# Energy Modeling and Energy Efficiency Opportunities for a Public Library Building in the Upper Peninsula of Michigan

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# Energy Modeling and Energy Efficiency Opportunities for a Public Library Building in the Upper Peninsula of Michigan

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## ABSTRACT

Energy modeling tools have been extensively used for analyzing building performance as well as for assessing energy efficiency opportunities. The present research has a twofold aim: (1) to model the natural gas consumption and the total electricity consumption of a 12600 sq. ft. public library building in Houghton, MI, and (2) to identify any opportunities to improve energy efficiency. This was accomplished by first developing and validating an eQUEST model for the library building in conjunction with a linear regression model correlating the natural gas consumption (during winter) with heating degree days and the electricity consumption (during summer) as a function of cooling degree days. The said library building, which is serviced by two rooftop furnaces, each with a DX coil, and a hot-water loop using two boilers, has been facing HVAC issues for a few years now, the most common complaint being that it gets too hot in the winter despite the thermostat being set to provide comfortable temperatures. This motivated us to model the building and try and discover the causes for complaints like the above-mentioned while keeping an eye on any energy saving opportunities. The eQUEST model Mean Base Error (MBE) is -3.60% and 2.48% for natural gas consumption and electricity consumption respectively. The coefficient of variation of Root Mean Squared Error - Cv (RMSE) is 7.33% and 4.14% for the natural gas consumption and for electricity consumption respectively. Having thus gained confidence in the ability of the model to provide reasonable predictions, the same was then exercised to understand the key factors responsible for energy consumption in the building and to check for energy efficiency opportunities. Preliminary results suggest that the principal factors affecting the building energy consumption are the lighting, HVAC loads, and occupancy and that the natural gas consumption of the building could be lowered by up to 20% using the furnace units alone (i.e., by dispensing with the boilers), while still meeting the building's heating requirements. One of the issues also identified in the course of the analysis was that the thermostat is located about 10 ft. away from the radiators and grills and hence it is possible that the HVAC system responds to a lower average temperature than that in the room.

## 1. INTRODUCTION

Energy modelling tools are used for predicting building energy consumption and verifying design parameters like HVAC system capacity and building schedules. In the design phase, results from accurately modeled buildings help engineers and architects to fine tune their design parameters and also ensure that their design is cost-effective. Energy modelling programs are also used for existing buildings to assess different energy efficiency improvement options and help consumers in cutting down energy consumption for heating, cooling, lighting, domestic hot water heating, etc.

eQUEST and EnergyPlus are two of the most commonly used open-source programs and there have been several studies comparing the accuracy and other capabilities of eQUEST and EnergyPlus. Rallapalli (2010) mentions in her whole building energy simulation study that EnergyPlus offers the advantages of sub-hourly time steps, independent radiation modelling, customizable HVAC systems, and integrated simulations for accurate results. eQUEST, on the other hand, is user-friendly and rapid (it gives results within minutes), but is limited to hourly time steps. Performance comparison showed that eQUEST energy consumption predictions were closer to the measured data than EnergyPlus results. Zerroug & Dzelzitis (2015) reiterated that eQUEST is easier to use compared to EnergyPlus. They also found eQUEST predictions to be much closer to the measured data than those of EnergyPlus. Zhu *et al.* (2013) compared EnergyPlus, DeST and DOE – 2.1E for their performance characteristics and found that DOE – 2.1E can provide relatively inaccurate results in double zone models (conditioned zone and adjacent non-conditioned zone) as DOE – 2.1E uses the previous hour's adjacent space temperature values for current calculations.

A public library building in Houghton, MI has been facing HVAC issues for a few years now. A common complaint from some of the library employees has been that it gets too hot in the winter despite the thermostat being set to a comfortable temperature. This motivated us to model the building to try and find the issues along with an examination of any energy efficiency opportunities. As previous studies have shown eQUEST to be user-friendly and since it had the relevant HVAC system (DX coil with furnace) in its library, we decided to use this software for modelling the library building. Before we modelled the building, it was important to understand prior research work using eQUEST and confirm its capability in modelling existing buildings, and the following studies have been summarized with this purpose in mind. Xing *et al.* (2015) modelled a hotel building in Tianjin, China using eQUEST and were able to successfully determine the factors affecting the accuracy of the baseline model. The study found that, as expected, increasing the space heating efficiency would significantly reduce the total energy consumed. Wang *et al* (2015) modelled a hotel building in Taiwan and their validated model indicated that energy savings of up to 10.5% per month could be obtained by optimizing the chiller capacity. Sobha *et al.* (2016) modelled a house in Missouri for demand side cooling management using eQUEST for energy consumption estimation. This work mainly focused on managing HVAC loads when the utility costs were low. Algarni *et al* (2017) used eQUEST to model a residential system in Jazan, Saudi Arabia. The air treatment process employed in the HVAC system leads to removal of condensate water which is usually wasted. In this study, the authors used this waste condensate water to clean the dusty roof surfaces (which increased building cooling loads) and observed up to 19% reduction in the annual building cooling energy consumption.

From the above studies, it is clear that eQUEST can be successfully used for modelling buildings and can be further employed to explore energy conservation opportunities. For the present study, the public library building (whose HVAC system includes two rooftop furnaces with DX coils and a hot-water loop using boilers) is modeled using eQUEST software and the model is validated using actual monthly utility bills for the building. The results show that by shutting off the hot water loop (boilers), energy savings of up to 20% could be realized, while still meeting the building's heating requirements. Details of the HVAC system and the eQUEST model for the same will be discussed in the following section.

## 2. ENERGY MODELING & VALIDATION

The eQUEST model was developed for the 12,600 sq. ft. (1170.6 $m^2$) library area (single floor) located in Houghton, Michigan (Figure 1). For modelling the HVAC system, HVAC and maintenance documents available with the library were used. The library has two roof-top units, each consisting of a furnace and a direct expansion (DX) coil cooling system. The total furnace output power rating is 600 kBtu/hr (175.8 kW). A hot water loop (comprising boilers and radiators) is also included in the library to provide supplemental heating in addition to the heating provided by the furnace. The loop has two boilers each having an output power rating of 134 kBtu/hr (39.3 kW) with 84% boiler efficiency, as well as a dedicated domestic hot water heating (storage) system with a tank capacity of 48 gallons (0.23 $m^3$) and an input power rating of 60 kBtu/hr (17.6 kW).

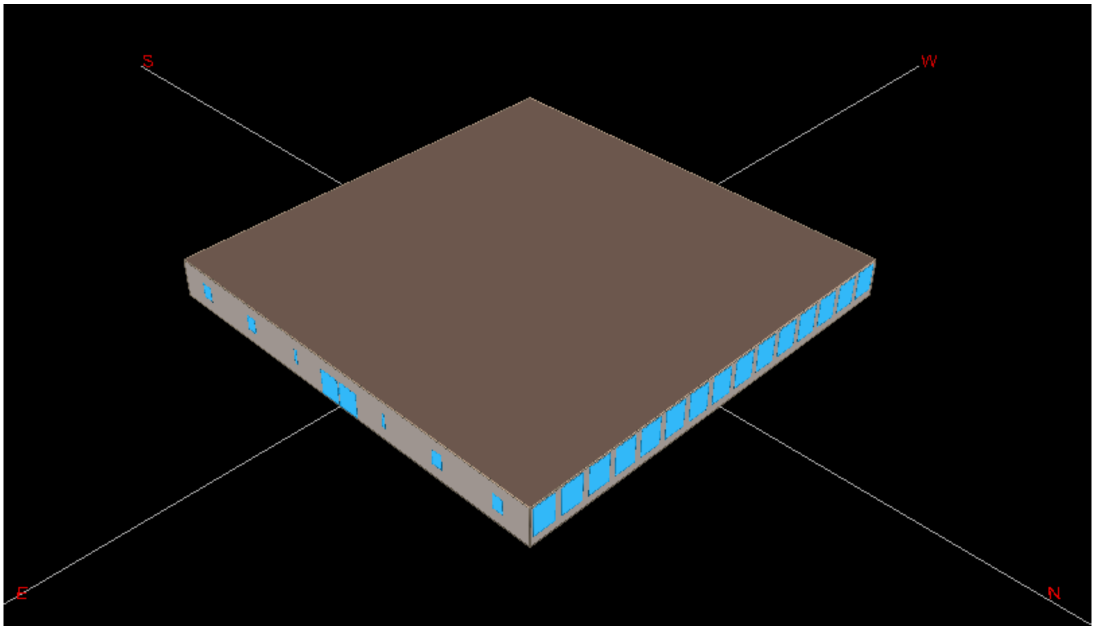


**Figure 1**: eQUEST model of the library building

Once the library building is modelled on eQUEST, the model needs to be validated to ensure its accuracy. The actual utility bills for the building can be used to verify the energy consumption predicted by eQUEST. An issue which arises here is that the weather profile used by eQUEST is not the same as the actual weather profile observed during the test period. Gould & Hawkins (2015) have suggested a simple linear regression model to overcome this issue. Natural gas consumption can be directly related to the Heating Degree Days (HDD) (during winter) and electricity consumption can be directly related to the Cooling Degree Days (CDD) (during summer). HDD are a measure of how low the temperature was on a given day or during a specified number of days compared to a standard temperature, usually 65°F (291.5 K) in the United States. Here, HDD is the difference between 65°F and the average daily temperature at the location of interest. Similarly, CDD are a measure of how high the temperature was on a given day or during a specified number of days compared to 65°F. Here, CDD is the difference between the average daily temperature at the location of interest and 65°F. An equation can be developed using simple linear regression to predict the natural gas consumption and electricity consumption respectively using HDD and CDD values and the actual utility bills. HDD and CDD can be calculated for the weather profile used by eQUEST and the regression equation generated from the actual utility bills can be used to generate the monthly electricity and natural gas consumption. These monthly values can then be used to validate the eQUEST model.

To generate the linear regression models, the utility bills for the years 2018-19 were collected from the library and the HDD and CDD were calculated for the bill periods. The HDD and CDD were calculated as suggested on BizEE Software and validated analytically. The HDD and CDD values were then divided by the relevant time period and the HDD/day and CDD/day values were obtained. Similarly, the natural gas consumption and electricity consumption obtained from the utility bills were divided by the time period to obtain therm/day ($1.055 \times 10^{8}$ J/day) and kWh/day ($3.6 \times 10^{-6}$ J/day) values, respectively. Figure 2 shows the plot relating the natural gas consumed per day to the HDD per day for the winter of 2018-19 and Figure 3 shows the plot relating the electricity consumed per day to the CDD per day for the summer of 2018. It is noted that the plots have been generated based on the available library utility bills.

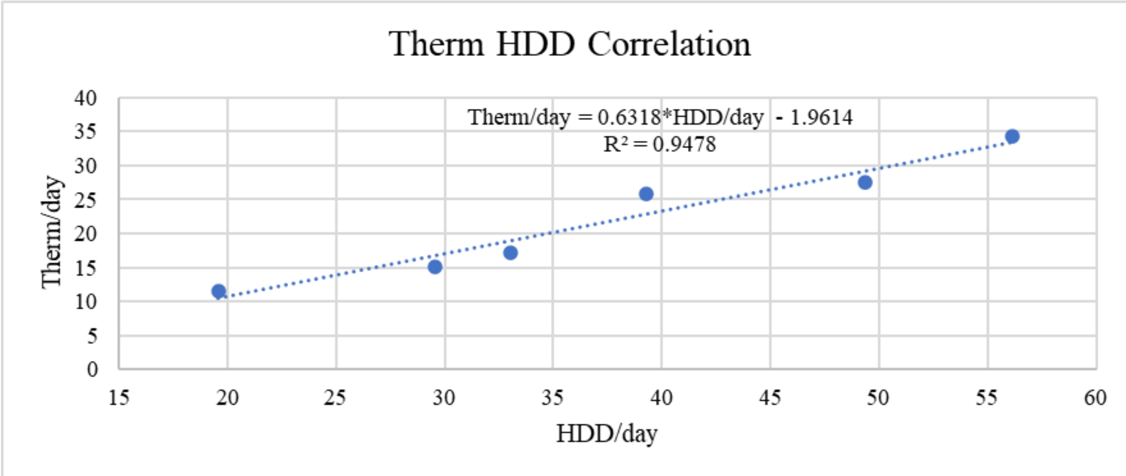


**Figure 2:** Therm/day (natural gas consumption) and HDD/day correlation (winter season)

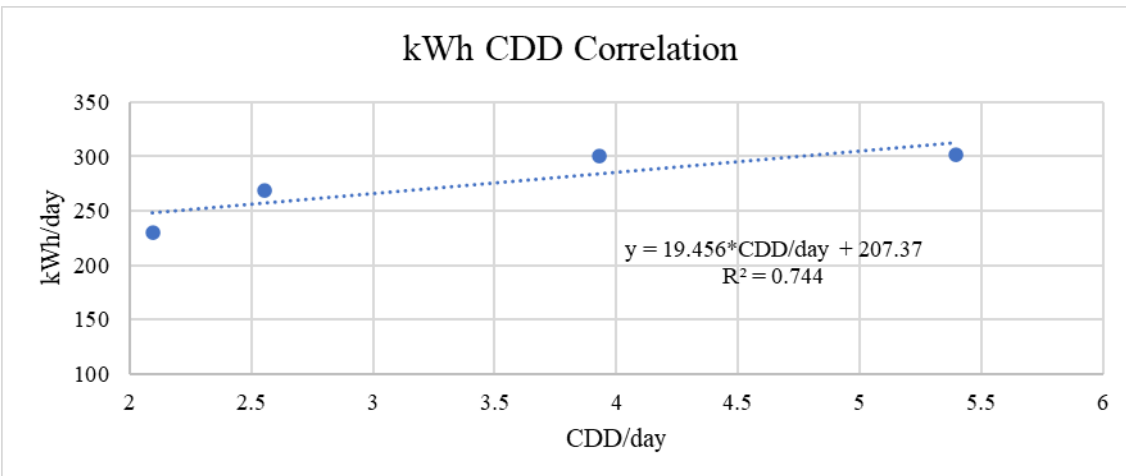


**Figure 3:** kWh/day (electricity consumption) and CDD/day correlation (summer season)

As observed in Figure 2, the $R^2$ value (0.9478) for the Therm/day – HDD/day, indicates a high positive correlation. The $R^2$ value for the kWh/day – CDD/day, 0.744, also shows a reasonable positive correlation. It should be noted that this latter value is not as high as the $R^2$ value for Therm/day – HDD/day, as electricity consumption is related not just to the cooling requirements but also to the lighting and miscellaneous equipment (such as computers, copiers, microwave ovens, etc.). If the HDD and CDD for eQUEST's weather profile are calculated and inserted in these equations, realistic utility bill values for the eQUEST model (with its associated weather profile) can be generated.

For the assessment of the eQUEST model and utility bill comparison, the statistical parameters of mean base error (MBE) and coefficient of variation of root mean squared error Cv (RMSE) were used as demonstrated by Xing *et al.* (2015). The parameters are defined as:

$$\mathrm{MBE} = \frac{\sum_{\mathrm{Period}} (\mathrm{M\text{-}A})_{\mathrm{Interval}}}{\sum_{\mathrm{Period}} \mathrm{A}_{\mathrm{Interval}}} \tag{1}$$

$$\mathrm{Cv\ (RMSE)} = \frac{\sqrt{\frac{1}{\mathrm{N}_{\mathrm{Interval}}} \sum_{\mathrm{Period}} (\mathrm{M\text{-}A})_{\mathrm{Interval}}^{\ 2}}}{\frac{1}{\mathrm{N}_{\mathrm{Interval}}} \sum_{\mathrm{Period}} \mathrm{A}_{\mathrm{Interval}}} \tag{2}$$

where,

M: Energy consumption predicted by the model

A: Actual energy consumption

Period: Time period considered for the analysis

Interval: Time span diving the period into equal parts, i.e., 1 month

$N_{Interval}$: Total number of intervals in the period, i.e., 12 (months)

Figure 4 shows the comparison of linear regression adjusted utility bills and the eQUEST model results for natural gas consumption. As observed in Figure 4, the highest absolute error was observed in the months of April, May, and October, when the heating requirement was not as high as in the other months. The highest absolute error of 16.4% was observed in the month of May. This observation indicates that the linear regression model works best when the heating requirements are high, and the heating systems are being used frequently. In other words, the model works best when the HDDs are relatively high. The mean base error (MBE) for the natural gas consumption is -3.60% and the Cv (RMSE) is 7.33% which is well within acceptable limits of ± 5% and 15% respectively, as discussed by Xing *et al.* (2015).

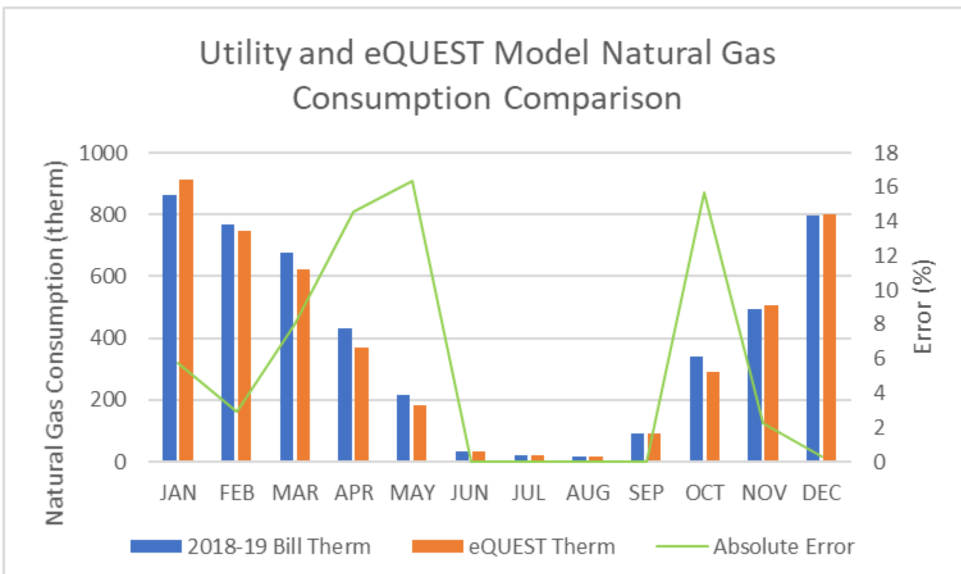


**Figure 4:** Utility and eQUEST model natural gas consumption

For electricity consumption, two models were used to predict the utility bills for the eQUEST weather profile. In the first model, the utility bill values for the cooling months (June through September) were calculated by directly using the equation obtained from the model shown in Figure 3 and for the other months, the utility bill values were obtained by extrapolating the equation and setting CDD equal to zero. In the second model, the equation from the model shown in Figure 3 was divided into two parts, a linearly increasing part and a constant part corresponding to the linear equation (kWh/day = m*CDD/day + c), where m is the slope of the line and c is the constant part of the equation. The constant part of the equation was calculated by averaging the utility bills from the winter months, October through May (when CDD = 0). Rebuilding the equation using the constant value c thus obtained, the utility bill values for electricity consumption can then be predicted.

The two models for kWh/day have been statistically compared in Table 1. The results indicate that model 2 provides more accurate expected electricity consumption values for the non-cooling months. For model 2, a maximum absolute error of 9.43% was observed in the month of May. This can be attributed to the fact that the month of May actually does consist of some days which require cooling. The month of May was not considered for deriving the equation in Figure 3 as it was considered to be part of the winter (heating) season.

**Table 1:** Statistical comparison of two models for kWh/day

| Model | MBE | Cv (RMSE) | Avg. absolute error |
|---|---|---|---|
| kWh/day Model 1 | -3.76% | 4.85% | 4.23% |
| kWh/day Model 2 | 2.48% | 4.14% | 3.33% |

Figure 5 and Figure 6 show the comparison of the linear regression adjusted utility bills and eQUEST model results for electricity consumption.

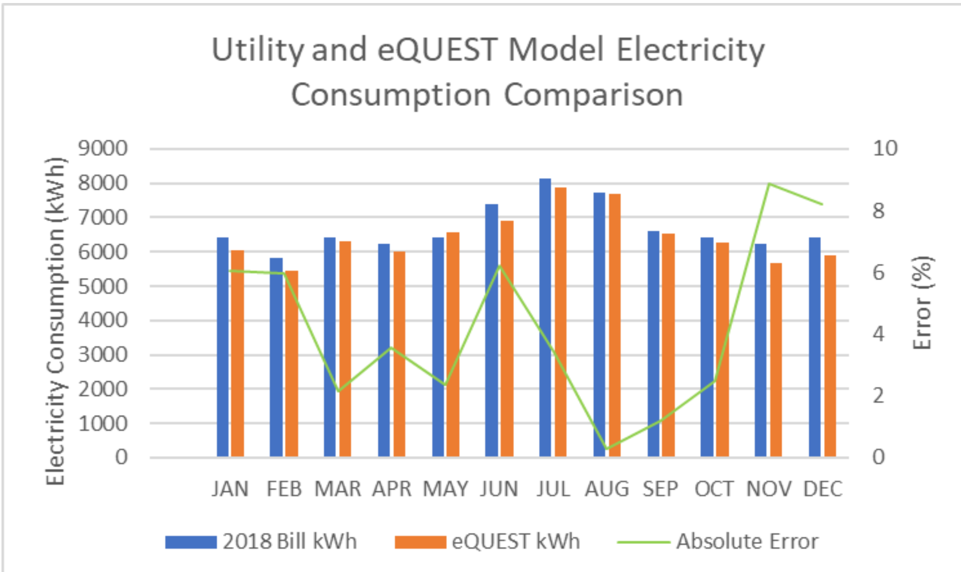


**Figure 5:** Utility and eQUEST model electricity consumption comparison

(from linear regression model – Model 1)

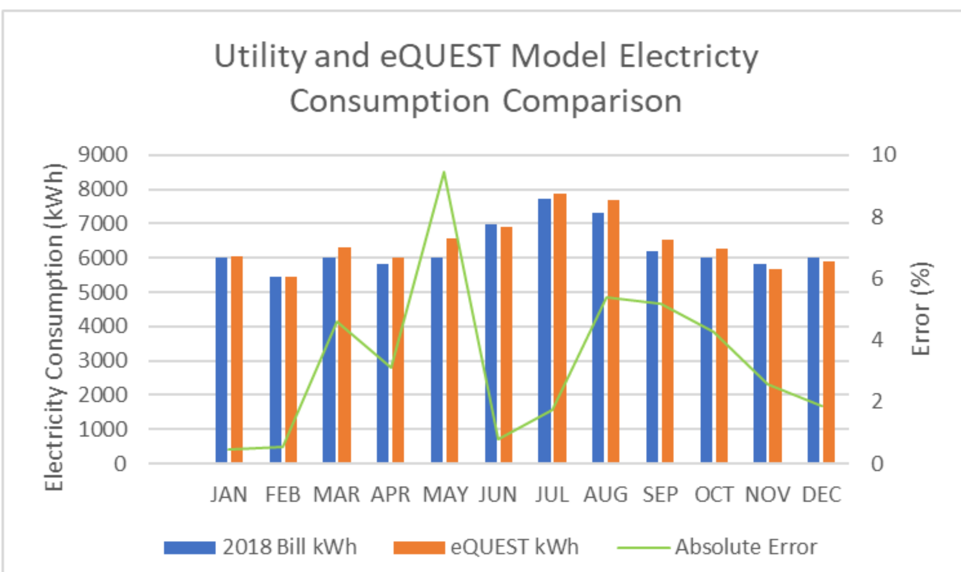


**Figure 6:** Utility and eQUEST model Electricity Consumption Comparison

(from modified method – Model 2)

This model discussed above has been used to identify the key factors affecting energy consumption and energy efficiency opportunities. The next section focuses on these aspects of this study.

# 3. RESULTS AND DISCUSSION

## 3.1 Model Results & Factors Affecting Energy Consumption

Annual electricity and natural gas consumption for the eQUEST library building model in 2018 is provided in Table 2 and Table 3 respectively. The principal factors affecting the building energy consumption are lighting, the HVAC loads and occupancy. 57.4% of the total electricity consumption in 2018 was used to provide lighting in the library. Space cooling accounted for 10.8% and other HVAC equipment (fans, pumps, etc.) accounted for 13.8% of the annual electricity consumption. In hot and humid locations, space cooling may account for the highest percentage share of the electricity consumption; however, as Houghton, MI does not experience such weather for most part of the year, the primary electricity usage turns out to be for lighting in this case. Natural gas is used to provide space heating and domestic hot water in the library. 97.4% of the total natural gas consumption in 2018 was used to provide space heating whereas domestic hot water accounted only for 2.6%.

**Table 2:** Library annual electricity consumption distribution in kWh ($3.6 \times 10^{-6}$ J)

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Space Cooling** | 0 | 0 | 0 | 40 | 340 | 1830 | 2870 | 2330 | 940 | 10 | 0 | 0 | 8360 |
| **Ventilation Fans** | 620 | 530 | 580 | 560 | 620 | 930 | 860 | 940 | 530 | 620 | 580 | 560 | 7930 |
| **Pumps & Auxiliary Equipment** | 250 | 230 | 250 | 240 | 220 | 200 | 200 | 200 | 210 | 240 | 240 | 250 | 2730 |
| **Miscellaneous Equipment** | 1160 | 1050 | 1220 | 1160 | 1210 | 1170 | 1160 | 1240 | 1080 | 1210 | 1080 | 1140 | 13880 |
| **Task Lights** | 30 | 20 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 350 |
| **Area Lights** | 3980 | 3620 | 4210 | 3980 | 4160 | 2770 | 2740 | 2940 | 3740 | 4160 | 3740 | 3920 | 43960 |
| **Total** | 6040 | 5450 | 6290 | 6010 | 6580 | 6930 | 7860 | 7680 | 6530 | 6270 | 5670 | 5900 | 77210 |

**Table 3:** Library annual natural gas consumption distribution in therm ($1.055 \times 10^{8}$ J)

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Space Heating** | 906.4 | 738.9 | 613.7 | 360.9 | 169.5 | 84.3 | 40.7 | 58.6 | 87.1 | 279.1 | 497.3 | 790.2 | 4626.7 |
| **Hot Water** | 11.2 | 10.5 | 12.1 | 11.4 | 11.1 | 10 | 9.4 | 9.6 | 8.5 | 9.7 | 9.3 | 10.4 | 123.2 |
| **Total** | 917.6 | 749.4 | 625.8 | 372.3 | 180.6 | 94.3 | 50.1 | 68.2 | 95.6 | 288.8 | 506.6 | 800.6 | 4749.9 |

It needs to be noted that higher lighting and occupancy help in reducing the HVAC loads in winter (which lowers the natural gas consumption) as these components add heat to the zone, which is the function of the HVAC system. In summer, these components increase the HVAC loads (which increases the electricity consumption). The results obtained were for a design occupancy of 50% (which is approximately 42 people in the 12600 sq. ft. library). For an occupancy of 75%, a decrease of 2.1% in the annual natural gas consumption was observed whereas an increase of 1.7% in the electricity consumption was observed. For an occupancy of 25%, an increase of 2.2% in the annual natural gas consumption was observed whereas a decrease of 1.7% in the electricity consumption was seen. The results are summarized in Table 4.

**Table 4:** Effect of occupancy on natural gas and electricity consumption

| **Occupancy (Occupancy for base model – 50%)** | **Change in Annual Natural Gas Consumption** | **Change in Annual Electricity Consumption** |
|---|---|---|
| 75% | -2.1% | +1.7% |
| 25% | +2.2% | -1.7% |

### 3.2 Energy Efficiency Opportunities

A maximum HVAC heating load of 330 kBtu/hr (96.7 kW) was observed in the month of January. The furnace installed in the library has a total output power rating of 600 kBtu/hr (175.8 kW). Also, as discussed earlier, one of the most common complaints among the library occupants/customers was that it got too warm in the winter months. These facts motivated us to check if the hot water loop for space heating is actually necessary. A parallel simulation was performed for the library building, with all the conditions remaining the same, but with only the furnace (i.e., with only the direct expansion coils) as the HVAC system. The results indicated that the furnace could still support the heating demand for the library. If the hot water loop were not used, the natural gas consumption would be lowered by 20% and the electricity consumption by 3.6% per year. In this study, it was also incidentally observed that the central thermostat was located about 10 ft. (3.05 m) away from the radiators and grills with a lot of the seating arrangement being around the radiators, which might have led to higher temperatures around the seating areas than the thermostat set temperature. Thus, as predicted by the validated model, turning off the hot water loop for space heating would be a significant energy saving opportunity for the library.

## 4. CONCLUSIONS

In this research, eQUEST was selected for modeling a public library building, due to its user-friendly interface and to the fact that it already included the HVAC system supporting the building's heating and cooling requirements in its system library,

After developing the eQUEST model for the building, it was essential to validate it with actual utility bills. Linear regression-based methodology was used to compare eQUEST results for natural gas and electricity consumption with the library's utility bills. The model to estimate natural gas consumption from HDDs indicated that it was more accurate for the months having higher HDDs, with a maximum absolute error of 16.4% observed in the month of May. The mean base error observed was -3.60% and the coefficient of variation of root mean squared error was 7.33%. Multiple models to estimate the electricity consumption from CDDs were developed and it was observed that the model using average electricity consumption values from the winter months for the constant part in the linear equation was more accurate than the model using the linear equation derived from the electricity consumption – CDD relation. For this model, the mean base error observed was 2.48% and the coefficient of variation of root mean squared error observed was 4.14%, with the highest absolute error being 9.43% for the month of May. Error analysis indicated that the errors observed in the models were within reasonable limits.

Based on the simulation, we found that the library could save up to 20% of its natural gas consumption and 3.6% of its electricity consumption per year by using the furnace units alone, while still comfortably meeting the library's heating requirements.

## NOMENCLATURE

| | | |
|---|---|---|
| HDD | heating degree day | (HDD) |
| CDD | cooling degree day | (CDD) |
| HDD/day | average heating degree day in a given period | (HDD/day) |
| CDD/day | average cooling degree day in a given period | (CDD/day) |
| therm/day | average natural gas consumption in a given period | (therm/day) |
| kWh/day | average electricity consumption in a given period | (kWh/day) |
| $R^2$ | linear regression coefficient of determination | (–) |
| MBE | mean base error | (%) |
| Cv(RMSE) | coefficient of variation of root mean squared error | (%) |
| m | line slope | (–) |
| c | constant part of linear equation | (–) |

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