Proceedings of the ASME 2014 8th International Conference on Energy Sustainability
ES2014
June 30-July 2, 2014, Boston, Massachusetts, USA

ES2014-6642

CALIBRATED BUILDING ENERGY MODELS FOR COMMUNITY-SCALE SUSTAINABILITY ANALYSES

Michael Waite
Department of Mechanical Engineering,
Columbia University
New York, NY, USA

Vijay Modi
Department of Mechanical Engineering,
Columbia University
New York, NY, USA

ABSTRACT

Building energy contributes approximately 40% of U.S. greenhouse gas emissions and 75% of emissions in some urban areas. Evaluating modifications to existing building stocks is essential to a proper assessment of GHG reduction policy at various levels. With deeper penetration of intermittent renewable energy resources, supply and demand effects at a high resolution (e.g. hourly) will become more important as variations in grid emissions will become more significant. City-level hourly electricity load data is available; however, effects of building stock changes on usage profiles are not easily analyzed, and on-site fossil fuel usage – the dominant loads in many urban areas – are generally only available annually. Building energy models allow for detailed simulation of building systems, but existing building models must be calibrated to actual energy usage to predict the effects of energy conservation measures.

Reference building models developed by the U.S. Department of Energy for the EnergyPlus software tool were used as the basis for a set of calibrated building energy models to perform community-scale energy conservation measures on the dominant building classes in NYC (i.e. residential and office buildings). A statistical analysis of zip code-level annual electricity and fuel usage data was performed to determine electricity, space heating fuel and domestic hot water (DHW) fuel usage intensities (EUIs) for three broad building categories encompassing these building types in New York City. Several parameters were adjusted for each model until simulations produced the EUIs from the statistical analysis: Thermal envelope characteristics, peak electric equipment and lighting loads, DHW flow requirements, cooling equipment coefficient of performance and heating equipment efficiency. Cooling energy demands were adjusted based on the electricity demand vs. temperature behavior during the cooling season. The hourly daily usage schedules of internal electric and lighting loads were then adjusted for all models, targeting the actual hourly electricity demands for NYC. Because hourly changes affect annual EUIs, the calibrations were performed iteratively until the model outputs, weighted by each building type's total NYC square footage, equaled the annual EUIs for each building type and the hourly electricity demand data.

This paper shows that this comprehensive calibration approach can achieve root-mean-square deviation (RMSD) of 7% from the average annual electricity demand for these building types, compared to a 31% RMSD for an approach using annual energy calibration only.

INTRODUCTION

Energy usage and emissions in dense urban areas are dominated by buildings requirements. In many cities, including New York City (NYC), the primary source of greenhouse gas (GHG) emissions is in-building combustion of fossil fuels for space heating and domestic hot water [1]. The use of electric heat pumps to meet significant greenhouse gas (GHG) emission reduction targets is typically recognized in broad renewable energy policy studies [2, 3]. Policy proposals to dramatically reduce GHG emissions often have this heating system fuel switching as a cornerstone [4]. These analytical and policy development approaches typically treat building demands and power supply as separate sectors. However, a large-scale shift of heating demands onto the electricity grid will have significant impact on transmission, grid operation and the electricity generation fuel mix. These effects cannot be reliably investigated on an annual or average performance basis and the hourly effects of community-scale shifts in building design or operation are not well understood. Therefore, tools to predict these effects are desired.

Building energy models provide an opportunity to analyze different types of building systems and to solve the thermodynamic equations governing many aspects of building energy systems [5]. However, these models require more inputs than a user could be expected to accurately estimate. Calibrating energy models to actual building energy usage data has been reviewed [6]. These approaches, even if accurate to the data set used, typically use annual or monthly data [7]. Diurnal building performance can vary significantly. Calibration procedures also typically focus on a single building [8]. While these approaches are likely helpful in comparing design or retrofit options for a particular building, they are insufficient to understand the hourly demand effects on a city of large-scale changes to building systems.

This paper describes a calibration approach that uses annual energy targets and hourly electricity data to calibrate a set of building energy models representative of the dominant energy demands in New York City. The aim of this research is to produce a model set that can be used to evaluate the system-wide effects of community-scale changes in building design and operation.

ANALYSIS

An iterative calibration approach was developed to create a set of building energy models representing the dominant building classes in NYC (i.e. residential and office buildings). The models were based on engineering models that solve building-and system-specific thermodynamic equations, computational statistical tools and several publicly available energy datasets. Actual 2010 weather data for NYC was used in the energy model simulations.

Model Classification

Table 1 lists the individual models constituting the set, the floor area of each model and the total NYC floor area assigned to each model. The table also includes the reference building model used as the basis for the calibrated model. The single-family reference building model is from the U.S. Department of Energy (DOE) Residential Prototype Building Model for slab-on-grade construction with natural gas-fired space heating furnace; the model was designed by DOE to comply with the 2006 International Energy Conservation Code (IECC) [9]. All other building models are based on the DOE's Commercial Reference Buildings, developed to be representative of Post-1980 construction [10]. The air conditioning equipment in Models 1 and 3 were removed to create Models 2 and 4, respectively.

The total floor area for each model type was determined using building stock data from the New York City Department of City Planning's 2010 PLUTO database [11]. Residential building area in buildings with 4 units or fewer were assigned to the Single Family building models. Residential building area with more than 4 units was assigned to the multi-family building models. According to the U.S. Energy Information Administration's 2009 Residential Energy Consumption Survey (RECS), 82.4% of Middle Atlantic Region housing units use air conditioning equipment [12]. As such, the model classification assigned 82.4% of total residential floor area to the models with air conditioning and the remaining 17.6% of residential floor area to the models without air conditioning. This split was applied equally to both single-family and multi-family residential floor area.

The total office floor area excluded office area in buildings classified as health care facilities, hotels and educational facilities. To separate each office building into the Small Office, Medium Office and Large Office classifications, the logarithmic mean between the Small Office and Medium Office model floor areas and between the Medium Office and Large Office model floor areas were calculated. Buildings with office area less that 1,963.6 m^2 were assigned to Model 5: Small Office. Buildings with office area greater than or equal to 1,963.6 m^2, but less than 18,540 m^2 were assigned to Model 6: Medium Office. The remaining office area, for larger buildings, was assigned to Model 7: Large Office.

Annual Energy Intensities

The annual energy use intensity (EUI) for electricity and fuel usage for single-family (1-4 Unit) residential, multi-family residential and office buildings were calculated using the methodology in Howard et al [13], applied to 2010 zip code level annual electricity and fuel data available from New York City's OpenData website [14] and the 2010 PLUTO data. Using data for 170 zip codes, a robust multiple linear regression was performed with annual electricity and fuel usage regressed against floor area for each of the following building area types: Single-family residential (as defined in this paper), multi-family residential, office, store, educational facilities, health care facilities, and other building area.

The estimated electricity EUIs for single-family residential, multi-family residential and office area were all statistically significant with p-values less than 2.04×10^{-15}. The estimated fuel EUIs for single-family and multifamily residential construction were statistically significant with p-values less than 2.2×10^{-16}. The p-value for the office fuel EUI was 0.044; this was deemed acceptable for the purpose of the analysis described in this paper given the wide variation in fuel usage that may be seen in office buildings and the low office fuel requirements compared to other buildings, particularly residential.

The electricity EUIs determined through the regression analysis were multiplied by the floor area of each model category to calculate the annual electricity targets. The fuel EUIs were used to determine space heating and DHW fuel usage targets by multiplying the total fuel usage by the fuel use split for each building type. The fuel use splits were determined from the total natural gas consumption for space heating, DHW and other uses by building type for the Middle Atlantic Region from the 2009 RECS for single-family and multi-family residential, and from the 2003 Commercial Buildings Energy Consumption Survey. Note that the values do not add to 1 as buildings also use fuel for other functions (e.g. cooking).

Table 2 summarizes the annual electricity and fuel usage targets for each group of models, as well as the models aggregated during the annual model calibration described below.

Table 1 – Building Model Summary

Model	Description	Reference Model	Model Floor Area (m^2)	Total Floor Area (m^2)
1	Single-Family Residential with Air Conditioning	Single Family[a]	334.64	1.1380×10^8
2	Single-Family Residential without Air Conditioning	Single Family[a]	334.64	2.4307×10^7
3	Multi-Family Residential with Air Conditioning	Midrise Apartment[b]	3,134.5	1.5405×10^8
4	Multi-Family Residential without Air Conditioning	Midrise Apartment[b]	3,134.5	3.2904×10^7
5	Small Office	Small Office[b]	511.15	6.9235×10^6
6	Medium Office	Medium Office[b]	4,982.2	1.1587×10^7
7	Large Office	Large Office[b]	46,320	3.5711×10^7

[a] U.S. DOE Residential Prototype Building Models, 2006 IECC-compliant.
[a] U.S. DOE Commercial Reference Buildings, Post-1980 Construction

Table 2 – Annual Total Energy Targets

Group	Category	Models	Annual Energy Targets (GWh)		
			Electricity	Space Heating Fuel	DHW Fuel
A	Single-Family Residential	1, 2	5,564.0	14,929	4,413.8
B	Multi-Family Residential	3, 4	14,041	32,301	9,549.9
C	Office	5, 6, 7	14,515	4,378.7	167.84

Calibration Overview

A multi-stage calibration process was performed to adjust the base models to NYC energy data. The following steps, described in detail in the sections below, were performed in sequence and repeated until the annual energy target convergence criteria were satisfied at the end of Step 3:

1. Annual Energy Calibration
2. Cooling Adjustment
3. Weekly Schedule Adjustment

The base building energy models from the DOE sources described above are IDF files run using the DOE-developed EnergyPlus building energy simulation tool. The text-based IDF files were modified through R scripts developed by the authors to perform the calibration steps described below, export the modified IDF file, run the model simulations in EnergyPlus, and import the appropriate results files.

Annual Energy Calibration

Several design parameters were adjusted for each model iteratively by multiplying the base parameter values by a modifier determined at each iteration. The modifiers were: x_{loads}, x_{DHW}, $x_{thermal}$ and $x_{thermal\text{-}reduced}$. Some parameters affecting the building thermal performance need to be decreased to increase heating fuel consumption (e.g. heating equipment efficiency and insulation thickness), whereas other parameters need to be increased to have the same effect (e.g. window U-factor). As such, $x_{thermal}$ and $x_{thermal\text{-}reduced}$ are related by the following so that increases $x_{thermal\text{-}reduced}$ reflect the same adjustment as decreases in $x_{thermal}$:

$$x_{thermal-reduced} = 1 - (x_{thermal} - 1) \quad \text{(Eq. 1)}$$

Annex A includes tables of the modified parameters and the associated initial values and variable modifiers for each model.

Each modifier was the same for each model in a particular group at each annual energy calibration iteration for that group, though modifier values across groups were different. For each iteration, the total electricity, space heating fuel and DHW fuel for each group was calculated based on the model results within that group and the total floor area for each model included in Table 1.

The first annual energy calibration iteration used the base values (i.e. all modifiers equal to 1). The second iteration step used modifiers calculated from the results of the first iteration and the target values:

$$x_{thermal,g,2} = 1 + \frac{1}{2}\left(\frac{Target\ Fuel\ Usage_{SH,Ann,g}}{Calculated\ Fuel\ Usage_{SH,Ann,g,1}} - 1\right) \quad \text{(Eq. 2)}$$

$$x_{DHWg,,2} = 1 + \frac{1}{2}\left(\frac{Target\ Fuel\ Usage_{DHW,Ann,g}}{Predicted\ Fuel\ Usage_{DHW,Ann,g,1}} - 1\right) \quad \text{(Eq. 3)}$$

$$x_{loads,g,2} = 1 + \frac{1}{2}\left(\frac{Target\ Electricity\ Usage_{Ann,g}}{Predicted\ Electricity\ Usage_{Ann,g,1}} - 1\right) \quad \text{(Eq. 4)}$$

Subsequent annual energy calibration iterations use half step interpolation/extrapolation using the modifiers and results of the previous two iteration steps and the corresponding annual energy targets.

The model continues to iterate until the convergence criteria are satisfied. The criteria used for total annual electricity, total annual space heating fuel and total annual DHW fuel were within 1% of the corresponding target annual values.

Cooling Adjustment

The hourly electricity results of the annual energy calibration simulations, aggregated across all models, and the hourly NYC electricity data from NYISO were used to modify the models' cooling system performance and simulate the resulting effects on predicted hourly electricity usage.

For each day in the simulation and in the year 2010 NYC data, the minimum overnight electricity demand was compared to the minimum overnight temperature. Because the simulations include only a subset (approximately 75% of total square footage) of the NYC building stock, the NYC data was scaled linearly so that the total annual demand from the data equaled the total annual demand for the residential and office buildings. The overnight minimum demand was used to eliminate day-to-day variation in daytime energy usage from non-temperature-dependent loads.

A segmented linear regression was performed on each data set to fit a line to the "cooling season" (i.e. increasing electricity use with increasing outdoor air temperature) and "heating season" (i.e. increasing electricity use with decreasing outdoor temperature) data. Figures 1 and 2 show these results for the NYC data and the simulation results of the first cooling adjustment iteration, respectively.

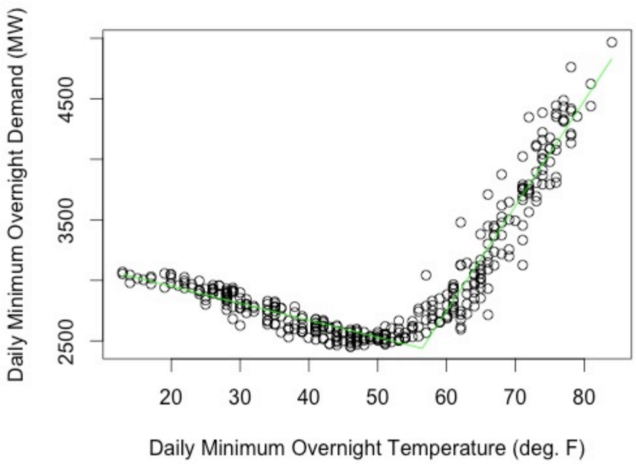

Figure 1 – Minimum Overnight Electricity Demand vs. Minimum Overnight Temperature – NYC 2010

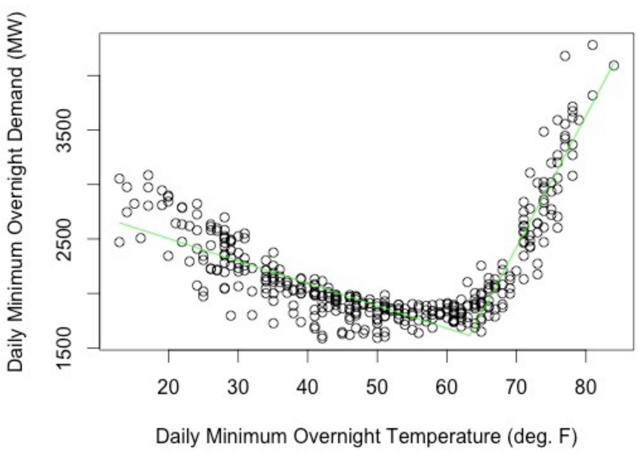

Figure 2 – Minimum Overnight Electricity Demand vs. Minimum Overnight Temperature – Simulation Results

The modifier x_{cool} was adjusted iteratively until the slope of the "cooling season" regression fit to the simulation data was within 1% of the slope of the corresponding regression fit to the actual data.

Weekly Schedule Adjustment

The EnergyPlus model files include hourly internal load schedules for:

- Weekends and Holidays
- Weekdays (Non-Holidays)

The average daily profiles of electricity usage for Weekends/Holidays and Weekdays/Non-Holidays were calculated for the aggregated building energy model results and the NYC hourly electricity data. The hourly schedules for all loads to which the x_{loads} modifier applies (see Annex A) were adjusted until predicted average hourly profiles for the two day types were within 1% for each hour.

The adjustments based on hourly data (Cooling Adjustment and Weekly Schedule Adjustment) affected the annual electricity and space heating fuel usage in the model simulations, necessitating that the three calibration steps described here be repeated until the annual energy calibration convergence criteria were met after the Weekly Schedule Adjustment process.

RESULTS AND DISCUSSION

The iterative analysis described above was performed using 2010 weather and electricity data. Table 3 summarizes the model set's ability to predict the actual hourly electricity data for 3 cases:

- Case 1: No calibration (base reference models)
- Case 2: Annual Energy Calibration only
- Case 3: Complete Calibration Methodology

The root-mean-square deviation from the actual hourly data is used as an overall metric. The sub-sections below investigate the calibration methodology performance further using data plots. This broad metric shows a clear improvement in the accuracy of the predictive model set from a calibration approach that goes beyond total annual energy-based calibration only.

Table 3 – Calibration Prediction Accuracy Summary

Case	Root-Mean-Square Deviation (MWh)	RMSD as % Average Demand
No Calibration	1210.2	31.1%
Annual Energy Calibration Only	1111.9	28.5%
Complete Calibration Methodology	266.36	7.07%

Plots of hourly electricity demand for annual, winter week and summer week periods are shown below.

Annual Hourly Electricity Demand

Figures 3 through 5 show annual hourly electricity demand for NYC and for the aggregated results of the model simulations, respectively, for the cases listed above.

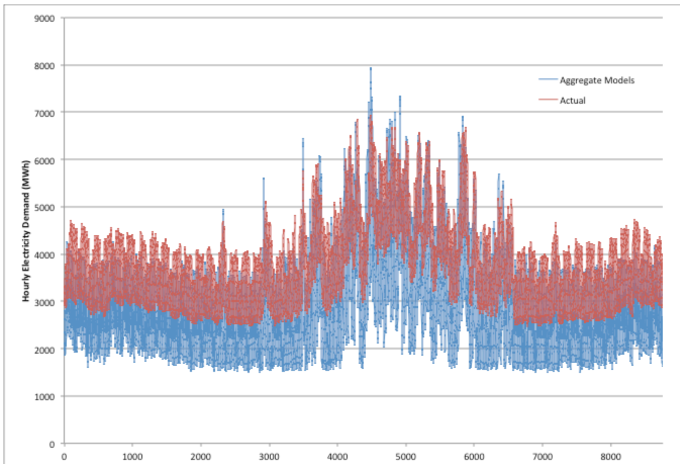

Figure 3 – Annual Hourly Electricity Demand, Case 1: No Calibration

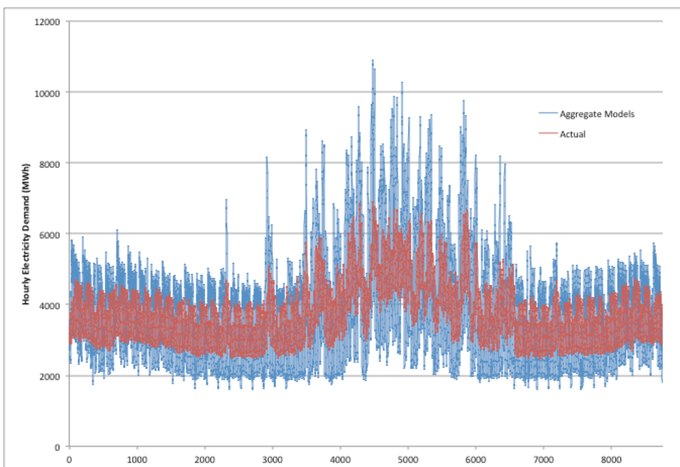

Figure 4: Annual Hourly Electricity Demand, Case 2: Annual Energy Calibration

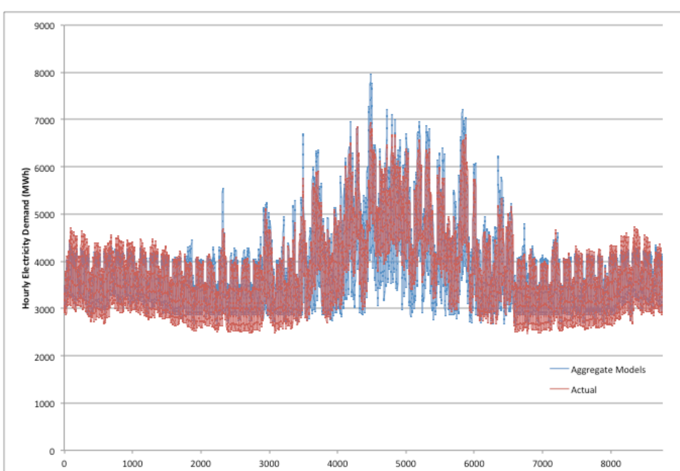

Figure 5: Annual Hourly Electricity Demand, Case 3: Complete Calibration Methodology

The annual demands show a clear under-prediction in the case with no calibration. While the daily averages and the overall total energy usage comes in line with the actual data when the model set is calibrated to annual energy usage targets, the fluctuations, both diurnally and seasonally, are far greater in the simulations than in the actual data. Using the Complete Calibration Methodology, brings the predicted hourly electricity usage much more closely in line with the actual NYC hourly electricity demand.

Winter Week Hourly Electricity Demand

Figures 6 through 8 show hourly electricity demand for a winter week (February 1-7) for NYC and for the aggregated results of the model simulations, respectively, for the cases listed above.

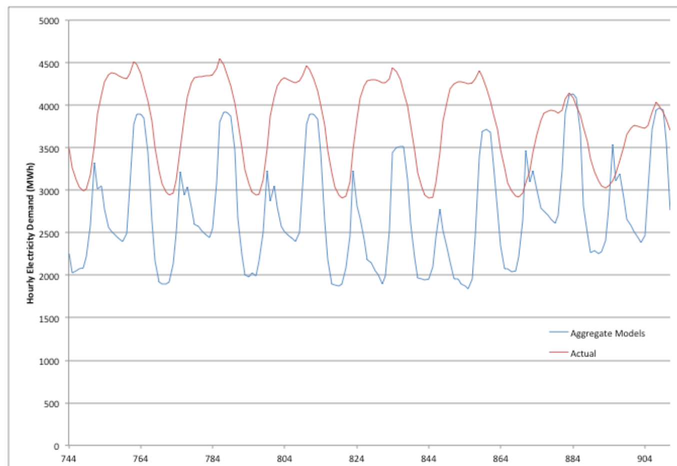

Figure 6 – Winter Week Hourly Electricity Demand, Case 1: No Calibration

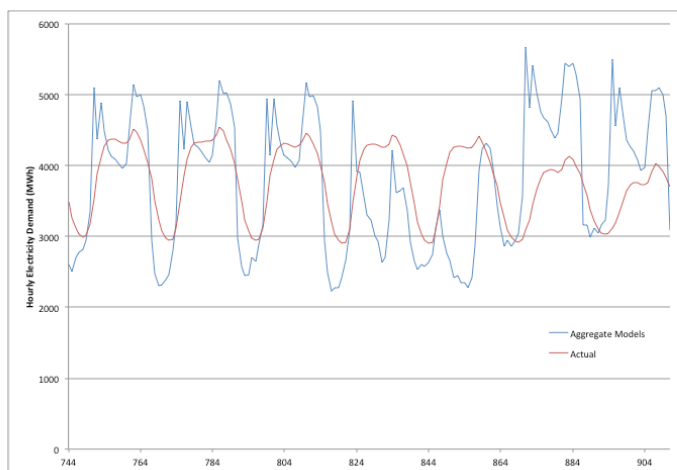

Figure 7: Winter Week Hourly Electricity Demand, Case 2: Annual Energy Calibration

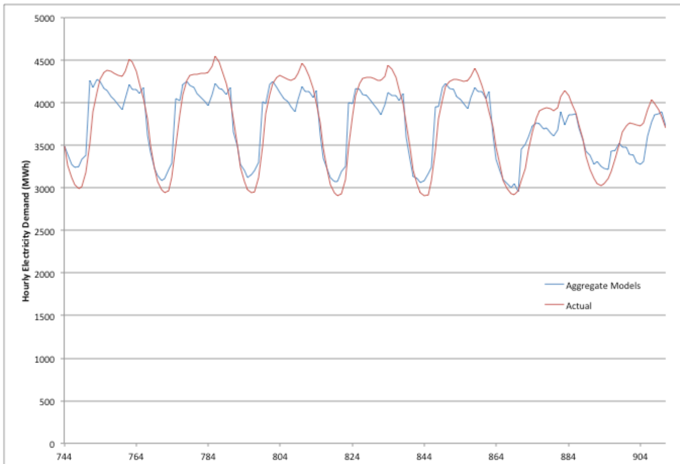

Figure 8: Annual Hourly Electricity Demand,
Case 3: Complete Calibration Methodology

As seen in the annual demand profiles, the annual energy calibration brings the predicted electricity demands more closely in line with the levels seen in the data. However, the hourly adjustments are required to more closely represent the hourly performance. There are some peculiarities to the hourly demand profile mid-day that are not captured in the calibration procedure.

Summer Week Hourly Electricity Demand

Figures 9 through 11 show hourly electricity demand for a summer week (August 1-7) for NYC and for the aggregated results of the model simulations, respectively, for the cases listed above.

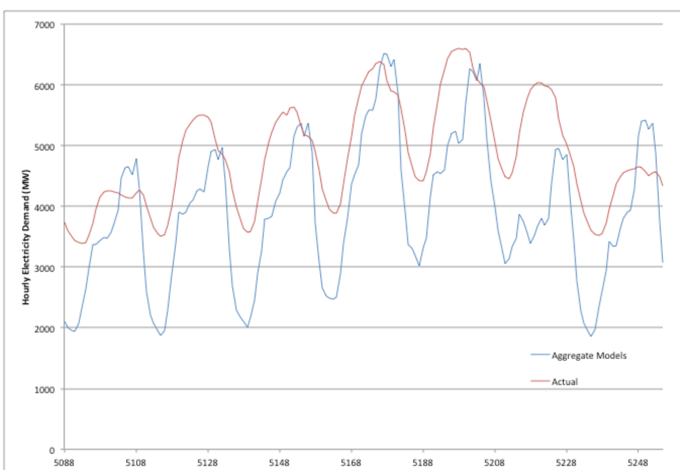

Figure 9 – Summer Week Hourly Electricity Demand,
Case 1: No Calibration

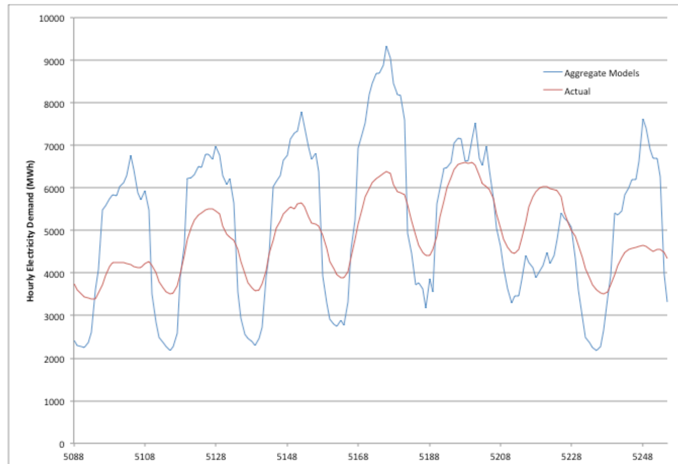

Figure 10: Summer Week Hourly Electricity Demand,
Case 2: Annual Energy Calibration

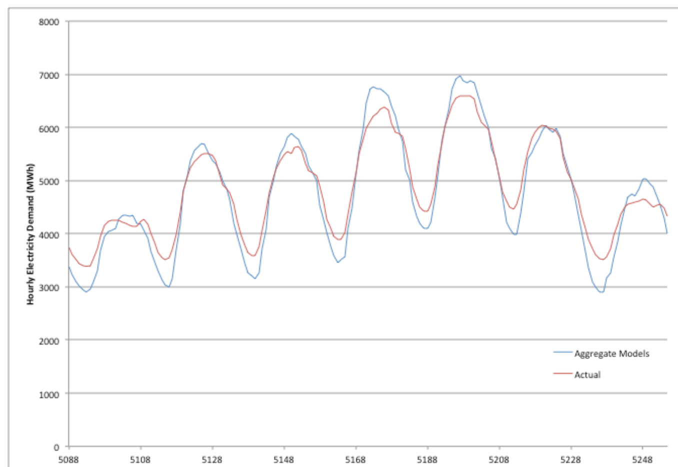

Figure 11: Annual Hourly Electricity Demand,
Case 3: Complete Calibration Methodology

The complete calibration methodology brings the hourly demand in the summer significantly more closely in line with the data than the annual energy calibration only. As with the winter week, there are likely some issues with using the daily average demand profiles to adjust the daily hourly schedules for the year.

Simulations for Alternative Year

The building model calibration set was simulated using the calendar and weather data for 2011 for NYC to review its performance for a year alternative to that used to calibrate the model set. The calibrated energy model set analysis approach applied to 2011 results in a predicted NYC electricity demand profile exhibiting a RMSD equivalent to 8.7% of the average aggregate hourly 2011 electricity demand for the relevant building types. Therefore, the year-to-year change in performance is relatively small when considering that a single year (2010) was used in the calibration process.

CONCLUSIONS

This paper validates an approach to calibrating whole building energy models to the annual electricity, space heating fuel and DHW fuel performance of average buildings for an urban area. The set of building energy models developed for different size residential and office buildings is further calibrated to hourly electricity data for NYC, showing good agreement to the portion of NYC electricity demand attributable to residential and office buildings, the dominant energy demands in NYC, as well as other dense urban areas. The calibrated energy model set exhibits a RMSD equivalent to approximately 7% of the average aggregate annual demand for these building types; an approach using annual energy calibration only exhibits an RMSD equivalent to 31% of this average annual demand. The approach of calibrating hourly equipment usage schedules based on the annual average demand profiles for Weekends/Holidays and Weekdays/Non-Holidays is the likely cause of some peculiarities in the hourly predictive ability of the approach seen in the summer and winter. However, this coarseness is required to be able to use the model set for years other than 2010. An analysis using 2011 weather data shows that the model set can reasonably be used for the anticipated applicable energy analyses for other years.

This set of energy models can be used to evaluate modifications to a subset these dominant building types on a community scale and their implications for electricity and fuel usage. Future research will utilize this set of energy models to analyze the overall GHG emissions impact of urban scale energy conservation measures, such as changes to mechanical systems (e.g. from on-site fossil fuel-burning heating systems to electric heat pumps) and thermal envelope improvements (e.g. reduced air infiltration and increased building envelope insulation). The models can also be used to assess the impact of micro-grid "islands" within a larger grid, in conjunction with a grid power flow model being developed in a parallel research effort.

REFERENCES

[1] City of New York, *Inventory of New York City Greenhouse Gas Emissions, December 2013*, by Jonathan Dickinson, Jamil Khan and Mikael Amar. Mayor's Office of Long-Term Planning and Sustainability, New York, 2013.

[2] Jacobson, M.Z. and M.A. Delucchi. Providing all global energy with wind, water and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. Energy Policy 2011; 39: 1154-1169.

[3] Jacobson, M.Z., R.W. Howarth, M.A. Delucchi, S.R. Scobie, J.M. Barth, M.J. Dvorak, M. Klevze, H. Katkhuda, B. Miranda, N.A. Chowdhury, R. Jones, L. Plano and A.R. Ingraffea. Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water and sunlight. Energy Policy 2013; 57: 585-601.

[4] City of New York, *New York City's Pathways to Deep Carbon Reductions, December 2013*. Mayor's Office of Long-Term Planning and Sustainability, New York, 2013.

[5] Zhao, H. and F. Magoules. A review on the prediction of building energy consumption. Renewable and Sustainable Energy Reviews 2012; 16(6): 3586-3592

[6] Manfren, M., N. Aste and R. Moshksar. Calibration and uncertainty analysis for computer models - A meta-model based approach for integrated building energy simulation. Applied Energy 2013; 103: 627-641

[7] Heo, Y., R. Choudhary, G.A. Augenbroe. Calibration of building energy models for retrofit analysis under uncertainty. Energy and Buildings 2012; 47: 550-560.

[8] Munshi, M., D. Tuhus-Dubrow, J. An and B. Coffey. Practical techniques for automated calibration of existing models for use in building operations. Proceedings of IBPSA SimBuild 2012. 2012.

[9] U.S. Department of Energy (DOE). *Residential Prototype Building Models*. (http://www.energycodes.gov/development/residential/iecc_models)

[10] U.S. Department of Energy (DOE). United States Department of Energy (DOE) Commercial Reference Building Models (http://www1.eere.energy.gov/buildings/commercial/ref_buildings.html)

[11] New York City Department of City Planning. MapPLUTO (Edition 10v2)

[12] Howard, B., L. Parshall, J. Thompson, S. Hammer, J. Dickinson and V. Modi. Spatial distribution of urban building energy consumption by end use. Energy and Buildings 2012; 45: 141-151.

[13] City of New York. NYC OpenData. (https://data.cityofnewyork.us/)

ANNEX A

MODEL SIMULATION PARAMETERS

Tables A1 through A5 include the parameters modified in the calibration procedure described in this paper, as well as the applicable modifier variable and the initial value for each parameter.

Table A1 – Simulation Parameters for Models 1 and 2

Parameter	Modifier	Initial Value
Refrigerator (W/m2)	x_{loads}	91.0939726
Misc Elec (W/m2)	x_{loads}	2.46
Washer (W)	x_{loads}	29.58183123
Dryer (W)	x_{loads}	222.1129282
Dishwasher (W)	x_{loads}	68.32757089
Misc Elec Load (W/m2)	x_{loads}	182.5215358
Living Hardwired Lighting1(W/m2)	x_{loads}	2.0565
Living Plug Lighting (W/m2)	x_{loads}	0.5141
Exterior lights (W)	x_{loads}	79.5
Garage lights (W)	x_{loads}	14.02
DHW Peak-Washer (m3/s)	x_{DHW}	1.62E-06
DHW Peak-dishwash (m3/s)	x_{DHW}	6.37E-07
DHW Peak-sinks (m3/s)	x_{DHW}	2.12E-06
DHW Peak-showers (m3/s)	x_{DHW}	3.78E-06
DHW Peak-baths (m3/s)	x_{DHW}	9.70E-07
EffLkgeArea-living	$x_{thermal}$	962.7009566
EffLkgeArea-attic	$x_{thermal}$	370
wall_consol insul thick (m)	$x_{thermal-reduced}$	0.0889
sheathing insul thick (m)	$x_{thermal-reduced}$	0.0127
ceil_consol insul thick (m)	$x_{thermal-reduced}$	0.318439882
floor_consol insul thick (m)	$x_{thermal-reduced}$	0.1397
Window U (W/m2-K)	$x_{thermal}$	2.27144
Window SHGC	$x_{thermal}$	0.4001
Heating Efficiency	$x_{thermal-reduced}$	0.780001
COP-Cool	x_{cool}	3.9700885

Table A2 – Simulation Parameters for Models 3 and 4

	modifier	value
Light-Apt (W/m2)	x_{loads}	3.88001
Light-Office (W/m2)	x_{loads}	21.9501
Light-Corr (W/m2)	x_{loads}	9.90001
Equip-Apt (W/m2)	x_{loads}	5.38001
Equip-Office (W/m2)	x_{loads}	12.9001
Equip-Elevators (W)	x_{loads}	16054.94505
DHW Peak Flow (m3/s)	x_{DHW}	3.66E-06
Infiltration	$x_{thermal}$	0.001133
Wall Insul Thick (m)	$x_{thermal-reduced}$	0.081284786
Roof insul thick (m)	$x_{thermal-reduced}$	0.136472153
Window U (W/m2-K)	$x_{thermal}$	3.35002
Window SHGC	$x_{thermal}$	0.360001
Heating Efficiency	$x_{thermal-reduced}$	0.800001
COP-Cool	x_{cool}	3.133805819

Table A3 – Simulation Parameters for Model 5

	modifier	value
Lights (W/m2)	x_{loads}	19.48001
Equipment (W/m2)	x_{loads}	10.76001
DHW Peak Flow (m3/s)	x_{DHW}	3.15E-06
Infiltration	$x_{thermal}$	0.001133
Core infiltration	$x_{thermal}$	0.360001
Wall Insul Thickness (m)	$x_{thermal-reduced}$	0.051303484
AtticFloorInsul Thickness (m)	$x_{thermal-reduced}$	0.129101769
Window U (W/m2-K)	$x_{thermal}$	3.35002
Window SHGC	$x_{thermal}$	0.360001
Heating Efficiency	$x_{thermal-reduced}$	0.800001
COP-Cool	x_{cool}	3.067195993

Table A4 – Simulation Parameters for Model 6

	modifier	value
Lights (W/m2)	x_{loads}	16.890001
Equipment (W/m2)	x_{loads}	10.760001
Elevators (W)	x_{loads}	32109.89011
DHW Peak Flow (m3/s)	x_{DHW}	1.04E-05
Infiltration	$x_{thermal}$	0.001133
Wall Insul Thickness (m)	$x_{thermal-reduced}$	0.081284786
Roof Insul Thickness (m)	$x_{thermal-reduced}$	0.136472153
Window U (W/m2-K)	$x_{thermal}$	3.35002
Window SHGC	$x_{thermal}$	0.360001
Heating Efficiency	$x_{thermal-reduced}$	0.800001
COP-Cool	x_{cool}	2.800756688

Table A5 – Simulation Parameters for Model 7

	modifier	value
Lights (W/m2)	x_{loads}	16.1401
Equipment (W/m2)	x_{loads}	10.7601
Elevators (W)	x_{loads}	244443.956
DHW Peak Flow (m3/s)	x_{DHW}	2.24E-05
Infiltration	$x_{thermal}$	0.001133
Wall Insul Thickness (m)	$x_{thermal-reduced}$	0.051303484
Roof Insul Thickness (m)	$x_{thermal-reduced}$	0.136472153
Window U (W/m2-K)	$x_{thermal}$	3.35002
Window SHGC	$x_{thermal}$	0.360001
Heating Efficiency	$x_{thermal-reduced}$	0.705001
COP-Cool	x_{cool}	5.20001