IMPACTS OF BUILDING FUNCTION ON NORMALIZED-STEAM CONSUMPTION: ANALYSIS OF FLOOR AREA NORMALIZATION VERSUS LINEAR REGRESSION ON HEATING DEGREE-DAYS IN A HEATING-DOMINATED CLIMATE

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ABSTRACT

Linear regression analysis is one the most common methods for weather-normalizing energy data, where energy versus degree-days is plotted, quantifying the impacts of outside temperature on buildings' energy use. However, this approach solely considers dry-bulb temperature, while other climate variables are ignored. In addition, depending on buildings' internal loads, weather impact can be less influential, making the linear regression method not applicable for energy data normalization in internally driven buildings (such as research laboratory buildings, healthcare facilities, etc.). In this study, several existing buildings from different categories, all located on the University of Massachusetts Amherst campus and exposed to the same weather conditions in a heating-dominated climate, were analyzed. For all cases, regression of monthly steam use on heating degree-days and floor-area normalized steam data were used, investigating applicability of the former when the latter changes. It was found that internal loads can skew steam consumption, depending on the building functionality, making the effect of degree-days negligible. For laboratory-type buildings, besides heating and domestic hot water production, steam is also used for scientific experiments. Here, daily occupancy percentage, even during weekends and holidays, was higher than that of other buildings, indicating the intensity of scientific experiments performed. This significantly impacted steam consumption, resulting in higher floor-area-normalized steam usage. In these cases, steam use did not provide an outstanding correlation to heating degree-days. Whereas, for cases with other functionality-types and lower floor-area normalized steam, coefficients of determination in regressions were high. This study concludes that even for buildings located in the same climate, depending on how building functionality and occupancy schedule influence floor-area normalized steam use, multivariate linear regression can provide more accurate analysis, rather than simple linear regression of steam on heating degree-days.

KEYWORDS

linear regression, weather normalization, heating degree-days, heating loads, internal loads, steam consumption, energy usage

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1. INTRODUCTION

The major constituents of energy usage in buildings include heating/cooling systems, hot water production, and electricity consumption (Catalina et al. 2013). The overall energy efficiency of buildings is influenced by internal and external environmental factors, including occupant intensity, relative humidity, precipitation, and outside temperature (Lee 2008). Outside temperature is used for heating and cooling loads calculation. To do so, the average outside temperature is subtracted from/by a pre-defined base temperature, resulting in heating/cooling degree-days, which are then used for buildings' energy loads measurement.

To normalize building energy consumption data, one of the most common approaches is by removing the effect of weather conditions, using linear regression of energy data on degree-days. This method of energy data normalization eliminates the impact of deviance in dry-bulb temperature on energy consumption. However, one shortcoming of this method is that it only considers dry-bulb temperature, ignoring other climatic factors that can influence energy performance. These factors include insolation, humidity, and wind speed (Eto 1988). In addition, in the regression method, dynamic heat transfer throughout the building is ignored. Heat transfer can be due to internal heat gains and/or envelope losses/gains. The former is caused by occupants, appliances, and lighting equipment. The latter is due to climatic factors, such as wind speed (impacting convective heat losses through the envelope), solar irradiance, and temperature difference between the inside and outside (Catalina et al. 2013).

Besides simple linear regression, a multivariate linear regression model is another method to describe variations of energy data (i.e., dependent variable) according to all significant factors (i.e., independent variables), used as inputs in the models (Catalina et al. 2013). Multivariate regression models define a mathematical function, representing the best correlation coefficient (coefficient of determination or R^2) between dependent and independent variables. R^2 in the scatter plot of dependent vs. independent variable(s) represents percentage of variation in the dependent factor caused by the variability of independent variable(s). It also reflects the goodness of fit test ("good" R^2) in the regression models (Chung et al. 2006).

Multivariate and simple linear egressions share the same assumption of correlations, but multivariate regression includes more than one independent variable (Akpinar and Yumusak 2013; Catalina et al. 2013). The advantage of using a multivariate regression model is to develop normalized data, considering all significant factors that affect energy consumption. However, requiring too many technical details as inputs is the major shortcoming of this approach, making it less practical for the end-users (Chung et al. 2006). In this study, linear regression analysis was used, investigating its applicability for various buildings that are exposed to the same external environmental conditions, but have different building functionality and occupancy schedules.

2. LITERATURE REVIEW

Multivariate regression model was used in a study to analyze buildings' Energy Usage Intensity (EUI) (Lee 2008). In the model, independent factors affecting EUI were defined as internal and external loads. Internal loads included occupant intensity and building area. External loads considered climate conditions, such as dry-bulb temperature, hours of rain, and irradiation amount. Multivariate regression model used in the analysis is shown in Equation 1, where "*a*" was the intercept, "*b's*" were regression coefficients, and "*x's*" were significant independent variables (occupant intensity, dry-bulb temperature, and hours of rain).

$$EUI = a + b_1x_1 + b_2x_2 + \cdots + b_kx_k$$

Equation 1. Energy usage intensity multivariate linear regression model.

The study showed that the higher the occupancy density, the more electricity was used for air-conditioning of interior spaces. With higher outside temperature and relative humidity (caused by rain), heat rejection of the air-conditioning system worked at lower efficiency. In addition, more hours of rain increased outdoor air enthalpy, which had to be removed by air-conditioning systems to maintain constant indoor air quality (Lee 2008). In another study, it was found that energy performance in buildings is significantly influenced, not only by weather conditions, but also by occupant density, building-type and building age factors (Piper 1999).

Chung et al. showed that the relation of EUI with significant variables most accurately can be presented by multivariate linear regression analysis (Chung et al. 2006). In the study, the number of factors in the regression model was a trade-off of having the "best" predictive model that included many factors, or a simple interpretable model with only a few significant factors. While the former could provide the best correlation, the latter needed less technical information about building characteristics. Using EUI multivariate linear regression, an EUI benchmarking model for commercial buildings was developed. Here, the argument was that simple floor-area normalization of EUI data is not an accurate representation of buildings' energy performance. In this study, other variables, such as building age, floor area, operational hours, occupants' behavior, set-point temperature, and energy systems were considered as significant factors. The developed multivariate regression model was determined by backward elimination of insignificant variables, whenever their coefficient of determination was not satisfactory (Chung et al. 2006).

Catalina et al. proposed a multivariate regression model with three independent variables (heat loss coefficient, south equivalent surface, and temperature difference), predicting heating demand in buildings (Catalina et al. 2013). This study suggested that these three variables are an optimal solution, since a higher number of inputs could make the model too complicated, while smaller number of inputs could cause less accuracy. The model was validated by comparing predictions with simulations, as well as on-site data from seventeen real buildings. Compared to the simulation, regression model provided a rapid and simple assessment of the energy demand, making their application useful for parametric studies and optimization processes (Catalina et al. 2013).

Regression analysis can be used both for investigating the impact of significant factors on building energy consumption and predicting energy consumption (Zhou and Zhu 2013). In this study regression models were developed to evaluate the effect of eight key building envelope properties, influencing energy consumption of an office building. Significant factors considered were thermal performances of building envelope components (wall, roof, glazing, and window frame), glazing optical performances (solar heat gain coefficient and solar reflectivity rate), and shading coefficients (internal and external). Results of the regression analysis were then compared to the results of TRNSYS simulations and actual energy consumption data, verifying accuracy and feasibility of the regression models. It was concluded that the model can be used to estimate energy consumption of office buildings with various building envelope characteristics and climate conditions. Similar studies investigated influence of building design factors that impact energy use, using multivariate regression models (Carlo and Lamberts 2008; Catalina et al. 2008; Lam et al. 2010).

TABLE 1. Case study buildings and their functions.

Building category	Subcategory	Building name
Academic	Laboratory and office	Life Science Laboratories & Integrated Science Building
	Library	W.E.B. Du Bois Library
Health services	N/A	University Health Services
Recreational	Gymnasium	Recreation Center
	Swimming pool	Totman Physical Education

3. RESEARCH METHODS AND CASE STUDIES

This study was conducted by analyzing the correlation between monthly steam consumption data and monthly heating degree-days (HDD), using several existing buildings as case studies. Case studies were selected among buildings from the University of Massachusetts Amherst (UMass Amherst) campus, located in a heating-dominated climate. Three main building categories and four sub-categories were selected, aiming to expand the analysis over a variety of building types, as a continuation to the previous study (Farid Mohajer and Aksamija 2021). Building categories included: (i) Academic (laboratory and library) buildings, (ii) Health Services, and (iii) Recreational (gymnasium and swimming pool). Table 1 shows a list of selected case study buildings and the corresponding categories.

3.1 Case Study Buildings Overview

Academic building category included two subcategories (i.e., laboratory and library) that are shown in Figure 1. Life Science Laboratories (LSL) and Integrated Science Building (ISB) were the two investigated laboratory buildings. LSL is an interdisciplinary research facility, built in 2013, with an area 174,200 sf. It includes various spaces, such as laboratories, offices, and classrooms. ISB, which was built in 2008, has an area of 188,332 sf. The spaces in ISB include laboratories, offices, and classrooms, mostly used by the Department of Chemistry at UMass Amherst. W.E.B. Du Bois Library was built in 1972 and includes 406,480 sf of library-related spaces, such as book storage, computer laboratories, offices, collaborative spaces, etc.

In health services category, University Health Services (UHS) building was selected and is shown in Figure 4. UHS was originally built in 1962 (with an area of 35,088 sf) and extra spaces were added to the building in 1973 (total area of 58,506 sf).

FIGURE 1. Academic case studies: Life Science Laboratories (left), Integrated Science Building (middle), and Du Bois Library (right).

FIGURE 2. Health Services case study: University Health Services building.

Recreational building typology included Recreation Center (RC) and Totman Physical Education (TPE) buildings, as shown in Figure 3. Recreation Center is a gymnasium-type building that includes various recreational and sport spaces, as well as offices. It was built in 2009, with an area of 160,191 sf. Totman Physical Education building was built in 1959 and has an area of 110,505 sf. It is used mostly by the Department of Music and Dance for performance purposes. Also, this building includes one pool and related facilities on its first floor.

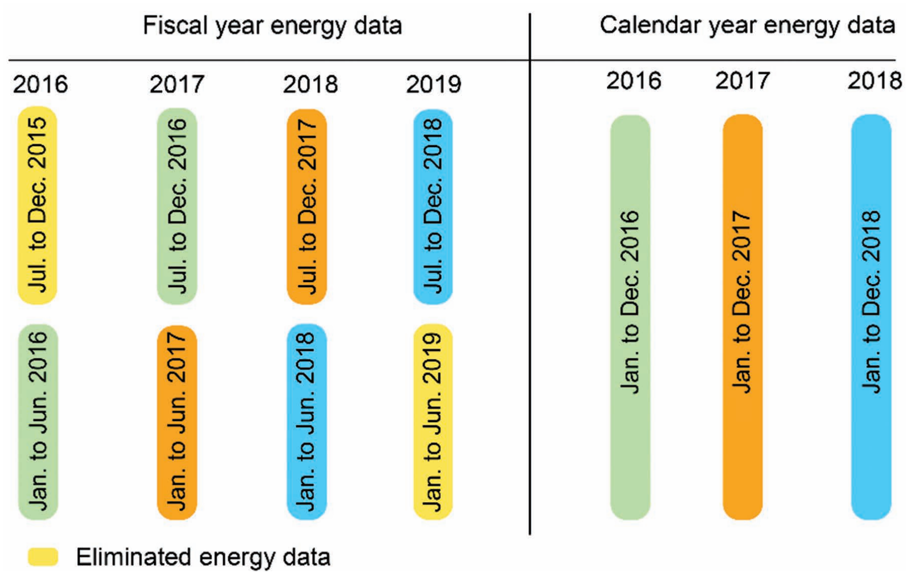
3.2 Monthly Energy and Weather Data

For each case study building, monthly steam consumption data was collected from UMass Amherst Facilities & Campus Services' reports. The extracted data was based on Fiscal Years (FY), starting from July of the previous year to June of the following year. In this study, FY 2016 to 2019 was the time span of collected energy data, covering July 2015 through June 2019. The reason for this time limit was, firstly, availability of energy data, which determined the upper time limit as FY 2019. Secondly, access to calendar years' weather data through UMass Computer Science Weather Station, dictated the lower time span as CY 2016 (UMass Amherst Computer Science n.d.). To investigate correlation of monthly steam use with heating degree-days in each CY, FYs' energy data was adjusted to CYs, as shown in Figure 4.

To make the data adjustment for FY 2016, steam use from January 2016 to December 2016 was considered, eliminating data from July 2015 to December 2015. The same was applied to FYs 2017, 2018, and 2019. This provided monthly steam use of each case study building for three successive calendar years (2016 to 2018).

FIGURE 3. Recreational case studies: Totman Physical Education (left) and Recreation Center (right).

FIGURE 4. Energy data adjustment from fiscal year to calendar year.



3.3 Regression of Steam on Heating Degree-Days

Heating degree-day (HDD) is computed as the positive temperature difference between a constant indoor temperature (i.e., base/reference temperature) and the average outdoor temperature, extended over a twelve-month period. So, HDD is higher than zero only when outdoor temperature falls below the base temperature during the heating season, meaning the building needs heating system to maintain the indoor comfort conditions (D'Amico et al. 2019).

Monthly HDD is the summation of daily HDDs during each specific month. To calculate the monthly HDDs in this study, first, the lowest and the highest daily outside temperatures were measured by UMass Computer Science Weather Station. Using this information, daily average outside temperatures were calculated. Next, daily HDDs were computed by subtracting the average temperature from the base temperate of 65 °F, which were then summed up to calculate the monthly HDDs of the three calendar years (2016 to 2018), as shown in Equation 2 (ASHRAE 2013; UMass Amherst Computer Science n.d.).

$$HDD = \sum_{i=1}^{N} \left(65 - T_i\right)^{+}$$

Equation 2. Monthly heating degree-day calculation formula.

In the equation, "*N*" in the number of days in the month and "*Ti*" is the average outdoor daily temperature. The + superscript indicates that only bracketed values that are positive are taken into account in the sum. Using monthly HDDs and steam consumption data, regression analysis was used to investigate the significance of HDD on steam use, using a coefficient of determination (R^2). The monthly steam consumption data and HDDs that were used in the scatter plot of case studies are shown in Table 2 (Scholarworks UMass Amherst n.d.). For some of the case studies, there were months that steam usage was not accurately measured,

TABLE 2. Academic, administrative, and recreational buildings' monthly steam consumption and HDDs (Scholarworks UMass Amherst n.d.; UMass Amherst Computer Science n.d.).

			Monthly steam use (MBtu)					
	CY	HDD	TPE	UHS	Du Bois	RC	LSL	ISB
Jan.	2016	1,043.4	1,232	277	2,778	770	3,964	3,698
	2017	959.3	1,162	343	2,536	970	4,751	2,993
	2018	1,165.2	1,541	360	3,657	1,226	3,256	3,254
Feb.	2016	925.6	1,160	280	2,454	733	3,233	3,321
	2017	802.9	990	291	2,246	665	3,945	1,873
	2018	789.7	1,080	278	2,533	794	2,312	2,692
Mar.	2016	643	868	220	2,060	603	2,276	2,884
	2017	937.7	1,194	351	2,958	824	4,621	2,676
	2018	819.4	1,083	315	2,889	741	1,986	3,046
Apr.	2016	458.9	628	210	1,439	474	3,018	2,806
	2017	339.6	766	223	2,022	467	2,666	1,880
	2018	597.6	866	267	2,337	493	2,355	2,989
May	2016	181.9	298	179	1,506	394	1,519	1,991
	2017	222.7	468	218	1,706	388	2,507	4,330
	2018	75.5	292	187	1,677	330	1,967	2,913
Jun.	2016	18.1	252	159	751	187	1,215	1,813
	2017	34.2	415	185	0	237	185	4,650
	2018	23.7	258	173	1,441	242	1,938	2,713
Jul.	2016	0	175	162	1,053	164	1,696	2,141
	2017	5.4	203	177	3,754	237	1,313	4,611
	2018	0	209	173	1,329	193	222	2,732
Aug.	2016	0	171	162	613	160	1,650	2,409
	2017	1.5	193	177	1,209	246	1,245	2,092
	2018	0	202	169	1,131	88	1,315	2,718
Sep.	2016	48.2	208	162	8,61	335	1,805	2,269
	2017	42.8	213	182	1,294	276	1,343	1,912
	2018	72.6	234	174	1,418	462	926	12,901
Oct.	2016	340	638	202	1,599	431	2,585	2,456
	2017	185.5	332	194	1,387	340	1,831	2,216
	2018	400.7	611	236	2,152	799	957	1,062
Nov.	2016	640	881	270	2,372	503	3,140	2,489
	2017	685.8	961	268	2,251	695	2,932	3,033
	2018	754.6	1,045	288	0	898	1,058	1,866
Dec.	2016	985.7	1160	343	2460	872	4664	3158
	2017	1127	1,421	373	3,475	1,081	3,710	3,536
	2018	943.7	1,227	311	3,487	1,088	1,456	2,192

representing significantly lower quantities compared to the previous and subsequent months. These errors were due to metering system's malfunctioning. Steam data for these months were eliminated from the scatter plots, preventing their inappropriate impact on the regressions' R^2.

Correlation coefficients of the linear regressions divided case studies into two categories of high and low R^2, determining relation between dependent and independent variables. Totman Physical Education, University Health Service, Recreation Center, and Du Bois Library were the cases with high R^2, ranging from 0.98 to 0.83. Correlation coefficient of 0.98 indicated that 98% of monthly steam use changes in TPE building was due to variations in monthly heating degree-days. Scatter plots of the regression with high R^2 are shown in Figure 5.

On the other hand, LSL and ISB had the lowest R^2 (0.55 and 0.02), as shown in Figure 6. In these two cases, weather condition was not a significant factor causing changes in monthly steam consumption.

To investigate case study buildings' characteristics causing the distinction in linear regression results, a comparative analysis was conducted, capturing the relation of floor-area normalized steam use and linear regression of steam on heating degree-days.

FIGURE 5. Case study buildings with higher coefficient of determination (R^2).

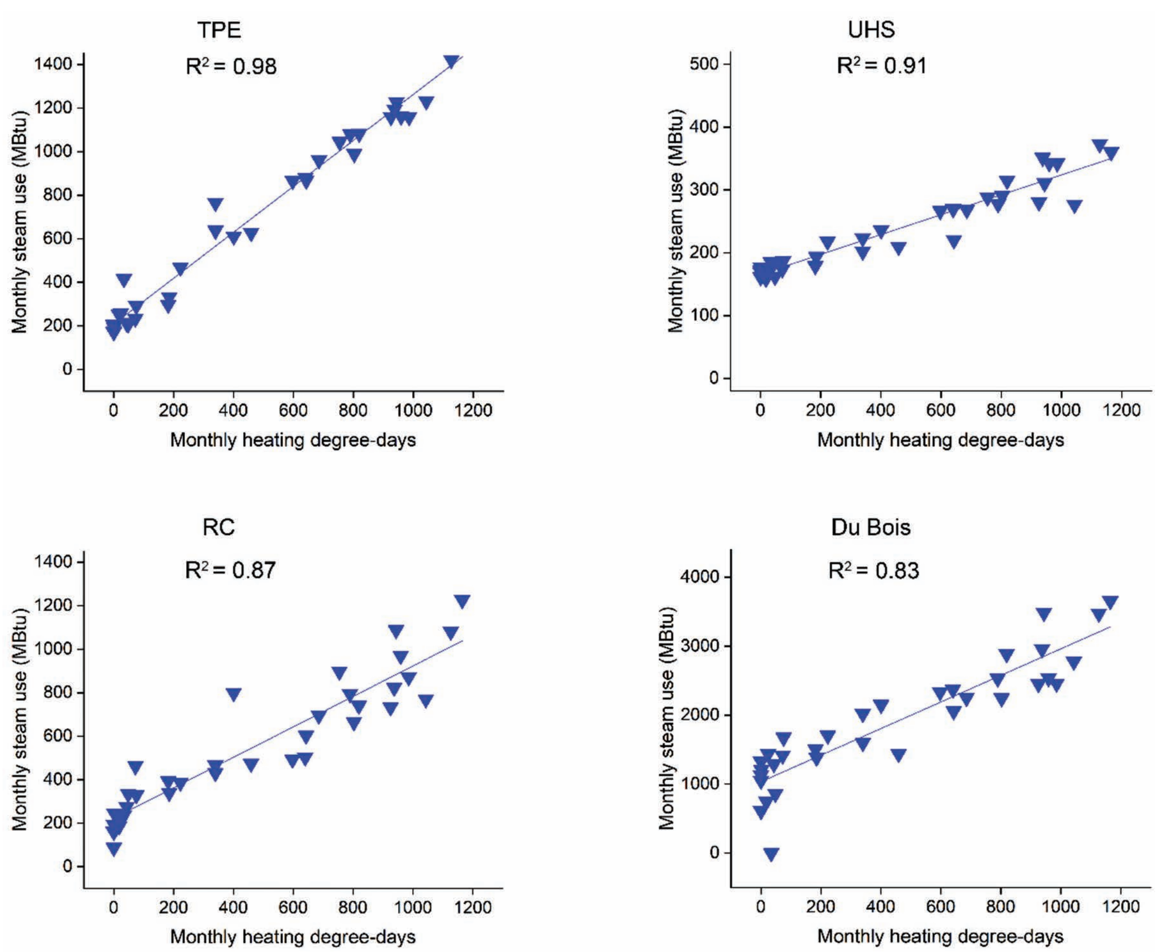
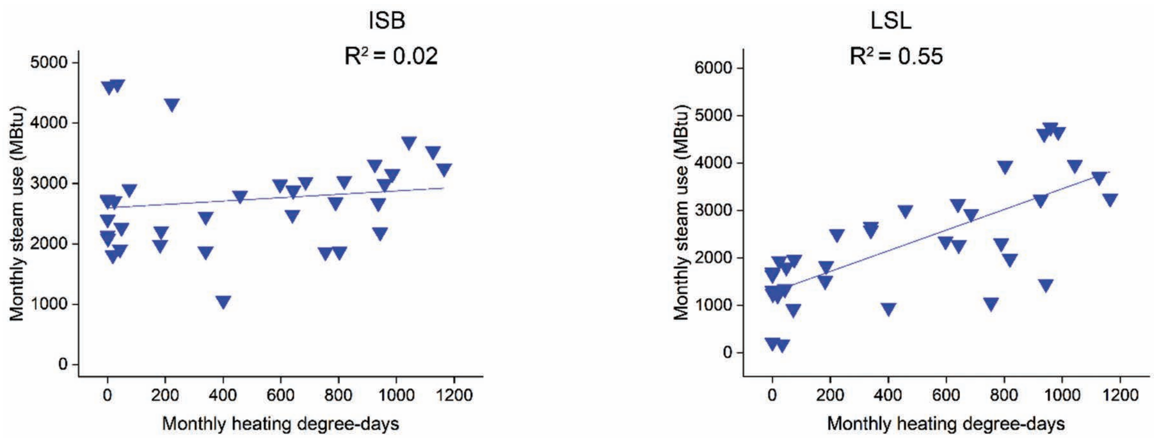


FIGURE 6. Case study buildings with lower coefficient of determination (R^2).



4. COMPARATIVE ANALYSIS OF RESULTS

R^2-deviation in regression models was investigated, using three-year average of floor-area normalized steam use (kBtu/sf/yr), also introduced as Steam Usage Intensity (SUI). To compare the results, SUI of Totman Physical Education building, with the highest R^2 of 0.98, was adopted as the baseline. The purpose of baseline selection was to investigate, based on SUI-deviations, how R^2 in the regression analyses was impacted. SUI-deviations from the baseline are shown in Table 3.

Comparison of the results segregated case studies with lower SUI from the ones with higher SUI. In case studies with lower SUI (i.e., negative deviation from the baseline), R^2 was high, even close to that of the baseline. These cases included the University Health Services, Du Bois Library, and Recreation Center, with R^2 of, 0.91, 0.83, and 0.87, respectively.

Life Science Laboratories and Integrated Science Building, on the other hand, had much higher SUI (large positive deviation from the baseline), and much lower R^2 (0.55 and 0.02). For LSL and ISB, scatter plots of steam use on HDDs did not indicate an outstanding correlation between the two, meaning weather condition was not the significant factor. In LSL

TABLE 3. Comparison of floor-area normalized steam use for the case study buildings.

Building name	Area (sf)	3-year average annual steam use (MBtu)	Average SUI (kBtu/sf/yr)	SUI deviation	Regression R^2
TPE	110,505	8,213	74	0%	0.98
UHS	58,506	2,847	49	-34%	0.91
Du Bois	406,480	22,945	56	-24%	0.83
RC	160,191	6,469	40	-46%	0.87
LSL	174,200	27,188	156	111%	0.55
ISB	150,325	36,105	240	224%	0.02

and ISB buildings, not only general offices and classrooms are located, but also laboratories are used for scientific experiments. Laboratory buildings were the only category using steam for experimental and cleaning purposes, which significantly increased internal loads and energy demand. As shown in Table 3, steam usage intensity in LSL and ISB had, respectively, 111% and 224% deviation from the base SUI.

Generally, steam is used for heating loads and domestic hot water (DHW) in buildings. Heating loads are mainly dependent on thermal transmittance of envelope components and temperature difference between the inside and outside. However, due to building functionality, steam use can be impacted, regardless of the envelope properties and/or weather conditions. Impact of laboratory-type building on higher SUI was in line with expectations, as in laboratories steam was also used for scientific experiments and cleaning purposes. It is worth noting that both LSL and ISB laboratory buildings were the most recently built cases and LSL is a LEED-Gold certified building. Due to more stringent and demanding building codes, envelope heat losses in these newer buildings are not higher than that of other, older buildings. And, higher steam use in LSL and ISB buildings cannot be due to heat losses through the building envelope. In addition, building envelope deterioration that occurs with building aging cannot be a significant factor impacting higher steam consumption.

One critical factor causing higher SUI in LSL and ISB was the hourly occupancy percentage, which inferred higher internal loads and demands. Compared to other buildings, laboratory facilities are used more often, even during Winter/Summer breaks, weekends, and holidays. Besides, laboratories are more occupied before 7 am (not the case for recreational buildings) and after 5 pm (not the case for classrooms/offices), as shown in Figure 7 (Mostafavi et al. 2015).

Du Bois Library has a similar schedule as offices/classrooms, as shown in Figure 8, as its occupancy schedule depends on students' attendance for office/classrooms (Mostafavi et al. 2015).

Recreational building category has the lowest hourly occupancy percentage, compared to the other two building types. As shown in Figure 9, the highest occupancy percentage in this category is during Fall/Spring semesters, from 11 a.m. to 9 p.m (Mostafavi et al. 2015).

FIGURE 7. Hourly occupancy percentage in laboratory buildings.

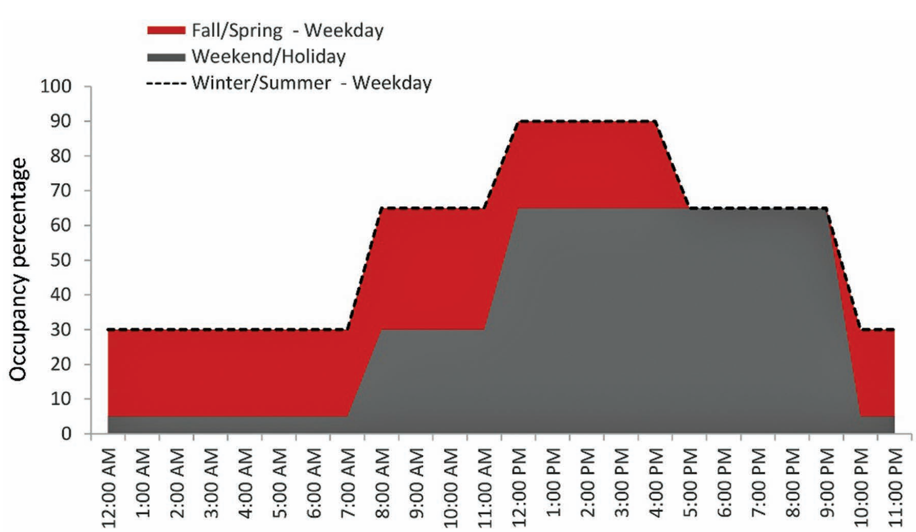


FIGURE 8. Hourly occupancy percentage in offices, classrooms, and library buildings.

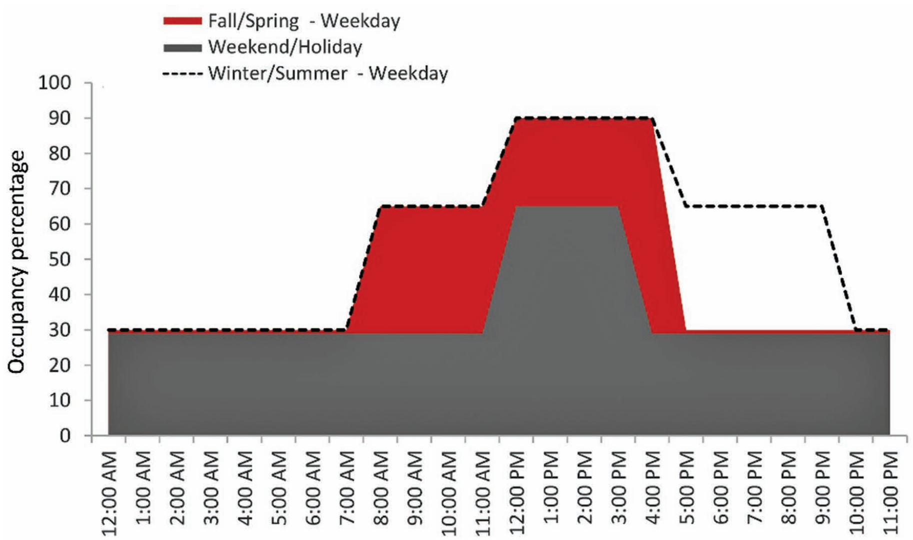
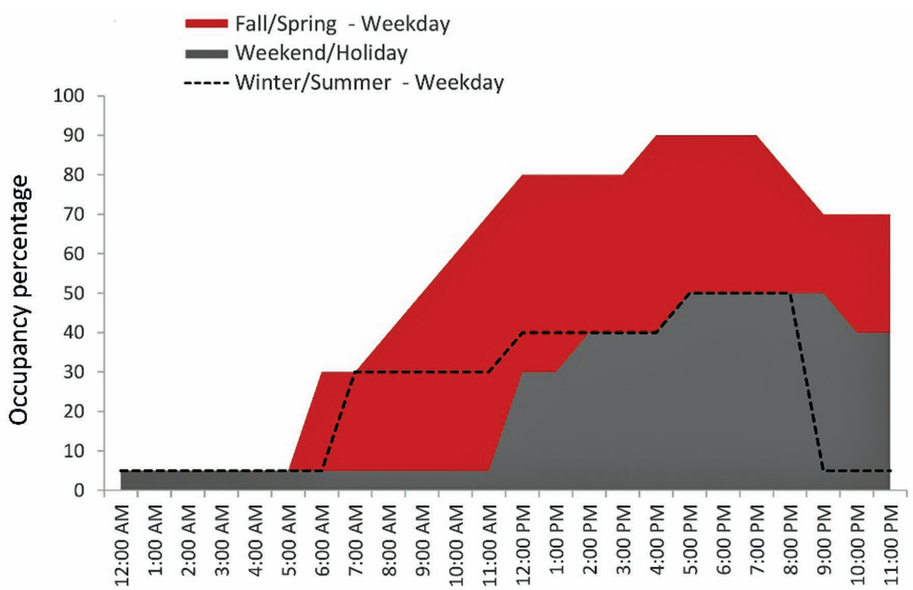


FIGURE 9. Hourly occupancy percentage in recreational buildings.



To compare occupancy schedule for the case studies, daily occupancy percentage during an academic year (Fall/Spring semester, weekend/holiday, and Winter/Summer breaks) were compared. Occupancy percentage of laboratory-type buildings was assigned as the baseline, quantifying deviation of other cases' occupancy percentage from the baseline, as shown in Table 4.

As shown in Table 4, library building was slightly less occupied, compared to laboratories. This small difference, along with the fact that in library, steam is used only for heating and DHW, reasonably explained steam consumption in the Du Bois Library (–24% SUI-deviation) to be less than that of LSL (111% SUI-deviation) and ISB (224% SUI-deviation). In addition, in the Recreational Building category (TPE and RC), steam is used for heating and DHW. The

TABLE 4. Daily occupancy percentage of the case study buildings during a whole academic year.

Building Type	Daily occupancy percentage in case study buildings				
	Fall/spring weekday	Weekend & holiday	Winter/ summer weekday	Daily average	Deviation form baseline
Recreational	53%	24%	25%	34%	–29%
Offices/classrooms/ library	48%	35%	56%	46%	–4%
Laboratory	56%	34%	56%	48%	0%

amount of DHW used in this type of buildings, especially in shower and pool spaces, should be higher than a library, if occupancy density and schedule are considered to be the same. However, due to percentage of occupancy to be one third of the baseline, steam was consumed less than laboratories, especially during weekend/holiday and Winter/Summer breaks. It is worth noting that the TPE building is mostly used by the Department of Music and Dance for academic purposes and rehearsal practices, and DHW demand is limited to one pool and related facilities, such as showers rooms. Given daily occupancy percentage of one-third, steam use in Recreation Center and Totman Physical Education buildings was, unsurprisingly, smaller than in the laboratory buildings.

Comparative analysis of the results showed that for all cases, except for laboratory-type buildings (LSL and ISB), linear regression of steam use on heating degree-days can be used to weather-normalize steam data. However, for LSL and ISB, it is not only the weather condition that impacts steam consumption. Other significant factors, such as occupancy schedule, monthly number of experiments performed, and the amount of steam used for that purpose need to be considered. Therefore, multivariate linear regression can better capture the relation of steam use with other significant explanatory factors.

5. CONCLUSION

This study was conducted to investigate the applicability of linear regression of steam on heating degree-days (weather-normalization of stream use) for various building functions located in a heating-dominated climate, using actual existing case studies. Results showed that, depending on the buildings' function, besides weather condition, other factors can have significant impact on energy performance. Steam use in some case study buildings indicated a strong relation with heating degree-days, when exposed to the same weather conditions. In these cases, heating degree-days in the linear regressions became the surrogate for all influences, climatic or otherwise, on steam consumption. Whereas, low R^2 in other linear regressions indicated an insignificant correlation between steam use and heating degree-days. It was found that for laboratory-type buildings, internal loads and occupancy schedules significantly influenced steam consumption, making HDDs less influential. Here, weather normalization of steam use was not an accurate approach to factor out the effects of weather conditions. It was concluded that multivariate regression analysis, which considers all explanatory factors, can be a more accurate analysis method.

Future studies will investigate the development of a multivariate linear regression model of steam use in laboratory buildings. For that purpose, a laboratory building will be modeled, and its energy performance will be analyzed, using parametric changes in simulations. Results of the analysis will be used to determine the regression coefficient of the significant factors in multivariate regression, aiming to develop a multivariate model.

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