ft²h°F)

ΔT = *[temperature outside - temperature inside] (°F)*

Impact of rising relative and absolute humidity levels

Relative and absolute humidity are important factors in understanding building cooling loads as high relative humidity combined with high temperatures can lead to undesired and uncomfortable conditions. In conventional air-conditioned buildings relative humidity above the set point is removed by condensing the water vapor out of the air, which requires a significantly larger amount of energy than simply cooling the air. In order to calculate the impact of changing humidity levels due to climate change on building energy demand, we calculate the energy requirement for removing humidity as it is current practice.

Enthalpy evaluation to calculate humidity concentration

Enthalpy is a measurement of the total energy of a thermodynamic system. Enthalpy of dry air includes the internal energy, which is a function of temperature only, and the amount of energy required to displace its environment and establish its volume and pressure. The enthalpy of moist air can be calculated by summing the enthalpy of dry air and the enthalpy of water vapor.

Equation for Specific Humidity Air-Vapor Mixture (Saturation)

In order to solve for the enthalpy of humidity, the saturation of the air-vapor mixture first needed to be calculated.

$$x = 0.622\ \varphi\ \rho_{ws} / (\rho - \rho_{ws})\ 100\%$$

where

x = *specific humidity of air vapor mixture (kg/kg)*

φ = relative humidity (%)
ρ_{ws} = density of water vapor (kg/m^3)
ρ = density of the moist or humid air (kg/m^3)

(1) Specific Enthalpy of Moist Air

Specific enthalpy (enthalpy per unit mass) of moist air can be expressed as:

$$h = h_a + x\, h_w$$

where

h = specific enthalpy of moist air (kJ/kg, Btu/lb)
h_a = specific enthalpy of dry air (kJ/kg, Btu/lb)
x = humidity ratio (kg/kg, lb/lb)
h_w = specific enthalpy of water vapor (kJ/kg, Btu/lb)

(2) Specific Enthalpy of Dry Air - Sensible Heat

The specific enthalpy of dry air can be expressed as:

$$h_a = c_{pa} t$$

where

c_{pa} = specific heat capacity of air at constant pressure (kJ/kg^oC, kWs/kgK, Btu/lb^oF)
t = air temperature (^oC,^oF)

For air temperature between *-100^{o}C (150°F) and 100°C (212°F) the specific heat capacity can be set to:*

c_{pa}= 1.006 (kJ/kg^oC) or
= 0.240 (Btu/lb^oF)

(3) Specific Enthalpy of Water Vapor - Latent Heat

The specific enthalpy of water vapor can be expressed as:

$$h_w = c_{pw}\, t + h_{we}$$

where

c_{pw} = specific heat capacity of water vapor at constant pressure (kJ/kg^oC, kWs/kgK)
t = water vapor temperature (^oC)
h_{we} = evaporation heat of water at 0^oC (kJ/kg)

For water vapor the specific heat capacity at constant pressure can be set to:

c_{pw} = 1.84 (kJ/kg^oC)
= 0.444 (Btu/lb^oF)
The evaporation heat (water at 0^oC) can be set to:
h_{we} = 2501 kJ/kg)
= 970 (Btu/lb)

Using (2) and (3), (1) can be modified to

$$h = c_{pa}\, t + x\, [c_{pw}\, t + h_{we}]$$

Specific Enthalpy of Moist Air in SI (Metric) units

$$h = (1.006\ kJ/kg^oC)\ t + x\ [(1.84\ kJ/kg^oC)\ t + (2501\ kJ/kg)]$$

where

h = enthalpy (kJ/kg)

x = mass of water vapor (kg/kg)
t = temperature (°C)

Specific Enthalpy of Moist Air in (IP) Imperial (Inch-Pound) units
h = (0.240 Btu/lb°F) t + x [(0.444 Btu/lb°F) t + (970 Btu/lb)]
where
h = enthalpy (Btu/lb)
x = mass of water vapor (lb/lb)
t = temperature (°F)

Results: Temperature
The results of these preliminary sensitivity studies to changing outside temperature conditions for this typical 2,400ft^2 house in Mason City, Iowa using the Typical Metrological Year Data indicate a direct relationship between changing outdoor temperature and the energy consumption needed to offset the effects of the temperature change (Table 3.1). The thermal transfer calculations show that:
1°F change = 12,945.4 BTU/day change / 1°C change = 23,301.7 BTU/day change
1°F change = 3.8 kWh/day change / 1°C change= 6.47 kWh/ day change.

°C	°F	Energy (BTU)	Energy (KJ)	Energy (kWh)
18.0	64.4	20,358.2	21,478.9	6.0
19.0	66.2	43,659.9	46,063.4	12.8
20.0	68.0	66,961.6	70,647.8	19.6
21.0	69.8	90,263.3	95,232.3	26.5
22.0	71.6	113,565.0	119,816.8	33.3
23.0	73.4	136,866.7	144,401.2	40.1
24.0	75.2	160,168.4	168,985.7	46.9
25.0	77.0	183,470.1	193,570.1	53.8
26.0	78.8	206,771.8	218,154.6	60.6
27.0	80.6	230,073.5	242,739.1	67.4

Table 3.1: Impact of temperature on energy demand for sensible cooling loads of typical house in Mason City, IA, (Average daily temperature changes)

°C	°F	Energy (BTU)	Energy (KJ)	Energy (kWh)
8.0	46.4	212,658.8	224,365.7	62.3
9.0	48.2	189,357.1	199,781.2	55.5
10.0	50.0	166,055.4	175,196.7	48.7
11.0	51.8	142,753.7	150,612.3	41.8
12.0	53.6	119,452.0	126,027.8	35.0
13.0	55.4	96,150.3	101,443.4	28.2
14.0	57.2	72,848.6	76,858.9	21.3
15.0	59.0	49,546.9	52,274.5	14.5
16.0	60.8	26,245.2	27,690.0	7.7
17.0	62.6	2,943.5	3,105.5	0.9

Table 3.2: Impact of temperature on energy demand for sensible heating loads of typical house in Mason City, IA. (Average daily temperature changes)

Results: Humidity

The results of the sensitivity studies for the same 2,400ft^2 typical house with Typical Metrological Year 3 Data for Mason City Iowa for changing humidity levels also indicate a direct relationship between changing saturation and the energy consumption needed to offset the effects of the humidity change (Table 3.2). If this particular house would be conventionally cooled the calculations indicate:

1% change in saturation = 0.5% change in energy consumption (BTU or KJ)

Results: Relativity

Removing humidity from air requires a phase change of water vapor, which requires removal of a substantial amount of enthalpy as previously described. Lowering the temperature of humid air and maintaining a constant relative humidity therefore requires both removing enthalpy of dry air and enthalpy due to the phase change of sufficient water vapor to keep the relative humidity constant. According to the Clausius-Clapeyron equation, the amount of water vapor in saturated air doubles for every rise of 10^{o}C. Hence saturated air at 22^{o}C has four times as much water vapor as saturated air at 2^{o}C. So to cool saturated air at 22^{o}C by 1 $^{\circ}$C degree requires four times the amount of energy for air conditioning energy as cooling saturated air at 2^{o}C by 1 $^{\circ}$C degree. The calculations summarized in Table 3.3 indicate that a 1% change in saturation yields significantly more energy demand in summer than in winter.

Month	Change (BTU/Day)	Change (KJ/Day)	Change (Wh/Day)
January	31.9	33.7	9.35
February	41.7	44.0	12.22
March	76.6	80.8	22.45
April	112	118.2	32.82
May	192.6	203.2	56.45
June	258.6	272.8	75.79
July	322	339.7	94.37
August	306.3	323.2	89.77
September	222.9	235.2	65.33
October	119.4	126.0	34.99
November	54.4	57.4	15.94
December	39.3	41.5	11.52

Table 3.3: Impact of relative humidity on energy demand for typical house in Mason City, IA

Further evaluations using energy modeling software

In order to understand the complex impact of future outdoor climate conditions on overall building energy consumption in a next step, the typical house was modeled in an energy performance modeling software tool (SketchUp Open Studio) and evaluated with US DOE's EnergyPlus (Fig.3.1 and 3.2). The house was modeled with default values to simulate a typical house with conventional climate control in this specific location (Fig. 3.3). First annual energy consumption, heating and cooling load were calculated with the TMY3 dataset currently in use, which is based on past observed data and secondly with three FTMY data sets based on future climate scenarios, which our team developed for Mason City Iowa (Table 4.1 – 4.4).

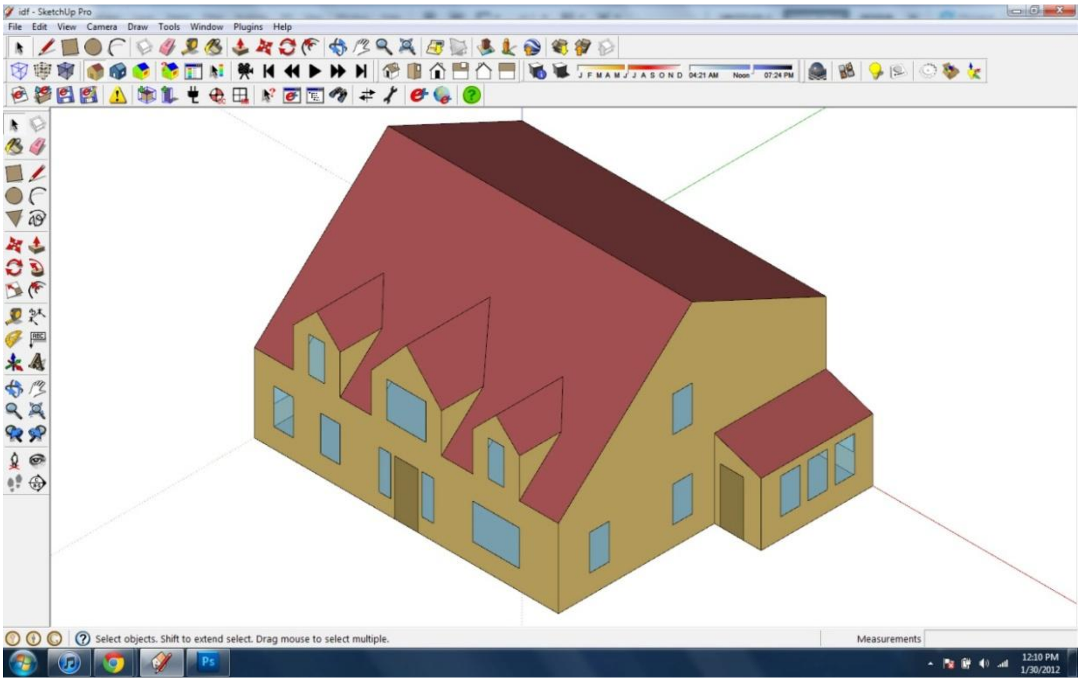

Figure 3.1: Typical house model for Mason City Iowa

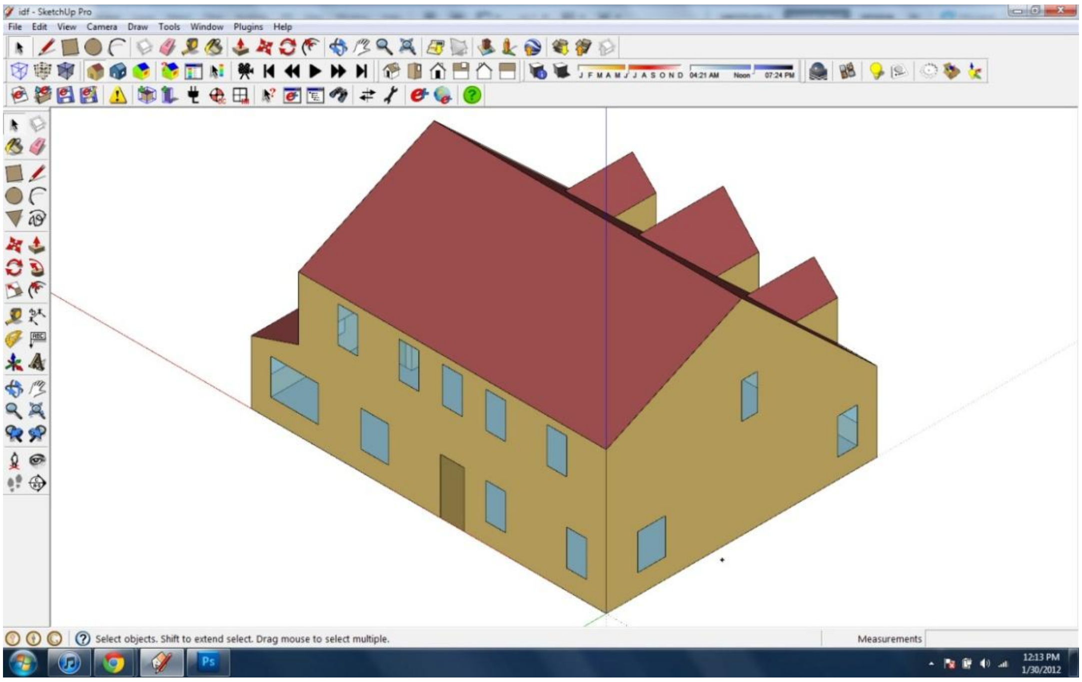

Figure 3.2: Typical house model for Mason City Iowa

Occupancy level	Light power density	Electric equipment power density	Outdoor air per Person	Infiltration rate	Construction
2 people/ 1000sq ft	1.0 W/ sq ft	1.0 W/sq ft	5 cfm/ person	0.5 ACH	ASHRAE 90.1
2 people/ 100 m^2	0.3W / m^2	0.3W / m^2	2.46 l/s	0.5 ACH	ASHRAE 90/1

Figure 3.3: Default energy modeling values

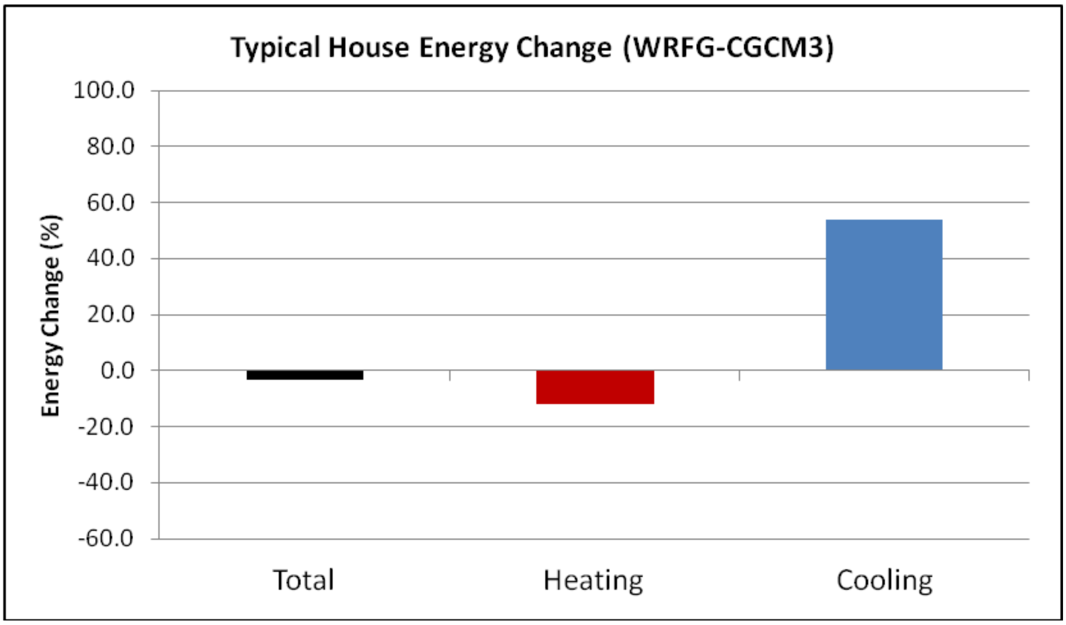

Table 4.1: Predicted changes in energy consumption based on low change scenario (WRFG-CGCM3)

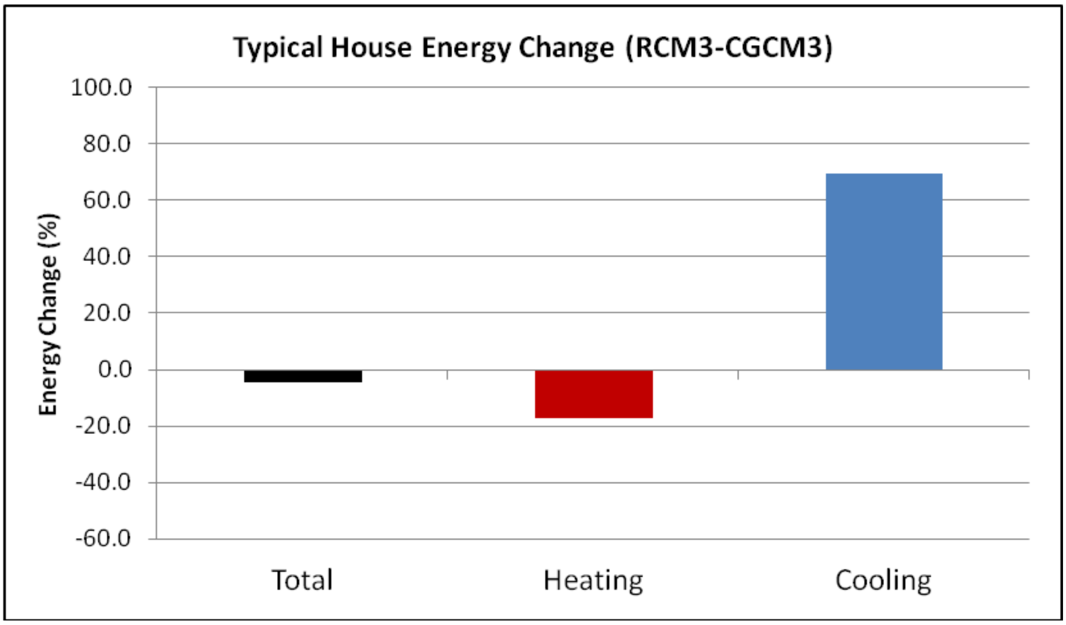

Table 4.2: Predicted changes in energy consumption based on medium change scenario (RCM3-CGCM3)

Evaluation of US DOE reference buildings with Future Typical Meteorological Year data

The United States Department of Energy provides 16 commercial reference buildings for modeling energy consumption. Each can be adapted to any of the 16 DOE ASHRAE climate zones and can be modeled with the respective TMY3 dataset. For our next study we used the software EnergyPlus to conduct energy simulations with those reference buildings for the weather data of Mason City, Iowa (TMY 3). As there are no reference buildings available directly for this location we used the reference buildings prepared for the climate zone of Chicago, Illinois. Three of the most common building types are represented here: Medium offices, secondary schools and stand-alone retail (Table 5).

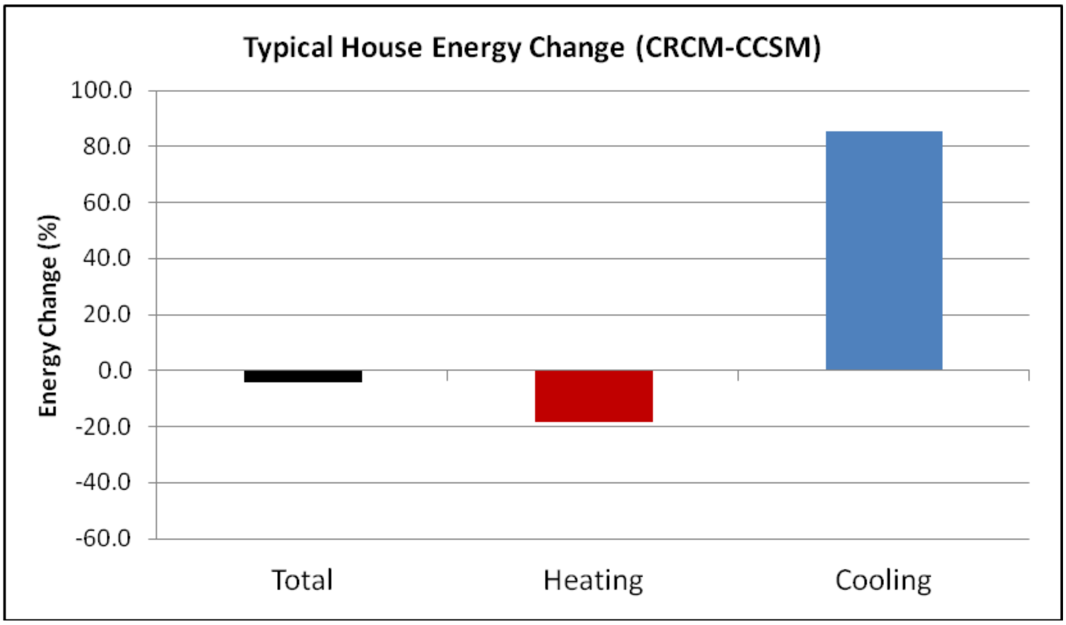

Table 4.3: Predicted changes in energy consumption based on high change scenario (CRCM-CCSM)

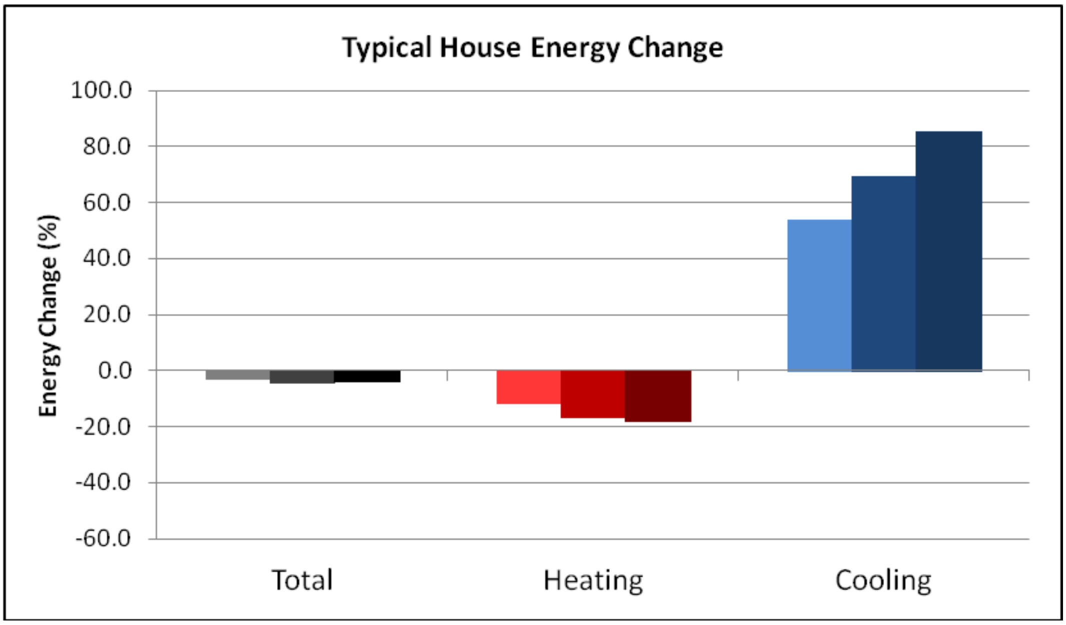

Table 4.4: Comparison of predicted changes in energy consumption based on all three climate models

Each of these reference building types were modeled with TMY 3 data and then compared with a simulation conducted with a FTMY based on a "moderate" climate change prediction scenario. In order to do this the FTMY datasets were converted into EPW files (Table 6.1-6.3).

Building Type	Floor Area (m²)	Floor Area (ft²)	Energy (MMBTU/Year)	Energy (GJ/Year)	Energy (kWh/Year)
Medium Office	511	5,502	3,132	3,304	917,778
Secondary School	19,592	210,886	20,829	21,976	6,104,444
Stand Alone Retail	2,293	24,692	2,338	2,467	685,278

Table 5: Summative specifications of the selected 3 reference building typologies

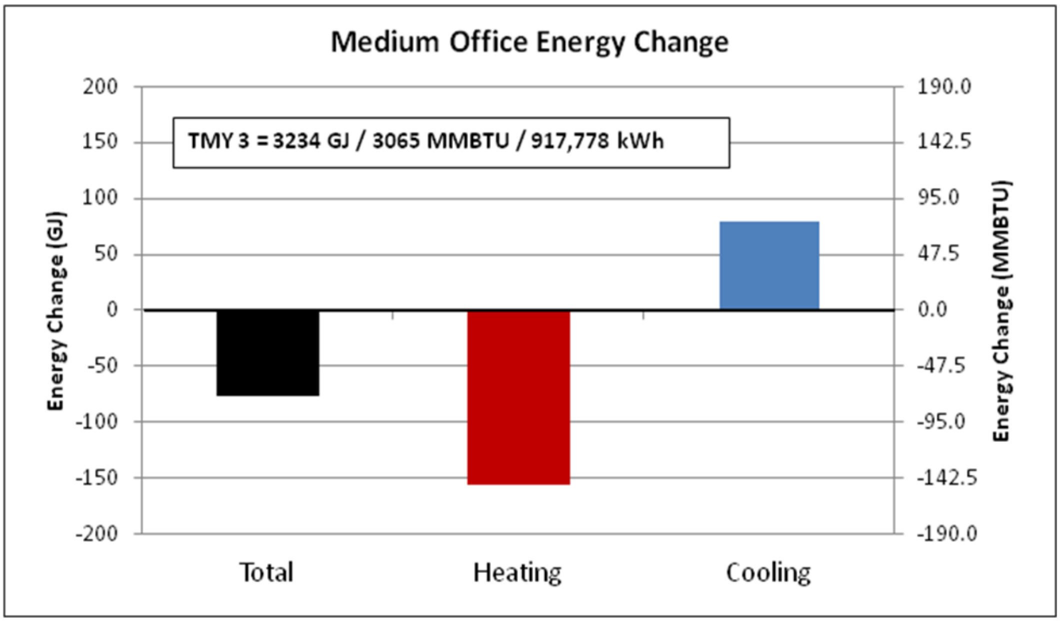

Table 6.1: Energy consumption changes predicted for medium offices based on medium change scenario

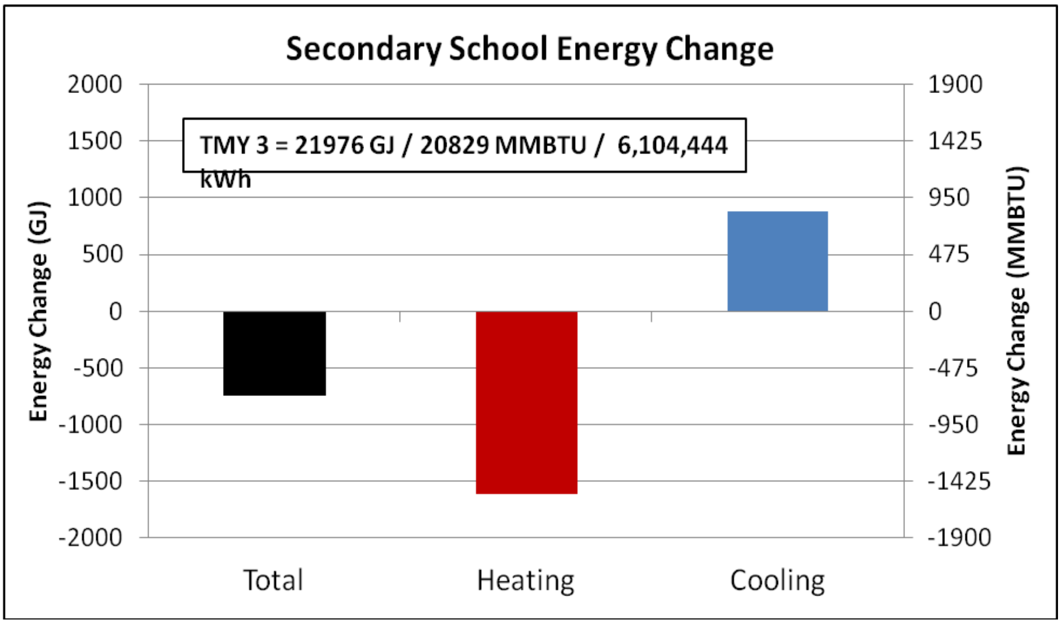

Table 6.2: Energy consumption changes predicted for secondary schools based on medium change scenario

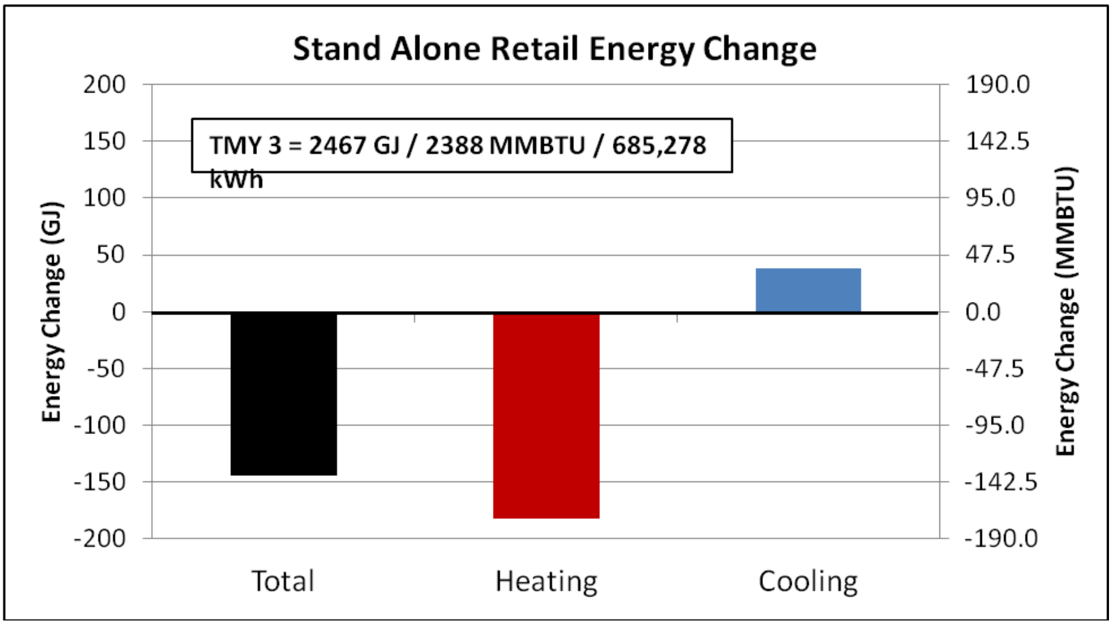

Table 6.3: Energy consumption changes predicted for stand-alone retail based on medium change scenario

Discussion of results

Sensitivity studies related to changes in temperature and humidity levels

As expected, the heat transfer calculations showed a direct relationship between a change in outdoor temperature and the resulting energy consumption while keeping all interior set points the same. These numbers indicate that changes in outdoor temperatures have a significant impact on energy consumption.

As discussed earlier removing humidity from air requires a phase change of water vapor, which requires removal of a substantial amount of enthalpy. Lowering the temperature of humid air and maintaining a constant relative humidity therefore requires both removing enthalpy of dry air and enthalpy due to the phase change of sufficient water vapor to keep the relative humidity constant.

Additionally, human thermal comfort parameters include other complex variables like mean radiant temperature (MRT) and air velocity, which were not considered in this preliminary study. ASHRAE Standard 55-2010 gives reference for adaptive human thermal comfort related to increased air velocity as present with natural ventilation, adaptive clothing behavior, ceiling fans, shading and other design related practices, which could be retrofitted into the studies typical house, but are currently not present and are very often not practiced in many residences in the Midwest of the United States. None of these adaptive strategies were included in the presented calculations in order to keep the numbers consistent and to highlight the fact, that a changing climate would significantly increase energy demand or jeopardize human comfort.

Conclusion and future work

For the Midwestern climate of the United States, energy simulations conducted with FTMY based on regional climate models result in predicted reductions in heating demand, which are offset by larger increases in cooling demand, thus giving an overall increase in energy demand for a future climate at this location. The new ASHRAE 55-2010 thermal comfort standard adds significant information on thermal comfort with elevated air speed allowing for natural ventilation, which can ventilate higher humidity, but air conditioned buildings with low air change rates and low air velocity will not easily adapt to warmer and more humid summer conditions.

A 2011 study conducted at University of Texas in Austin relates volatile organic compound (VOC) levels to high relative humidity levels. Results indicate that increasing relative humidity is associated with increases in VOC concentrations in residential indoor air (Nnadili 2011). Many of the chemicals that show enhanced off-gassing are associated with architectural coatings, moth repellents, and cleaning agents, which should ideally not be used in the first place, but which unfortunately are often present. Mold growth is also generally attributed to high relative humidity levels in calm air, but could be prevented with increased air velocity. Another recent research study (Barreca 2011) evaluates the relationship of climate change, mortality and humidity and concludes that increased humidity in winter might actually reduce mortality in the US, but also highlights the need to better control humidity especially in summer. These two studies indicate the complex impacts a changing climate might have on humans and their habitat. More studies are urgently necessary. It will also be important to understand, which levels of humidity are still acceptable with different more passive design and operation practices and find different ways to remove humidity from the incoming air stream than conventional compression refrigeration, which consumes large amounts of high grade electrical energy.

Our method can be used for any location across the US and Canada to better understand the impact of a changing climate on the most prevailing building typologies as they are represented by the U.S. Department of Energy (DOE) reference building files for 16 different US climate zones. Such a study would represent about 60% of the U.S. commercial building stock and could be expanded to include typical single and multi family residences. These future results could then be used by utility companies, building owners and policy makers to better prepare for future retrofits and investments. The new data sets could also be utilized as part of a risk analysis for new adaptive building design strategies utilizing natural energy flows in air and materials and to develop behavioral adaptation strategies for a future with a changing climate.

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