A Case Study in Energy Modeling of an Energy Efficient Building with Gas Driven Absorption Heat Pump System in eQUEST

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ABSTRACT

This paper presents a case study in the energy modelling of an existing energy efficient library building located in Tweed, Ontario. This particular building is using a gas-driven absorption heat pump to meet the heating and cooling loads of the building. This study is the first detailed analysis of gas-fired heat pumps in Canadian climate. The objective was to create a baseline model in eQUEST and compare the simulated energy consumptions with the actual energy bills. Through the eQUEST simulation a baseline model for the building was created for the full years 2012, 2013, 2014. On average the simulated annual electricity consumptions were 1.5% less than the actual electricity consumptions. The average difference for annual natural gas consumption was 7%. The accuracy of the simulation model in future studies could be improved by on-site weather measurement, collection of hourly energy consumption and occupancy data.

INTRODUCTION

Energy efficient buildings have been the subject of simulation and energy audit studies over the years to evaluate their performance. For an energy simulation study to be an accurate or representation of a building's energy use it must predict building energy consumption within an acceptable error margin.

Canadian Green Building Council (CaGBC) has approved eight energy simulation programs for conducting energy simulation studies [1]. eQUEST, which has been built upon the DOE-2 energy simulation engine [2] is one of those eight approved software programs. Even though eQUEST is widely used for energy consumption simulations yet it still has some limitations in the areas of zone loads, interior loads and solar/day lighting analysis. Therefore, it is essential to compare the simulation results with actual energy consumption data to ascertain the extent to which the software can model the actual energy consumed in a building.

CAN-QUEST is a Canadian version of eQUEST. It is based on eQUEST 3.62x. Difference between CAN-QUEST and eQUEST include support for metric and imperial units, and English and French language interfaces [3].

In this study eQUEST is to be used in conjunction with actual energy consumption bills and weather data from January 2012 and December 2014 to model an energy efficient library building (shown in Figure 1) located in Tweed, Ontario. Utility supply companies for the location under consideration are Hydro One for electricity and Union Gas for natural gas.

Figure 1: Tweed library

The main objectives of this study are the evaluation of the performance of eQUEST in simulating a building in Canadian climate equipped with gas driven heat pump. Furthermore, the differences between actual and simulated energy consumptions are also to be evaluated. This eQUEST study can then later be used to compare the energy performance of the building with conventional HVAC systems and thus would be helpful in providing an estimate of energy savings that the building under consideration is achieving as a result of the selection of gas-fired heat pump (GHP) over conventional HVAC systems.

Methodology

eQUEST v3.65 was used in creating a simulation model of the case study building based on building schematic drawings. In addition to building parameters weather data was also required. The closest weather station with complete weather data available for the period under consideration is in Trenton. The weather information for Trenton is available in eQUEST database. Therefore, Trenton was selected for weather data.

Utility bills for gas and electricity from January 2012 and December 2014 were compiled for comparison against simulated energy consumption. The main issue with using actual energy bills for comparison with simulation was that the meter readings did not coincide with the start and end of each month. For example, if the meter reading for the last 30 days is taken on January 20, it would include the energy consumption of 20 days of January plus 10 days of December. The energy consumption for the remaining 10 days of January would then be included in the reading taken in the month of February. Therefore, monthly energy consumption from the bills could not be used directly.

In order to adjust the bills the average daily consumption was used. This information was available from the utility bills. Using this information the energy consumption for any calendar month could be determined using Equation (1).

$$E_i = N_i * A_i + N_{i+1} * A_{i+1} \quad (1)$$

Where

- E_i is the energy consumption of i-th month
- N_i is the number of days in the i-th month included in the reading of i-th month
- A_i is the average energy consumption included in the reading of i-th month
- N_{i+1} is the number of days in the i-th included in the reading of (i+1) month
- A_{i+1} is the average energy consumption included in the reading of (i+1) month

In the instance explained above for the month of January when the reading is taken on January 20,

- N_i is the 20 (days of the month of January included in the utility bill of the month)
- A_i is the average energy consumption included in the utility bill of January
- N_{i+1} is the 10 (days of the month of January included in the utility bill of February)
- A_{i+1} is the average energy consumption included in the reading of February

Furthermore, since, eQUEST presents thermal energy (in this case natural gas) consumption in terms of British thermal units (BTU), a conversion factor from BTU to cubic metre (m^3) was required. This was obtained from Union Gas website [4] as follows:

$$1\ m^3 = 35{,}494\ BTU \quad (2)$$

The adjusted energy consumption bills along with the weather data obtained from the nearby weather station were used to conduct regression analysis using PRISM. PRISM provides reasonably accurate results for variation of energy consumption with weather and their correlation without the need of installing special end-use meters [5].

The weather adjusted or normalized annual consumption (NAC) can be determined using Equation (3) [6, 7].

$$NAC = 365\ \alpha + \delta_h\ \beta_h\ H_o(\tau_h) + \delta_c\ \beta_c\ C_o(\tau_c) \quad (3)$$

where

- α is the daily base level consumption
- β_h is the daily consumption per heating degree day
- β_c is the daily consumption per cooling degree day
- τ_h reference temperature for heating
- τ_c reference temperature for cooling
- $H_o(\tau_h)$ is the "long-term average heating degree-days" per year as a function of reference temperature for heating
- $C_o(\tau_c)$ is the "long-term average cooling degree-days" per year as a function of reference temperature for cooling
- δ_h is '1' for heating only (HO) and "combined heating and cooling" (HC) model, otherwise zero
- δ_c is '1' for cooling only (CO) and "combined heating and cooling" (HC) model, otherwise zero

The goodness of fit for the regression analysis is indicated by R^2 value of the regression model. The closer R^2 value is to 1.0 (maximum value) the stronger the correlation between two variables [8].

Simulation (Case Study)

The building under consideration is a single-storey 469.8 square metres library building built in 2011. The geographical coordinates of the library are 44°28'N and 77°18'W in Tweed, Ontario, Canada. The building had been designed for a maximum occupancy of 100 people.

The facility includes books circulation area, children's area, conference room which also serves as a venue for community events, kitchen and office rooms for the staff. Each of these areas were modelled as a separate zone in the eQuest simulation. All of the possible sources and uses of energy in the building were accounted for in the modeling and simulation. The actual schedules for the library along with the building schematics were provided by the library management. Plug loads were calculated for the computers, printers and electrical appliances. Table 1 provides a summary for the major inputs and parameters entered into eQuest during the modeling phase. Figure 1 shows the 3D geometry of the modelled building.

Table 1: Input Summary Table

Input and Design Model Characteristics	
General	
Location	Tweed, ON
Simulation Weather File	Trenton, ON
Building Area	469.8 m^2 (5056 ft^2)
Occupancy	100
Hours of Operation	
Monday	Closed
Tuesday	9 am – 5 pm
Wednesday	1 pm – 7 pm
Thursday	1 pm – 7pm
Friday	10 am – 5 pm
Saturday	10 am – 3 pm
Sunday	Closed
Electrical Design Loads	
Lighting	25 W/m^2
Air Handling Unit	3 @ 1467 W
Heat Pump	3 @ 2200 W
Computer loading	2000 W
Temperature Set Points	
Cooling	Occupied: 25 ºC (77 ºF) Unoccupied: 28 ºC (82.4 ºF)
Heating	Occupied: 22 ºC (72 ºF) Unoccupied: 18 ºC (64.4 ºF)
Heat Pump (integrated package of three modules)	
Heating Capacity (per Module)	10 tons (120,400 BTU/h)
Heating Capacity (three modules)	30.1 tons (361,200 BTU/h)
COP in Heating Mode	1.26
Ambient temperature	Max: 35 ºC (95 ºF) Max: -20 ºC (-4 ºF)
Hot water temperature	Max to hydronic system: 60 ºC (140 ºF) Max inlet to unit: 50 ºC (122 ºF)
Cooling capacity (per Module)	4.8 tons (57,700 BTU/h)
Cooling Capacity (three modules)	14.4 tons (173,100 BTU/h)
COP in Cooling Mode	0.6
Ambient temperature	Max: 49 ºC (120 ºF) Min: 0 ºC (32 ºF)
Chilled water temperature	Min to hydronic system: 3 ºC (37.4 ºF)

Three simulations for each of the full years from 2012 - 2014 were created. The results obtained from these simulation runs are provided in the next section. Three dimensional model of the library in eQUEST is shown in Figure 2.

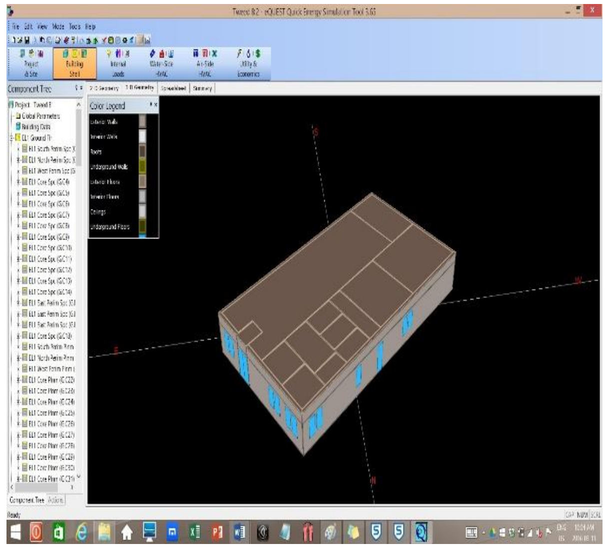

Figure 2: Three dimensional geometry of the building

CALIBRATION

Calibration of a building energy model is the process of developing and updating the model through changes of input parameters to predict the building annual/monthly energy consumption as close as possible to the actual or measured consumption. The process of calibration concludes when the difference between simulated and actual energy consumptions is below a given threshold. [9]. Calibration is necessary to ensure the accuracy and usability of energy simulation.

Comparison of simulated energy consumption with the monthly utility bills is a common practice [10]. Monthly bills combined with either a trial and error approach or an optimization algorithm or both could lead to an acceptable difference between simulated and actual energy consumption.

A trial and error approach could be used but it is time consuming and depends on the experience of the person developing the simulation model. [9].

In this case study energy consumption data from utility bills were used for calibration in conjunction with the energy consumption for heating and cooling estimated through by conducting a regression analysis using PRISM. The parameters with uncertainty were fine-tuned until the difference between simulated energy consumption and actual energy consumption was within allowable limits.

EVALUATION of CALIBRATION

In order for a model to be considered calibrated it is not sufficient to simply match simulated and actual annual energy consumption. The evaluation of calibration requires further analysis of the error and uncertainty in the results obtained from simulation. [11]

The most used acceptance criteria to evaluate the calibration of a building simulation involve calculation of two statistical indices i.e. normalized mean bias error (NMBE) and coefficient of variation of root mean square error CV(RMSE). The normalized mean bias error "NMBE" is defined as the mean difference between actual and simulated energy consumption values, normalized by mean value of the actual energy consumption. [12]. Normalized mean bias error is useful in determining how closely the simulated or predicted demand corresponds to the actual energy consumption. However, the offsetting of errors when positive and negative errors cancel each other out is a major drawback of this index. Therefore, a second index i.e. CV (RMSE) based on the variance of simulated energy consumption from the mean actual energy consumption is employed. Normalized mean bias error and coefficient of variance of root mean square error for a simulation model can be calculated using Equation (4) and Equation (5) respectively [12].

$$\text{NMBE} = \frac{1}{\bar{M}} \; \frac{\sum_i^n (M_i - S_i)}{n} \tag{4}$$

$$\text{CV(RMSE)} = \frac{1}{\bar{M}} \sqrt{\frac{\sum_i^n (M_i - S_i)^2}{n}} \tag{5}$$

Where

M_i is the measured or actual energy consumption during the i-th period

S_i is the simulated energy consumption during the i-th period

$\bar{M}$ is the average of actual energy consumption during the period of simulation

n is the number of data points in the simulation

Both indices are evaluated for each type of fuel used in a building for different measurement intervals (annual, monthly and hourly etc.). Acceptable tolerances for the two indices have been established in ASHRAE Guideline 14 (2002) [13], International Performance Measurements and Verification protocol (IPMVP) [14] Federal Energy Management Program (FEMP) Measurements and Verification (M&V) guidelines [15].

These tolerances for monthly and hourly intervals are shown in Table 2.

Table 2: Commonly used calibration criteria [16 –18]

Index	ASHRAE	IPMVP	FEMP
$NMBE_{month}$	± 5 %	± 20 %	± 5 %
CV $(RMSE)_{month}$	± 15 %		± 15 %
$NMBE_{hourly}$	± 10 %	± 5 %	± 10 %
CV $(RMSE)_{hourly}$	± 30 %	± 20 %	± 30 %

In this case study the calibration of the simulation model was evaluated using IPMVP criterion.

PRISM RESULTS

Annual electricity and natural gas consumptions were normalized in PRISM using long-term weather data from the nearby weather stations. Heating and cooling (HC) models were used for both electricity and natural gas. Reference temperature range option was used which allowed PRISM to identify the reference temperatures for best R^2 value. The results are shown in Table 3.

Table 3: Results from PRISM analysis

Estimated Parameter	Electricity	Natural Gas
Normalized Annual Consumption	40,569 kWh	5,534 m^3
R^2 Value	0.34	0.814
α	99.7 kWh	- 2 m^3
β_h	0.3 kWh/^{o}C-day (0.5 kWh per ^{o}F-day)	0.4 m^3/ ^{o}C-day (0.8 m^3/ ^{o}F-day)
β_c	0.3 kWh/^{o}C-day (1.4 kWh/^{o}F-day)	0.9 m^3/ ^{o}C-day (1.6 m^3/ ^{o}F-day)
τ_h	17.2 ^{o}C (63 ^{o}F)	14.4 ^{o}C (58 ^{o}F)
τ_c	17.2 ^{o}C (63 ^{o}F)	15.0 ^{o}C (59 ^{o}F)

The R^2 values for electricity and natural gas consumptions indicates the extent to which these consumptions are affected by outside weather temperature. Electricity consumption shows a very weak correlation with weather while natural gas consumption shows a very strong correlation. The correlations of natural gas and electricity are visual depicted in the form of energy plots which are shown in Figure 3 and Figure 4 respectively.

From the PRISM results it could be expected that the simulated monthly electricity consumption would not show much variation throughout the year while monthly natural gas consumption is expected to vary greatly depending on the heating and cooling demand caused by the changing weather conditions.

eQUEST RESULTS

Simulations were run for each year from 2012 – 2014. The results from eQUEST simulations are presented in this section. The results are presented separately for electricity and natural gas in Table 4 and Table 5 respectively.

In the case of electricity in all three simulation runs electricity consumption predicted by eQUEST simulation was found to be very close to actual electricity consumption. The largest percentage difference between overall simulated annual consumption is 1.5% below the actual electricity for the year 2014. The year 2014 had the most accurate run with the overall annual difference being 1.1%. For the years 2012 – 2014 the annual difference ranged between 1.1% and 2.0%. In all three simulations the annual consumptions from simulations were lower than their respective actual consumptions. On a monthly basis, the largest difference occurs in June of 2014 with a difference of 18.4%. The results show that eQuest is capable of simulating annual electricity consumption with reasonable accuracy. The NMBE values for 2012, 2013 and 2014 were –2.0%, –1.5% and –1.1% respectively which is well within the acceptance criterion of IPMVP.

Simulations results for natural gas were less accurate than the ones for electricity. Natural gas consumption shows greater fluctuations since, it is affected by weather to a greater extent than electrical consumption, as expected based on PRISM analysis. The largest percentage difference between overall annual consumption is 12.0 % for the year 2013. For the years 2012 – 2014 the annual difference ranged between 1% and 12 %. The NMBE values for 2012, 2013 and 2014 were 1.0%, –12% and –10.1% respectively which is well within the acceptance criterion of IPMVP.

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CONCLUSION

Three simulation models were created for the case study building for the years 2012, 2013 and 2014. It could be concluded from these simulations that eQUEST could produce reasonably accurate simulations for buildings in Canadian climate equipped with gas driven heat pump. However, it was observed that there were differences between monthly electrical and natural gas consumptions which should be addressed in the future studies. These differences between actual and simulated energy consumptions could have been caused by various factors such unavailability of occupancy and weather data from the site. Further analysis should be done especially for the shoulder season to determine the cause for the difference between actual and simulated energy consumptions.

It was evident from the PRISM analysis of energy consumption and weather data that the electricity consumption at the site under consideration is not greatly influenced by weather conditions. Natural gas on the other hand was greatly influenced by weather conditions.

All the simulations met the criterion for calibration established by International Performance Measurement and Verification Protocol (IPMVP) which suggests that although there are some differences between simulated and actual energy consumptions yet the calibration should give confidence in the energy model. This implies that these baseline simulation models can be used for future analyses.

FUTURE WORK

Future work for the building under consideration would include weather data measurement and collection of data for hourly energy consumptions and occupancy. These data will be used to improve the accuracy of the eQUEST baseline model which would subsequently be used to compare the energy consumption of the building in its current configuration to the energy consumption in the scenarios. These comparison studies could include:

- Comparison of current configuration with conventional heating and cooling equipment

- Comparison of current configuration with ASHRAE standard conventional heating and cooling equipment

These comparisons would also include cost and GHG emission analyses. Through these comparisons economic and environmental viability of gas-fired heat pump would be ascertained.

RECOMMENDATIONS

Gathering accurate hourly energy consumption data would be of great importance for creating a more accurate model in the future. This will provide accurate estimates for plug loads, office equipment and miscellaneous equipment. In addition occupancy data should also be collected. Furthermore, in order to increase the accuracy of the simulation model on-site weather data collection would be recommended. This could be done by installing an on-site weather station that collects temperature, relative humidity, solar radiation, wind direction and wind speed. These data can then be used to create custom weather file to be used in the simulation.

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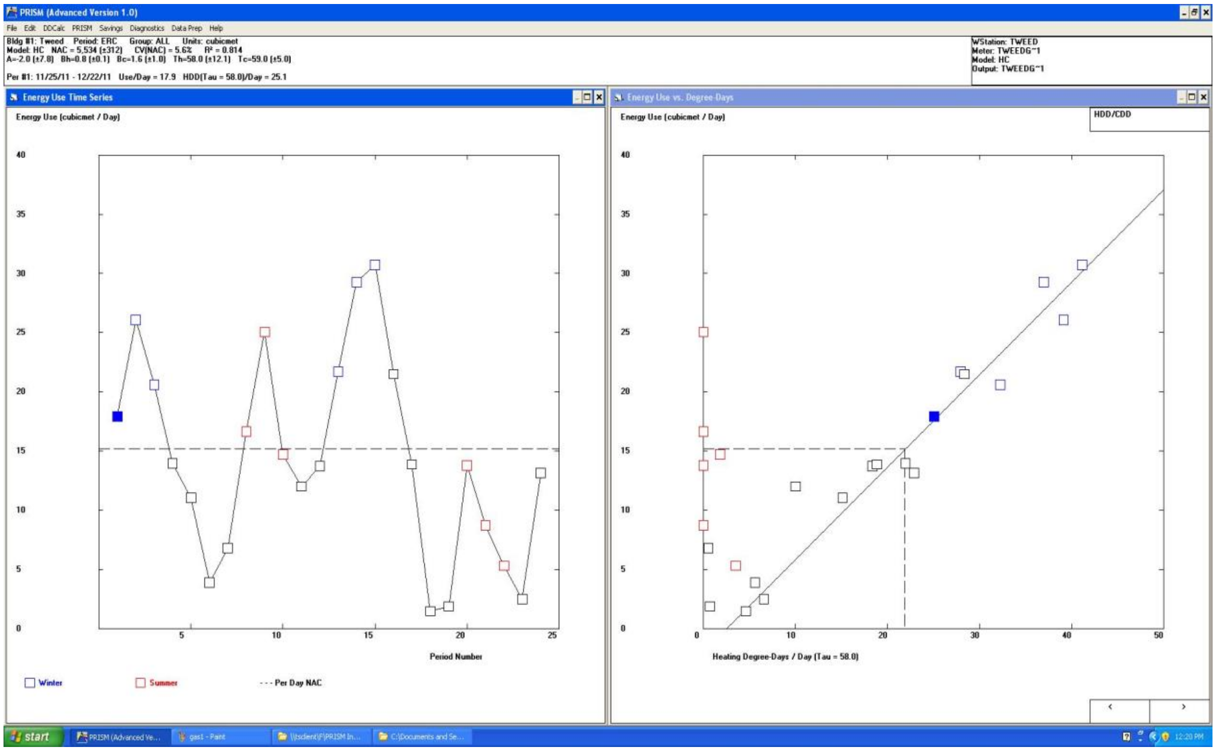

Figure 3: Natural gas consumption plot obtained from prism

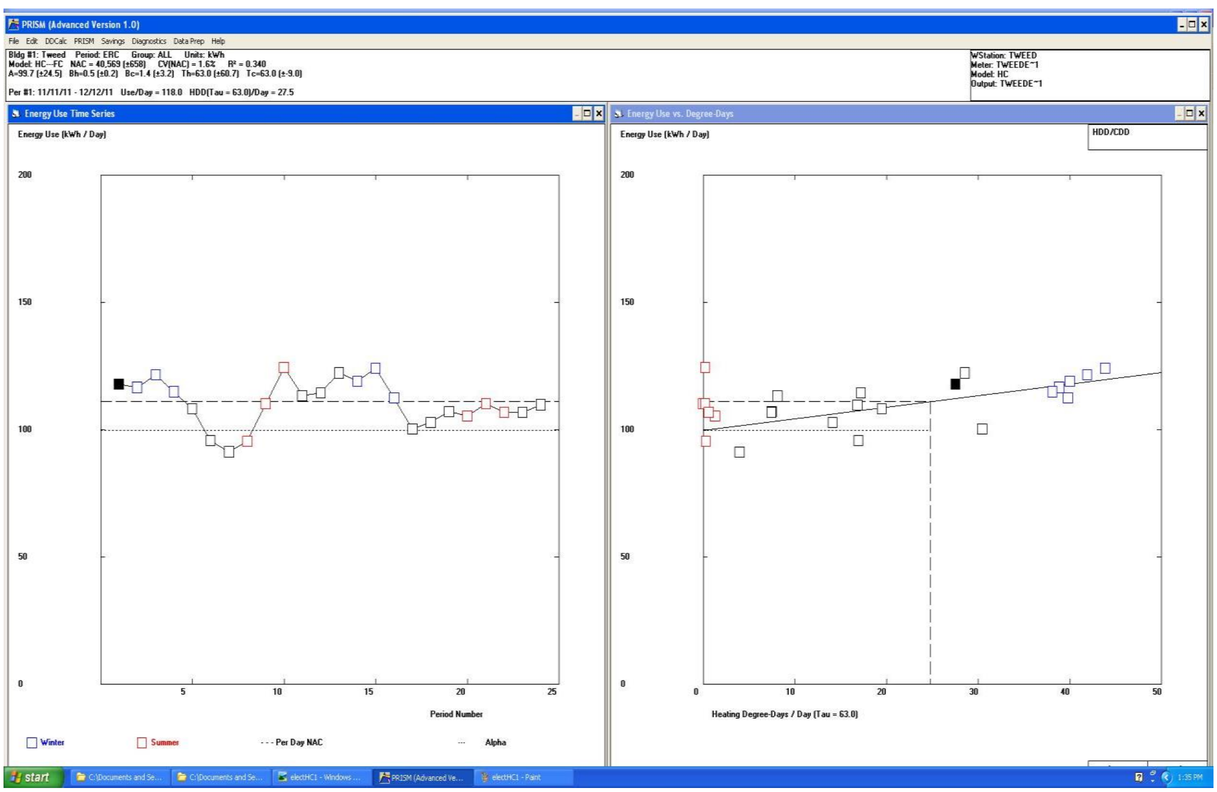

Figure 4: Electricity consumption plot obtained from PRISM

Table 4: Actual and simulated monthly electricity consumption

Month	2012		2013		2014	
	Actual (kWh)	eQuest (kWh)	Actual (kWh)	eQuest (kWh)	Actual (kWh)	eQuest (kWh)
January	3,711	3,736	3,814	3,736	3,692	3,736
February	3,375	3,523	3,209	3,336	3,339	3,361
March	3,400	3,835	3,198	3,684	3,555	3,835
April	2,924	3,295	3,066	3,395	3,223	3,219
May	2,864	3,113	3,286	2,959	3,071	2,976
June	2,846	3,315	3,172	3,315	2,795	3,315
July	3,344	3,339	3,396	3,339	3,309	3,339
August	3,818	3,585	3,322	3,585	3,458	3,585
September	3,456	3,170	3,208	3,001	3,204	3,001
October	3,548	3,273	3,395	3,119	3,480	3,135
November	3,633	3,592	3,546	3,592	3,559	3,592
December	3,707	3,682	3,542	3,682	3,658	3,682
Annual	40,626	41,458	40,154	40,744	40,344	40,775
NMBE	– 2.0 %		–1.5 %		– 1.1 %	

Table 5: Actual and simulated monthly natural gas consumption

Month	2012		2013		2014	
	Actual (m^3)	eQuest (m^3)	Actual (m^3)	eQuest (m^3)	Actual (m^3)	eQuest (m^3)
January	764	897	920	897	893	897
February	551	819	823	793	783	800
March	406	606	621	600	686	606
April	288	280	341	292	328	263
May	141	98	47	95	115	94
June	263	333	116	333	149	333
July	566	585	402	585	340	585
August	704	485	253	485	279	485
September	425	194	145	173	171	173
October	384	187	120	185	91	185
November	476	435	448	435	475	435
December	748	741	779	741	771	741
Annual	5,716	5,661	5,015	5,614	5,082	5,597
NMBE	1.0 %		– 12 %		– 10.1 %	