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1. Introduction

A preliminary energy audit was conducted on a home located in Upstate New York, which consumes around 70,000 kWh (electricity and gas) and costs the homeowners about $4500 (USD) annually. To address these high costs, the following report primarily aims to identify cost reduction strategies. Heating, ventilation, and air conditioning (HVAC) related consumption was chosen as the focus, as it accounts for around 50% and 30% of annual energy consumption and utility costs, respectively. It was believed that targeting HVAC usage offered a promising avenue for "passive" reductions in energy consumption and costs without significant lifestyle changes for the residents.

For a robust analysis of HVAC consumption, a computer program was developed that models monthly heat loss and gain through conduction, ventilation, and solar heat gain. This model utilizes on-site measurements and typical meteorological data to calculate monthly and annual heating and cooling energy consumption and costs. It was used to provide breakdowns of each contributing factor and to estimate the payback period for potential home improvements. The improvements investigated included sealing air leaks, enhancing insulation, and replacing windows, and are accompanied by comprehensive discussions of their impact on consumption, costs, and payback periods.

Due to time constraints and the in-depth analysis of HVAC, no analysis was performed relating to greenhouse gas emissions, and a thorough breakdown of electronics and appliance usage was omitted.

The following report includes an overview of the building, a preliminary analysis of the available utility data, a discussion of the model's construction, a breakdown of modelled heat transfer and HVAC usage, a detailed end-use breakdown, an investigation of potential home improvements, and conclusions drawn during this energy audit, in addition to a set of recommendations.

2. Building Overview

Located in Jamesville, New York, USA, the home under consideration is a Stringer-built contemporary constructed in 1986. It features 4,390 square feet of living space, including five bedrooms and four bathrooms, with an additional 1,100 square feet basement that accommodates an extra bedroom, bathroom, and a recreation area.

Specifications of the major electrical and gas loads identified during the on-site assessment are detailed in table 1, excluding electronics and appliances, which, although significant, are not the primary focus of this report. It is worth noting that no unusual electronics or appliances were identified during the assessment.

The central HVAC system, a critical element for this energy audit, is comprised of a gas-fired, forced-air furnace integrated with a split-system air conditioner. The circulation of conditioned air is facilitated by a 3/4 horsepower (559 W) draft inducer fan within the ductwork system.

Table 1. Specifications of Major Loads

<table>
<tr><th>Load</th><th colspan="2">Specifications</th></tr>
<tr><td rowspan="4">Furnace</td><td>Manufacturer & Product Name</td><td>Rheem Prestige EcoNet-Enabled Two-Stage Variable Speed Multi-Position Gas Furnace</td></tr>
<tr><td>Model Number</td><td>R96VA1152524MSA</td></tr>
<tr><td>Heating Capacity (Btu/hr)</td><td>109,000 (31.94 kW)</td></tr>
<tr><td>Rated Efficiency (%)</td><td>96</td></tr>
<tr><td rowspan="4">Air Conditioning System</td><td>Manufacturer & Product Name</td><td>(Indoor Unit) Rheem Cased Coils For Gas And Oil Furnace
(Outdoor Unit) Rheem Classic Series Air Conditioners</td></tr>
<tr><td>Model Number</td><td>(Indoor Unit) RCF6024STAMCA
(Outdoor Unit) RA1360AJ1NA</td></tr>
<tr><td>Cooling Capacity (Btu/hr)</td><td>60,000 (17.58 kW)</td></tr>
<tr><td>SEER</td><td>20.5 (COP ≈ 4.27)</td></tr>
<tr><td rowspan="5">Water Heater</td><td>Manufacturer & Product Name</td><td>A.O. Smith Residential Gas Water Heater</td></tr>
<tr><td>Model Number</td><td>GCG-50 400 00L010000</td></tr>
<tr><td>Rated Storage Volume (Gallons)</td><td>48</td></tr>
<tr><td>Heating Capacity (Btu/hr)</td><td>40,000 (11.7 kW)</td></tr>
<tr><td>Uniform Energy Factor</td><td>0.62</td></tr>
<tr><td rowspan="4">Hot Tub</td><td>Manufacturer & Product Name</td><td>Lifesmart 7-Person 65-Jet 230V Swim Spa with 14-Jet Nozzle Turbo Blaster</td></tr>
<tr><td>Model Number</td><td>LS600DX</td></tr>
<tr><td>Heater Rated Power (kW)</td><td>4</td></tr>
<tr><td>Pump Horsepower</td><td>3 (2.2 kW)</td></tr>
</table>

Lighting within the home is provided by 67 recessed LED ceiling lights, supplemented by a variety of lamps housing a total of 25 bulbs. The lamps contain a roughly 50/50 split of standard incandescent and compact fluorescent bulbs. For this audit, LEDs and lamp bulbs are assumed to consume 4.5 and an average of 40 W, respectively.

Windows and skylights are significant architectural features of this home, with a total of 45 windows and 3 skylights. The windows are distributed evenly between the south, west, and east faces of the house, which align closely with the cardinal points, as shown in figure 1. It is worth noting that thick vegetation reduces solar heat gain through the south-facing windows, especially in the winter months. Further details about the surface area and thermal properties of each building component (i.e., the roof, walls, and glazing) can be found in table 3 within the 'Model Construction' section of this report.

Figure 1. Top-down View of House

During the on-site assessment, residents reported discomfort with temperature regulation on the second floor, hinting at potential issues with the HVAC system's blower or roof insulation. They also tend to leave many lights on during the day, which could affect electricity consumption. As we move forward with the audit, these aspects, along with the major electrical and gas loads identified, will be evaluated to provide a comprehensive view of the home's energy usage.

3. Preliminary Analysis of Utility Data

Nearly three years' worth of electricity and natural gas utility data – spanning June 2020 to May 2023 – were made available by the homeowner for the purposes of this energy audit. The utility provider records usage and cost data on a billing period rather than monthly basis – with each billing period being roughly mid-month to mid-month.

Figures 2 and 3 depict the total energy usage and cost per billing period over the past three years. It should be noted that gas usage was reported in therms but was converted to kWh for easier comparison with electricity usage (1 therm ≈ 29.3 kWh). Evidently, there exists significant variance in both usage and cost for the same billing period between different years. Variance in energy usage could be owed to many factors including differences in weather conditions (i.e., colder winters require more heating and hotter summers require more air conditioning), changes in the number of occupants and occupant behavior, and hours spent indoors due to the likes of COVID-19 restrictions (affecting 2020-21 usage).

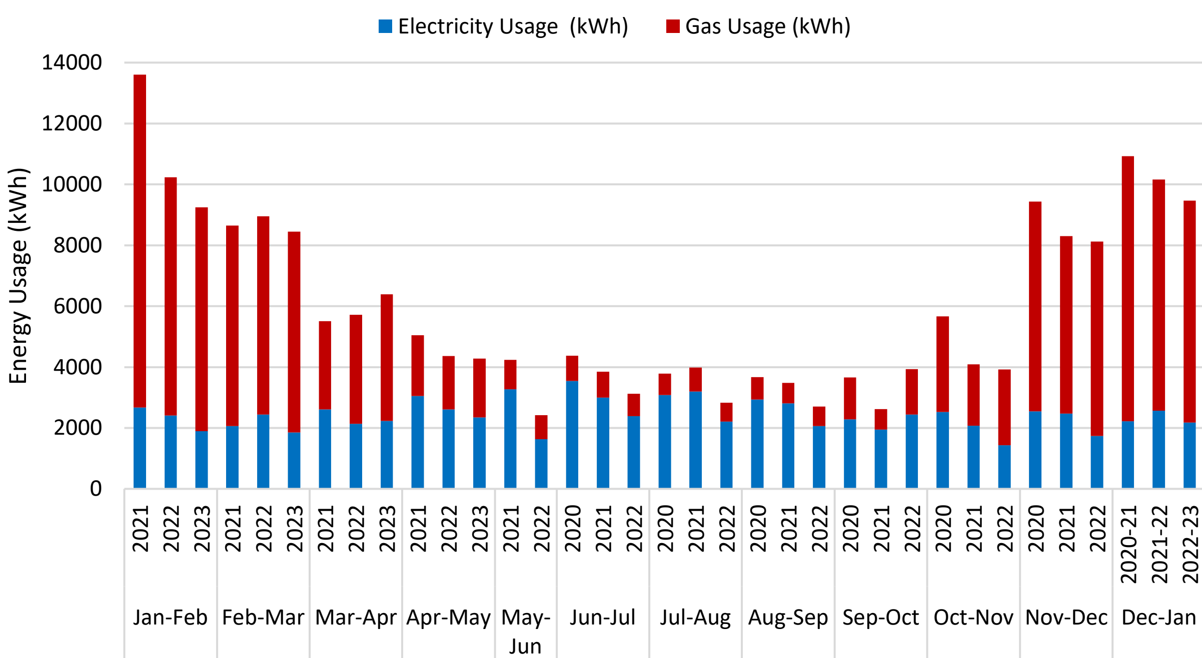

Figure 2. Energy Usage Per Billing Period Over Last Three Years

Interestingly, in certain cases energy costs seem to be disproportionate to usage. For instance, although the usage for the 2021 January-February billing period was roughly 30% greater than that of 2022 (due to far more gas usage), the 2022 bill was slightly more expensive than the previous year. This cost variance may be due to a combination of changes in rates and on-peak usage – whereby gas and electricity are more expensive to use at different times of the day depending on the demand on the grid.

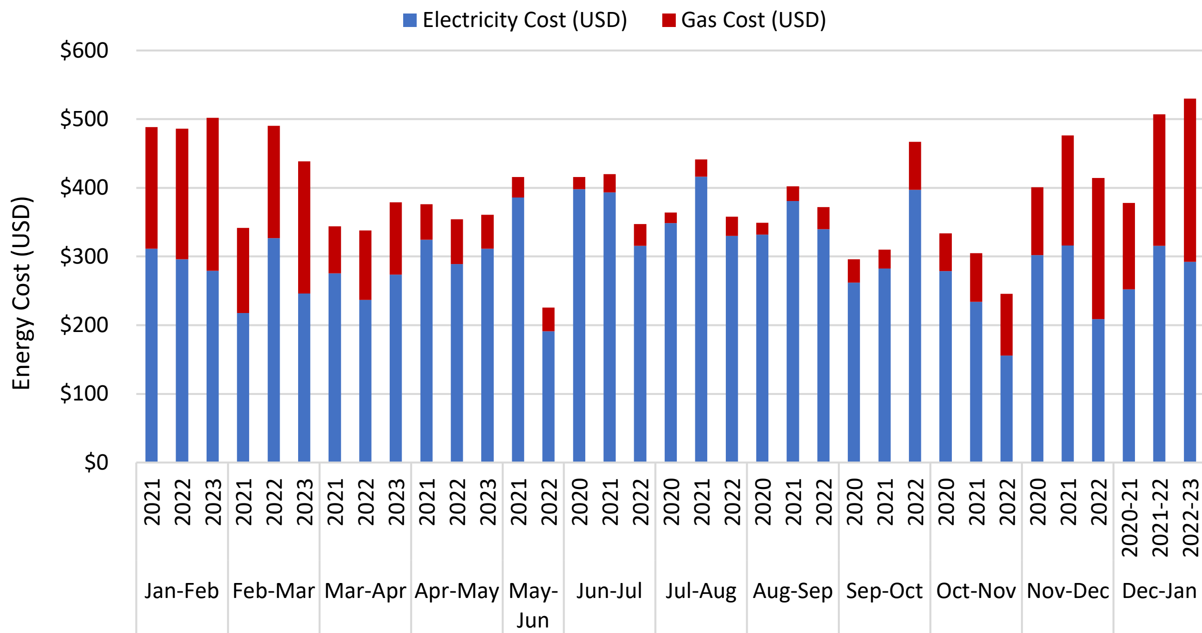

Figure 3. Energy Cost Per Billing Period Over Last Three Years

To gain a broader understanding of usage and cost trends, all the available utility data was averaged and presented in figures 4 and 5, along with the average local temperature for each billing period. The temperature data shown was taken from the utility provider and it is worth noting that these are hourly averages for a given billing period, rather than simple averages of high and low temperatures.

Unsurprisingly, gas dominates energy usage in the winter months, while electricity dominates cost throughout the year. Electricity dominates costs simply because it is far more expensive than gas with an average rate of 12.4 ¢/kWh compared to 2.6 ¢/kWh for gas.

Figure 4 suggests that there is an electrical base load (i.e., minimum level of usage) of approximately 2000kWh per billing period. Electricity usage peaks in the June-July billing period, exceeding the base load by roughly 980 kWh, which can likely be entirely attributed to the use of air conditioning. One potential explanation for why electricity usage rises above the base load in the winter months despite the lack of air conditioning may be due to increased use of lighting. This trend would be consistent with the fact that lights are typically kept on for longer portions of the day during the winter as the number of daylight hours is reduced.

Similarly, it appears the home has a gas base load of approximately 700 kWh; this is likely dominated by the water boiler, with minor contributions from the gas stove and grill. Gas usage peaks at more than 8000 kWh above the base load in the January-February billing period (coldest period in the year), meaning almost eight times more energy is consumed heating the home in the coldest months than is spent cooling it in the hottest months.

As will be discussed later in this report, the home loses far more heat in the winter than it gains in the summer since the temperature difference between interior and external environment is far greater in the winter, compared to the summer months. This dynamic explains why, for a home located in this region, far more heating is required than air conditioning. It is also worth noting that a gas furnace isn't (under ideal conditions) as efficient at heating compared to how efficient an air conditioning is at cooling. The reasons for this are beyond the scope of this report but are related to the fact that energy conversion (e.g., from chemical to thermal as is done by a furnace) is less efficient than energy transfer (which is done by the refrigeration system behind an air conditioning unit).

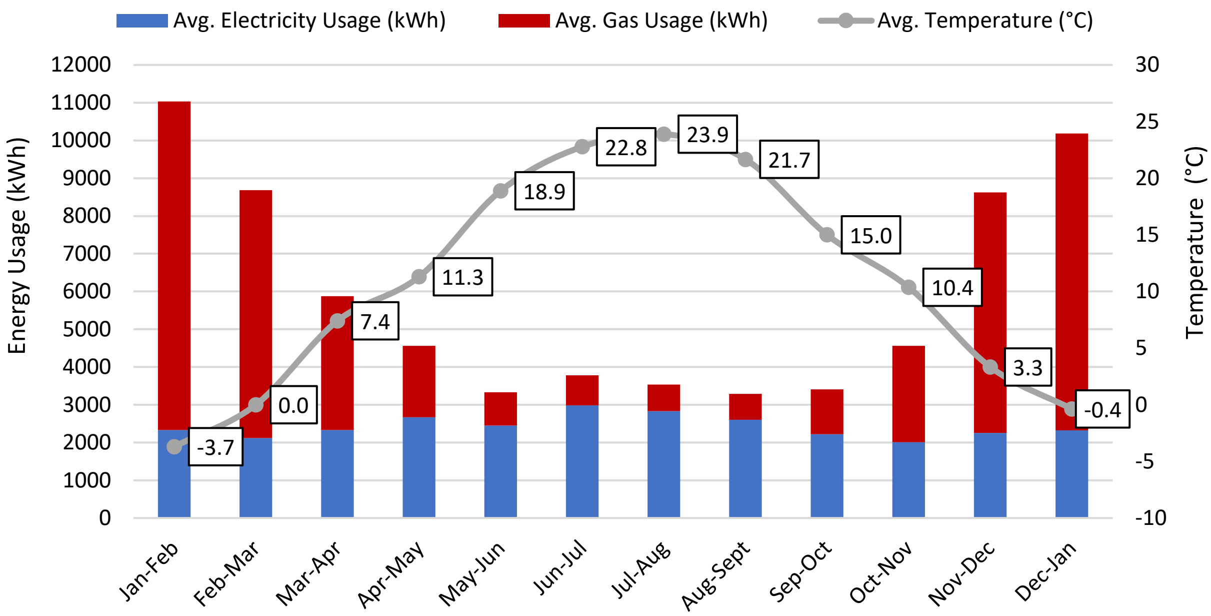

Figure 4. Average Energy Usage Per Billing Period

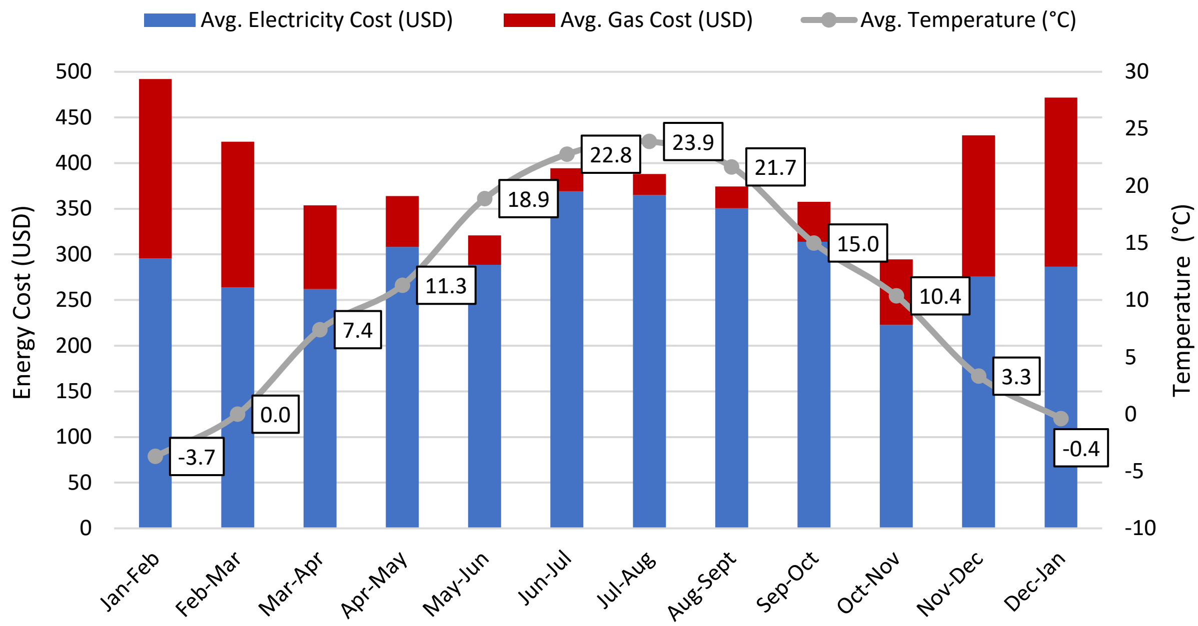

Figure 5. Average Energy Cost Per Billing Period

Finally, average usage and cost data for each billing period was totaled to generate the average annual usage and cost breakdowns shown in figures 6 and 7. Based on the provided utility data, we can see the home consumes an average of 70,842 kWh of energy per year, costing a total of $4665 USD – with gas accounting for 59% of all energy usage while electricity accounts for 77% of all energy costs.

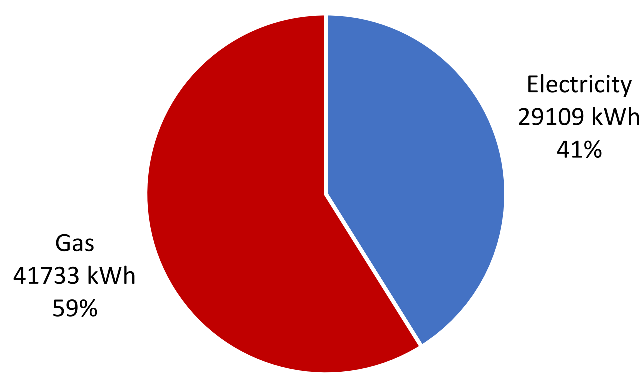

Figure 6. Basic Breakdown of Average Annual Energy Usage

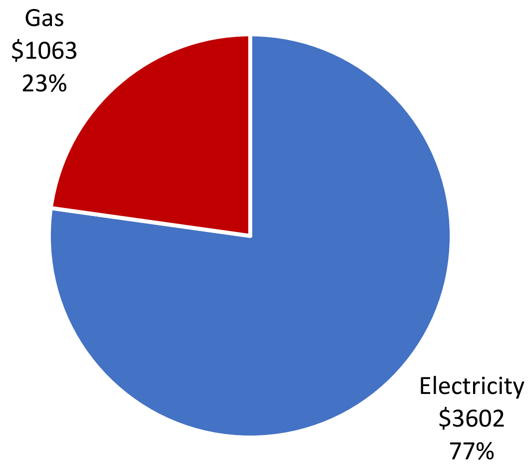

Figure 7. Basic Breakdown of Average Annual Energy Cost

According to the U.S. Energy Information Administration (EIA), the average home in the state of New York has an average square footage of 1,832 and consumes a total of 103 million Btu (30,186 kWh) of energy per year. This means that on a kWh per square foot basis, the audited home consumes roughly 2% less energy annually than an average New York home of the same size. This of course does not mean the home is energy efficient, rather it simply indicates its total energy usage is consistent with the state average.

The EIA also reports that the average New York home consumes roughly 6,200 kWh of electricity per year. Interestingly, on a kWh per square foot basis, this means the audited home consumes nearly double (96% more) the amount of electricity of an average home of the same size — explaining why utility costs are so high despite the total amount of energy consumption being nearly average.

4. Model Construction

The following sections describe the construction of the model used within this report.

The model is based on a simple thermodynamic principle known as an energy balance, wherein the rate of heat transfer (W) experienced by the building is the difference in the rates of heat gain and loss, as shown in equation 1. In this formulation, if the heat transfer rate, $\dot{Q}$, is positive, it indicates the building is gaining energy, and if it is negative, the building is losing energy.

$$\dot{Q} = \dot{Q}_{gain} - \dot{Q}_{loss} \dots eq.1$$

The sources of heat gain and loss depend on the season. Unlike solar heat gain (SHG), heat transfer via conduction and ventilation depends on the temperature difference between the interior and external environments, as shown in equation 2. In this equation, U represents thermal transmittance and A the surface area of a particular building component. Thermal transmittance is a measure of how easily an assembly of materials transmits heat (W / m^2°C). For each building component, namely the roof, walls, and glazing units (windows and skylights), we sum the products of thermal transmittance and surface area to find how much heat is transferred via conduction for every degree of temperature difference between the interior of the home and external environment.

The $\rho c_p \dot{V}$ term describes heat transfer via ventilation and air leakage. Since air carries energy, when air flows into or out of the home to and from the external environment, heat transfer occurs. Due to the limited duration of the on-site assessment, ventilation rates could not be meaningfully measured, and as a result, could not be factored into the model directly. Instead, a bulked ventilation heat transfer factor was computed by comparing gas usage data to the modelled usage when ventilation was not accounted for; this value was used instead of $\rho c_p \dot{V}$ in equation 2.

The SHG rate, represented by $\dot{Q}_{SHG}$, describes the rate of heat gain due to direct and diffuse solar radiation. Note that only SHG through glazing components was considered for this model. The amount of SHG through glazing components depends on several factors including the material and construction properties of the glazing component (reflectivity, emissivity, etc., which are bulked into a solar heat gain coefficient [SHGC]), the angle at which beams of sunlight strike the glazing (angle of incidence), the intensity of direct beam and diffuse solar radiation (irradiance), and the duration of time for which the glazing is exposed to direct sunlight.

$$\dot{Q} = \dot{Q}_{SHG} + \left[\sum(UA)_i + \rho c_p \dot{V}\right] \cdot (T_i - T_o) \dots eq.2$$

To compute the monthly heat gain or loss experienced by the house, we must integrate the heat transfer rate described in eq.2 over the timespan of a given month to account for changes in temperature and SHG over the course of each day in that month, as shown in equation 3. Since this would be computationally expensive to perform, we instead use single average monthly temperature and solar irradiance values to estimate the heat transfer rate for a given month. Monthly conductive and ventilation-based heat transfer were then calculated by multiplying their heat transfer rates by the total number of hours in a month, while monthly SHG was found by multiplying the solar heat gain rate by the total number of daylight hours in a month. The monthly heat transfer, Q, defines the thermal load that must be met by either the furnace or air conditioning systems each month.

$$Q = \int_0^{t_{month}} \dot{Q}\, dt \ldots eq.3$$

Finally, equations 4 and 5 show how monthly furnace and air conditioning consumption are found by dividing the thermal load by the furnace efficiency or coefficient of performance (COP), respectively.

$$If\ Q < 0\ (heat\ loss) \rightarrow E_{furnace,monthly} = \frac{Q}{\eta_{furnace}} \ldots \text{eq.4}$$

$$If\ Q > 0\ (heat\ gain) \rightarrow E_{AC,monthly} = \frac{|Q|}{COP} \ldots \text{eq.5}$$

Thermal load calculations require both monthly temperature and solar irradiance data, both of which are presented in table 2. The temperature data employed was sourced from the utility provider rather than typical temperature data for the region (i.e., from a typical meteorological year data set). This choice was made to facilitate a more accurate comparison between actual and modelled usage, and to present cost savings for different home improvements when the weather is similar to the past three years. The utility company provides average temperature data for each billing period. Since these temperatures are hourly averages, it allows us to compensate for the variance in temperature throughout an individual day and throughout the billing period when used to compute heat transfer rates. The temperature data for each billing period was first averaged over all the available years. To estimate the temperature for an individual month, the temperature data for adjacent billing periods were averaged.

Solar irradiance values were sourced from the National Solar Radiation Database. Irradiance values from a typical meteorological year dataset were averaged amongst every hour of every day in a specific month save for nighttime hours (detected when irradiance values are 0). As such, the irradiance values used should account for days where there is significant cloud cover and rain, etc.

Table 2. Monthly Meteorological Data

Month	Month Name	Number of Days	Avg. Temp. [°C]	Avg. Number of Daylight Hours	Avg. Beam Flux (DNI) [W/m^2]	Avg. Diffuse Flux (DHI) [W/m^2]
1	Jan	31	-2.04	8	315.68	91.85
2	Feb	28	-1.85	9	293.63	104.56
3	Mar	31	3.70	11	450.49	122.46
4	Apr	30	9.35	12	408.44	146.09
5	May	31	15.09	13	456.85	163.78
6	Jun	30	20.83	14	419.51	166.99
7	Jul	31	23.33	14	463.95	161.38
8	Aug	31	22.78	13	459.61	144.93
9	Sep	30	18.33	12	448.71	126.61
10	Oct	31	12.69	10	454.14	99.05
11	Nov	30	6.85	10	298.08	76.24
12	Dec	31	1.48	9	281.80	64.24

The thermal transmittance values for each component of the building envelope are presented in table 3. The values used are typical for New York homes constructed in the 1980's. It should be noted that these values do not account for thermal bridging and as such, likely underestimate the true U-values.

Table 3. Thermal Transmittance of Building Components

Component	Surface Area [m^2]	Resistance (R)	Resistance (RSI)	Transmittance (USI)
Walls	347.3	11	1.94	0.52
Roof	170.1	19	3.35	0.30
South-Facing Glazing	13.8	2	0.35	2.84
North-Facing Glazing	0.0	2	0.35	2.84
East-Facing Glazing	13.8	2	0.35	2.84
West-Facing Glazing	13.8	2	0.35	2.84
Skylights	3.6	2	0.35	2.84

For the purposes of SHG calculations, all glazing units were assumed to have identical material and construction properties. SHGCs values, shown in Table 4, were sourced from the ASHRAE Handbook of Fundamentals for a double glazed, clear glass panes with a 12.7 mm air space – which is consistent with the actual glazing components present within the home.

Table 4. SHGC Values

Angle of Incidence [°]	SHGC
0	0.7
40	0.67
50	0.64
60	0.58
70	0.45
80	0.23
90	0
Diffuse	0.6

Lastly, to simplify SHG calculations, rough approximations were made quantifying the average angle of incidence and exposure to direct sunlight each glazing component is subjected to – these are summarized in Table 5. Even though south-facing glazing is usually subjected to the greatest amount of solar radiation during winter months (due to the low altitude of the sun), the percentage of exposure for these glazing units reflect the fact that they are largely shaded by surrounding vegetation.

Table 5. SHG Parameters

Months	Orientation	Average Angle of Incidence (°)	Exposure to Sunlight (% of daylight hours)
6,7,8	N	60	20
6,7,8	S	40	40
6,7,8	E	40	50
6,7,8	W	40	50
6,7,8	SL	80	70
12,1,2	N	80	10
12,1,2	S	60	30
12,1,2	E	70	40
12,1,2	W	70	40
12,1,2	SL	60	40
3,4,5,9,10,11	N	70	15
3,4,5,9,10,11	S	50	35
3,4,5,9,10,11	E	60	45
3,4,5,9,10,11	W	60	45
3,4,5,9,10,11	SL	70	55

5. HVAC Usage & Heat Transfer Breakdown

The constructed model was used to estimate the monthly heat gain and loss experienced by the home and the resulting energy required to maintain the temperature of the house year-round. Additionally, the model was used to compute a breakdown of each heat loss and gain component.

Figure 8 presents the modelled heat loss, gain and HVAC energy usage during each month of the year. Note that it is only the furnace usage (i.e., difference between the total gas usage and base load of 732.5 kWh) and cooling electricity usage (i.e., as used by air conditioning system) that is shown. Interestingly, we can see that the there is some minor heat loss in June since the average outdoor temperature (20.8 °C) is slightly lower than the assumed indoor temperature of 21.1 °C.

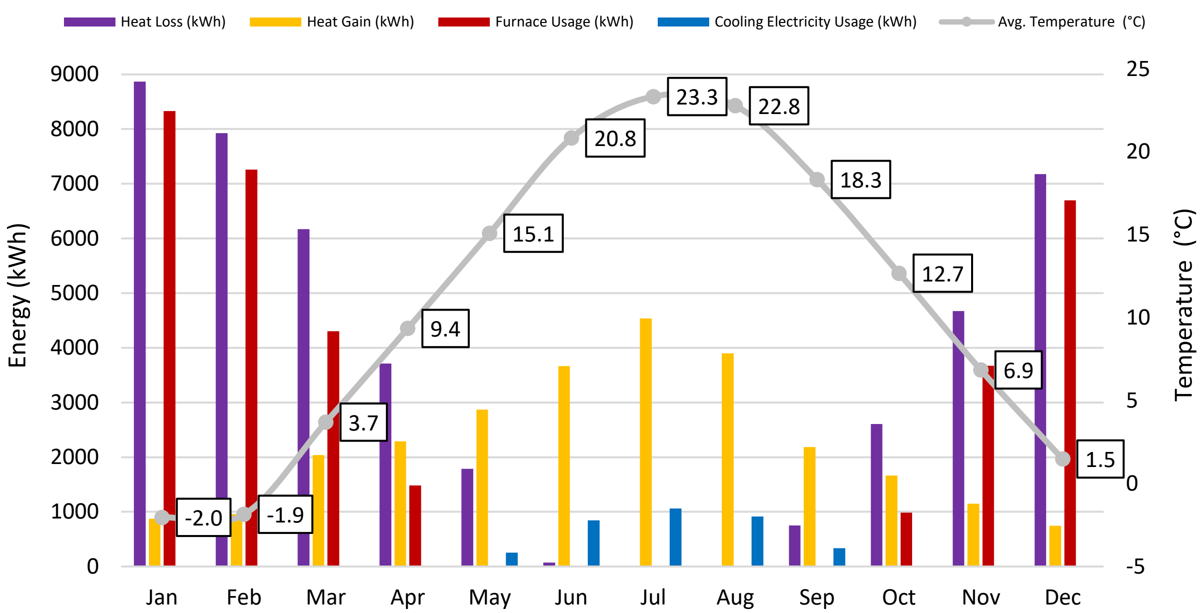

Figure 8. Modelled Monthly Heat Gain, Loss and HVAC Usage

Figure 9 shows the proportion of monthly heat loss owed to conduction and ventilation. Clearly, heat loss is dominated by conduction year-round, responsible for around 70% in the winter months and up to 99% of heat loss in June. Ventilation is still significant, responsible for 30% of heat loss in the winter months but with a contribution that wanes in the transition and summer months. The reason for the drop in ventilation's contribution is because the ventilated air flow rate is proportional to the pressure difference between the inside of the house and outside environment, which in turn is proportional to the temperature difference. In the summer months, the average temperatures are much closer to the interior temperature of the house, thereby significantly reducing the air flow rate and by extension, ventilation-based heat transfer.

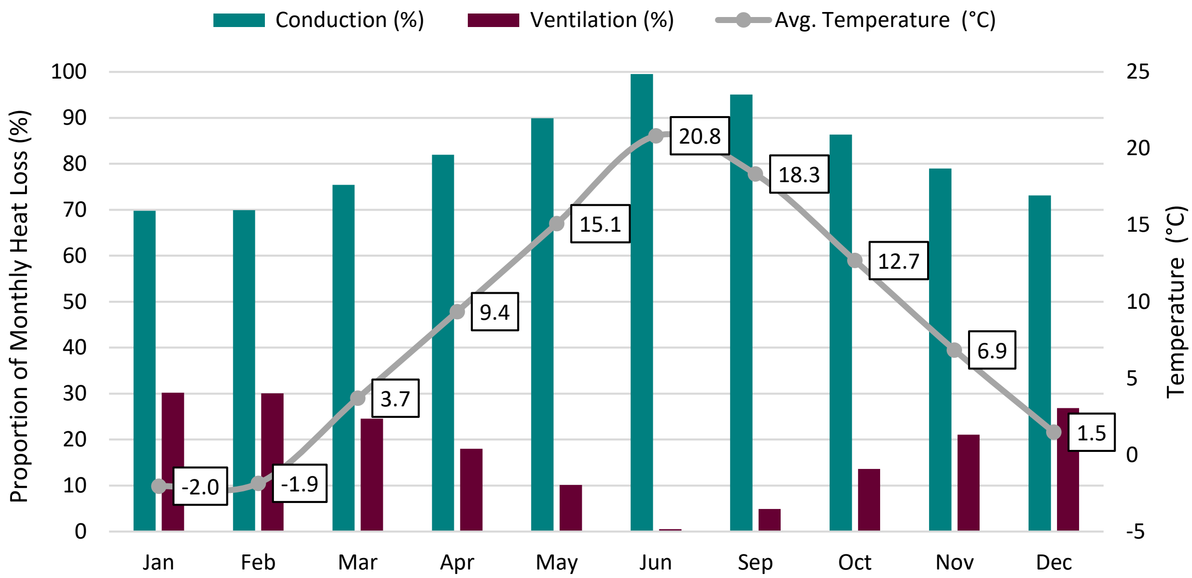

Figure 9. Contributions of Conduction and Ventilation to Monthly Heat Loss

In a similar vein, figure 10 presents the proportion of monthly heat gain owed to conduction, ventilation, and solar heat gain. Only July and August appear on this graph because they are the only months where the average temperature is higher than the assumed indoor temperature. In the months which are not shown on the graph, the heat gain is entirely solar, as this was assumed to be the only temperature-independent source of heat gain factored into the model. In reality, there would be other minor heat gains such as heat dissipated from electronics, appliances, and the residents of the home; however, compared to solar heat gain, these are all quite small. Heat gain is predominantly solar year-round, comprising a minimum of 88% of total monthly heat gain.

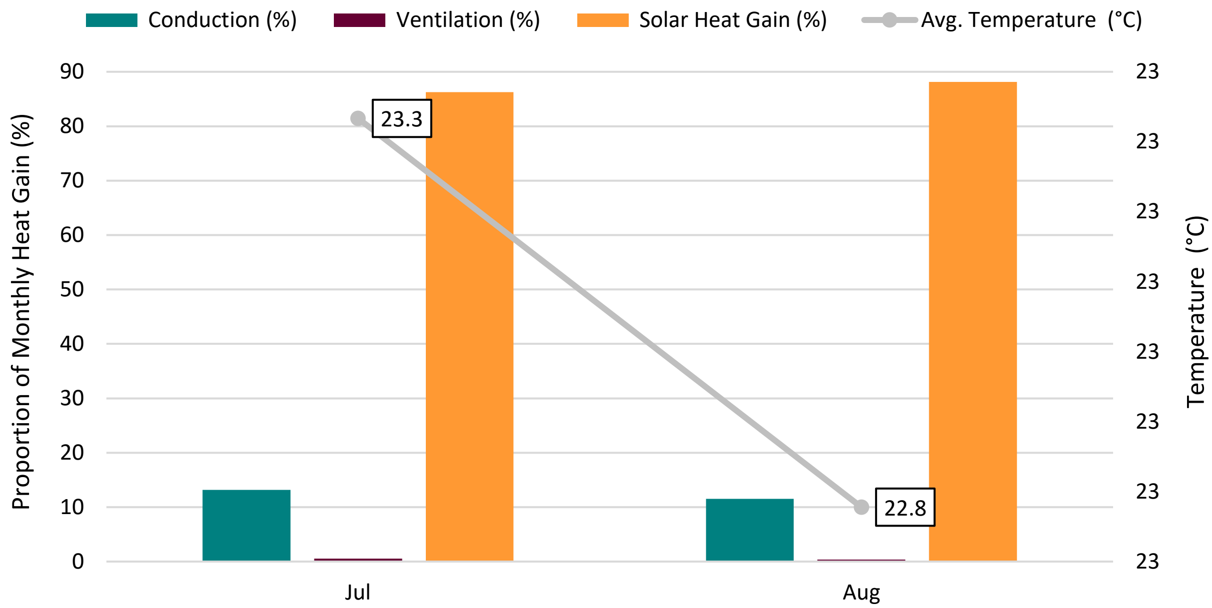

Figure 10. Contributions of Conduction, Ventilation and Solar Heat Gain to Monthly Heat Gain

Finally, figure 11 displays each building component's contribution to conductive heat transfer. While conductive heat transfer is itself temperature-dependant, the contribution each building component has towards conductive heat transfer is constant; only depending on the thermal transmittance and surface area of a given component. We can see that despite glazing components having the smallest total surface area, they comprise 36% of all conductive heat transfer because they are very poor insulators.

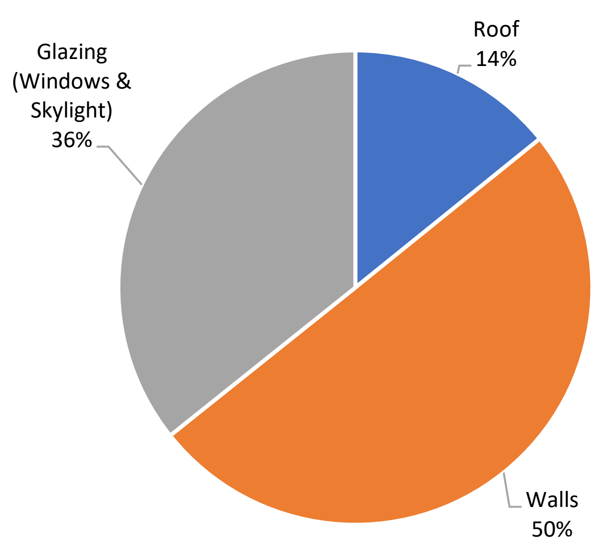

Figure 11. Conduction Contribution Breakdown

Considering the graphs shown in this section, we might think that enhancing the building's insulation and sealing leaks will have the biggest impact on reducing the amount of gas burned for heating, while making the glazing components more opaque (i.e., reducing SHGCs) will reduce the amount of cooling required. While there is some truth to that rationale, it is not that simple. More "efficient" glazing components are both better insulators and less conducive to solar heat gain which introduces an interesting dynamic during the winter months. Better insulated windows reduce the amount of conductive heat transfer while also reducing the amount of passive heating taking place due to the coupled reduction in solar heat gain. This is one of the main reasons the model was developed: in order to evaluate whether upgrading windows will have a net positive effect on reducing the heating load, and if so, by how much.

6. End-Use Breakdown

The model output, supplemental electrical load calculations and available utility data were combined to generate the end-use breakdown presented in this section. Figures 12 and 13 showcase the estimated energy usage and cost contribution attributed to various sources, respectively. This breakdown employs the average annual electricity usage from the utility data (since the model does not compute this quantity) and the modelled annual gas usage.

In addition to heating and cooling energy consumption, the presented end-use breakdown includes estimates for three significant electrical loads, namely, the electricity consumed by the HVAC system's draft inducer (blower fan), lighting and the hot tub. These loads were selected for analysis as they are the only ones which could be practically estimated given the limited time for on-site measurements.

A single draft inducer and ductwork system is used to supply conditioned air to the home. It is fair to assume that whenever the HVAC system is active, so is this fan. Knowing the heating and cooling capacity, efficiency, COP, and annual usage of both the furnace and AC system, the draft inducer's annual electricity consumption can be estimated by multiplying the total HVAC system on-time by the draft inducer's rated power, as follows:

$$E_{draft\ inducer,annual} = (\frac{32{,}729\ kWh \cdot 0.96}{31.94\ kW} + \frac{3407\ \mathrm{kWh} \cdot 4.2}{17.48\ kW}) \cdot 0.559kW = 1008\ kWh/yr$$

The lighting electricity usage was estimated by multiplying each bulb's power usage by an estimate of yearly on-time; it was assumed that lighting on-time is inversely proportional to the average number of daylight hours in a particular month.

To estimate the annual electricity consumption of the hot tub, we assume that its heater and pump operate simultaneously for an average of 3 hours per day. Knowing the hot-tub is kept operational year-round, we can estimate its electricity consumption by multiplying the heater and pump power usage by its yearly on-time (in hours).

$$E_{hot\ tub,annual} = (4\mathrm{kW} + 6\mathrm{kW}) \cdot 3\mathrm{h/day} \cdot 365\ \mathrm{days/yr} = 6570\mathrm{kWh/yr}$$

While 3 hours of on-time per day may seem high, this estimate was made considering the fact that the hot tub is located outdoors and as such, loses a significant amount of heat during the winter months. That being said, the reported electricity consumption associated with this load should be taken as a very rough estimate which simply illustrates that hot tubs can have significant impacts on electricity usage and cost. Additionally, the associated cost is highly dependent on what time of the day the heater is turned on (off vs. on-peak); however, the associated cost shown in the breakdown was computed using the average annual electricity rate from the past three years.

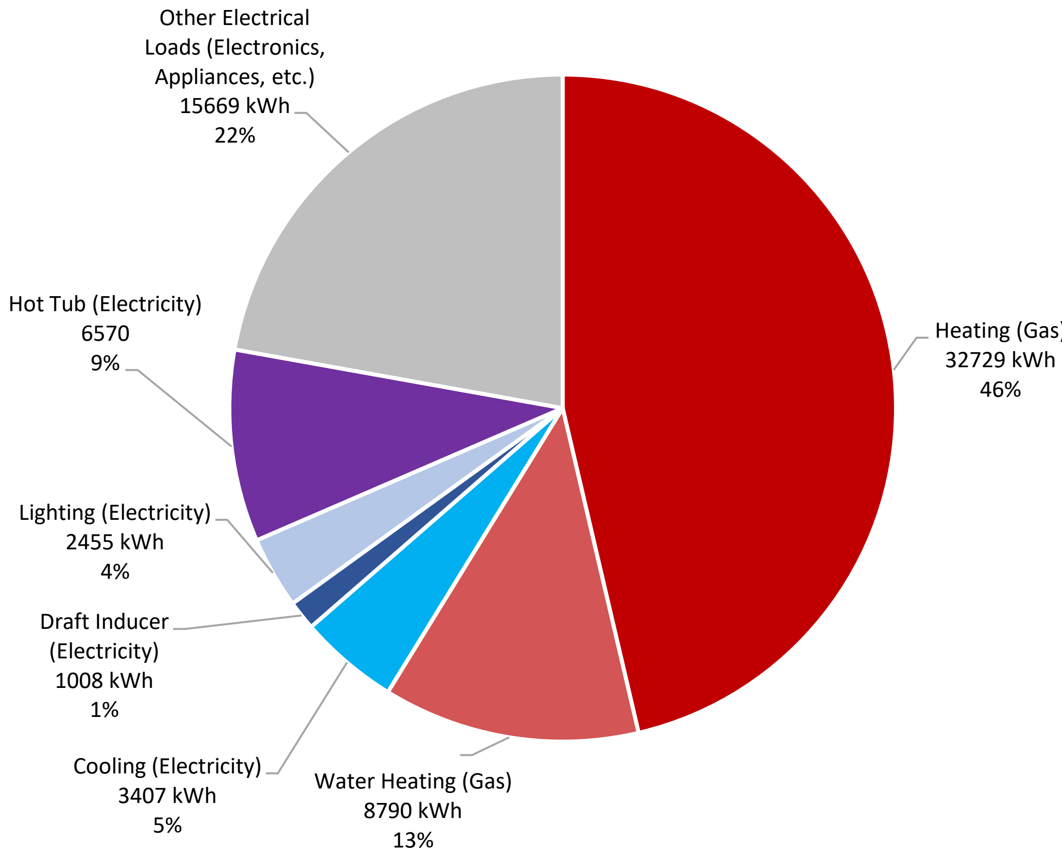

Figure 12. Modelled Energy Usage Breakdown

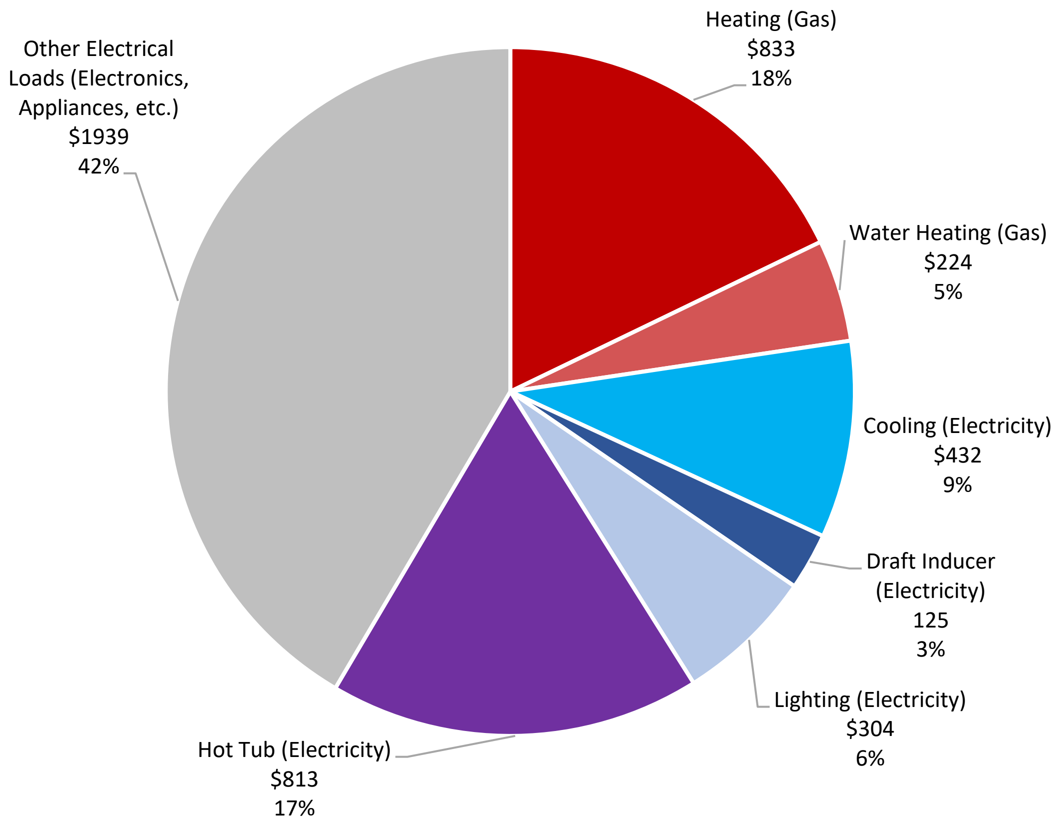

Figure 13. Modelled Energy Cost Breakdown

7. Investigation of Potential Home Improvements

In this section, we explore the impact various home improvements may have on the home's energy use and cost. To achieve this, the model was supplied with updated building parameters (e.g., reduced ventilation heat transfer factor, lower thermal transmittance values for building components, etc.) and the output usage and cost data were compared to the base model representing the home in its current state. It should be noted that each improvement was investigated separately (i.e., only the model parameters relating to a single improvement were changed at a time). Through this comparison, reductions in gas and electricity usage as well as cost could be quantified.

The first improvement under consideration is the sealing of air leaks. By minimizing the amount of air that leaves or enters the home from the external environment, the heating and cooling load placed on the furnace and air conditioner can be significantly reduced. Common areas where minor to medium-sized air leaks occur include windows, doors, outlets, and where walls meet the ceiling. Such leaks can be identified using the Blower Door test or thermal imaging, for example, and are often inexpensive to fix using weather stripping and or caulk. For the purposes of this investigation, we'll assume that \$1000 can be spent for a combination of a leakage-identification audit, sealing materials and labor, and will result in a 20% reduction of the Blower Door number, resulting in a proportional reduction of the base ventilation heat loss factor) — as is typical for sealing most minor and medium sized leakage zones.

The model predicts that a 20% reduction in ventilation-based heat transfer yields a 5.3% reduction in annual gas usage and a negligible impact on cooling electricity usage. The lack of impact on cooling usage is consistent with the findings from section 5. The reduction in gas usage – coupled with the reduced usage of the draft inducer – results in approximately \$60 of annual savings, meaning the payback period for this improvement is around 16 years.

Another common home improvement we can consider is the use of blown-in roof insulation to stifle heat loss. For the purposes of this investigation, it is assumed the entire roofed section of the house receives additional insulation, either by laying down insulation on the attic floor or by drilling. It is also assumed that the total surface area of additionally insulated space equals the total exterior roofed surface area. If 12 inches of blown-in cellulose insulation were employed (R-42), that could raise the roof thermal resistance to a value of R-61. Assuming an installed cost of about \$2.80 per square foot, the total cost of this improvement would be about \$5127. Interestingly, if the roof's insulation was raised to R-61, the model predicts the gas usage would be reduced by nearly 8% while cooling electricity usage would be raised by around 1%. The increase in air conditioning usage is due to reduced heat loss during the transition months – namely in May and September – not offsetting solar heat gain, resulting in a net heat gain which must be met by the air conditioner. Factoring in the reduced gas, increased air conditioning, and reduced draft inducer usage, this home improvement is predicted to save around \$85 annually resulting in a 60-year payback period.

The final home improvement under consideration is a complete window retrofit. Replacing all 45 windows with double pane, low-e coating, argon-filled units would cost around \$45,000, including material and labor costs (\$8,000-\$11,000 is a typical range to replace 10 windows in a home). These improved windows would have a thermal resistance of R-4, and solar heat gain coefficients which are roughly half that of the existing glazing components. Given these parameters, the model predicts a 1.4% reduction in gas usage and a 50% reduction in cooling electricity consumption. As we may have expected, this home improvement has some unintended consequences, namely, in months like March and April when the temperature is low and there is significant solar radiation, these glazing units would reduce passive solar heating, thereby increasing the load on the furnace. In the summer months, when there is no or minimal heat loss, the improved windows greatly reduce the amount of solar heat gain and thus reduce the cooling load on the air conditioner. The combined reduction in gas and cooling electricity usage, along with the reduced usage of the draft inducer, would save around $285, resulting in a payback period of 158 years.

8. Conclusions & Recommendations

Given their exceedingly long payback periods – some of which exceed a human lifetime – none of the common home improvements considered in section 7 seem particularly promising. That being said, there are hidden costs and factors which should be taken into account when deciding whether or not to pursue one of these home improvements.

For instance, sealing air leaks and enhancing the roof insulation may result in significant improvements to thermal comfort. Air leaks tend to introduce cold, dry air into homes during the winter, and hot, humid air during the summer – both of which can degrade the comfort of the occupants. Given the residents reported uncomfortable temperatures on the second floor, perhaps installing additional insulation on the roof may help regulate this floor's temperature, thereby improving thermal comfort throughout the year.

There might also be substantial tax breaks associated with reducing energy – particularly gas – consumption. Sealing air leaks and improving roof insulation were estimated to result in a combined 13.3%, or 5400kWh, reduction in gas usage and by extension greenhouse gas emissions; if such a reduction were to save the homeowner a few thousand dollars in taxes, this would make such home improvements far more tenable from a financial perspective.

This energy audit revealed that the home's high energy costs mostly stem from electricity usage. If costs are to be aggressively reduced, the home's electricity usage must be directly addressed. The lighting usage reported in this audit is likely an underestimate since the residents' habits of leaving lights on during the day weren't accounted for. There are many inexpensive lighting automation solutions which turn a home's lights off and on at specified times of the day. Considering the number of lights in the home, it might be a wise decision for the homeowners to invest in such a solution to reduce lighting-related electricity consumption without requiring any major changes to their habits. It is also worth noting that most of the lighting-related energy consumption comes from the inefficient lamp bulbs, so it might be worth gradually replacing all the bulbs in the house with LEDs.

A massive contributor to energy consumption identified in this audit was the hot tub. It is likely that many homeowners don't fully appreciate how energy intensive operating a hot tub can be, especially in cold climates. Although the values provided in this report are rough estimates, emptying out the hot tub for half the year is estimated to save $400 in annual electricity charges; nearly as much as all the investigated home improvements combined. As such, it would be advisable for the homeowner to consider only having the hot tub operate for the portion of the year where it is most likely to be used.

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