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Minimizing Space Heating Energy Requirements in the Residential Sector

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Executive Summary

This paper is motivated by a need to reduce energy demand on the main utility grid and alleviate energy consumption from non-renewable sources.

A case study was undertaken on a Canberra household's heating system with the aim of improving the home's energy efficiency, with a strong focus on thermodynamic analysis.

In addition to the obvious cost and energy factors involved, this report applies analytical methodologies to other aspects such as a materials audit, queue theory, dynamics and control analysis, and a public survey to provide a comprehensive assessment of the system, pinpointing opportunities for improvement with respect to cost and energy usage.

Through these methods the ideal ambient temperature for thermostat setting is determined, and the most cost effective solutions to minimize heat loss to the outside. A number of other improvements are suggested to maximize the operating efficiency of the heater itself.

The proposed improvements in this report culminate in an increase in energy efficiency, leading to a reduction in annual energy usage and an annual energy cost saving that has a pay back period of just a few years. As well as the quantifiable benefits, the improved system will provide a more comfortable living experience and better quality of life for the residents.

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1. Introduction

With the residential sector accounting for a third of global energy consumption *(Isaac and van Vuuren, 2009),* and with more than half of this energy being pumped into space heating systems (*IEA, 2004*), there is a notable opportunity to reduce non-renewable energy consumption by improving residential space heating energy requirements.

Despite the introduction of minimum shell performance standards in Australia, the energy consumption for space heating is projected to increase by 2020, due to an increase in the share of dwellings with whole house heating systems, and an increase in floor area per occupant (*Energy Efficient Strategies, 2008*). Thus it is imperative that opportunities to improve efficiency and minimize household heat loss be identified and acted upon.

By applying systems analysis techniques in conjunction with thermodynamic theory to a case study, it is hoped that the methodologies documented in this paper will provide a means to identify inefficiencies in any household heating system.

In addition to proposing a number of improvements to the system, this paper will asses the economic and environmental implications of the proposed solutions so as to equip the reader with all the knowledge required to make similar assessments and decisions on improving a home's heating energy efficiency.

2. Preliminary Research

A survey was conducted to determine how residents felt about their heating situation. 190 responses were received, and the data is summarized in table 1.

Table 1. Summarised Survey Responses

Heating Type	% Residents Using Type	Temperature Setting	Most Reported Best Aspect	Most Reported Worst Aspect	Average Performance Satisfaction (1-5)	Average Cost Satisfaction (1-5)
Closed Gas Burner	5.6%	23	Fast	Single Room Only	3.43	2.71
Ducted Electric (FAH)	6.5%	19.71	Fast , Heats Whole House,	Uneven Heat Distribution	3.57	2.86
Ducted Gas (FAH)	32.4%	20	Fast, Heats Whole House	High Cost, Temperature Fluctuates, Noise	3.87	2.56
Open Fire	2.8%		Ambience, Low Cost	Maintenance	2.66	1.66
Portable Electric	9.3%	23.8	Fast, Portable, Consistent	High Cost, Slow, Inefficient	3.09	1.82
Radiator	4.6%	22.58	Efficient, Low noise, Low cost	Slow, Single Room Only	3.57	2.86
Reverse Cycle (Electric)	21.3%	22.1	Fast, Efficient, Dual purpose	High Cost, Single Room Only	3.92	2.96
Slow Combustion Wood Burner	9.3%		Ambience, Low Cost	Maintenance	3.9	3.9
Other	7.4%	20.87	Low Noise, Fast, Timer	High Cost	3.5	2.5
Don't Know	0.9%	-	Heats Whole House	Faulty Thermostat	4	2
Total		21.14			3.7	2.7

The purpose of the survey was to produce qualitative data regarding various heating types, and to observe any trends or links between the type of heating, construction type, and the satisfaction of the user, including strong attributes and weak attributes of each system.

On scale of 1 to 5, with 1 being least satisfied, and 5 being most satisfied, the percentage of respondents that rated the performance and cost satisfaction of their heating system below 3 was 11% and 44% respectively, with 64% rating above 3 for performance, and just 24% rating above 3 for cost satisfaction. The remainder indicated a neutral satisfaction rating of 3. This shows that residents are overall happy with the performance of their systems, but unhappy with the operating costs.

The most satisfied users are those with slow combustion wood burners. The primary benefits of these systems are the ambience and the low cost of running them. Respondents with this type of system indicated that the maintenance factors were the worst aspect, which includes gathering/chopping wood, and the regular cleaning required.

The most prevalent system is a ducted gas, or forced-air heating (FAH) system, with 32% of residents using this system. While the benefits of a ducted system are that it is fast to heat up the home, and heats the entire house, respondents indicated that they were costly to run, the temperature tended to fluctuate, and that the heat distribution was uneven.

In addition to the strength and weaknesses, and satisfaction rating, data was collected about the construction of the respondents' homes. In particular, details on wall construction, window and floor type, insulation configuration, and foundation type were gathered.

Figure 1 shows the satisfaction ratings of respondents with respect to construction type.

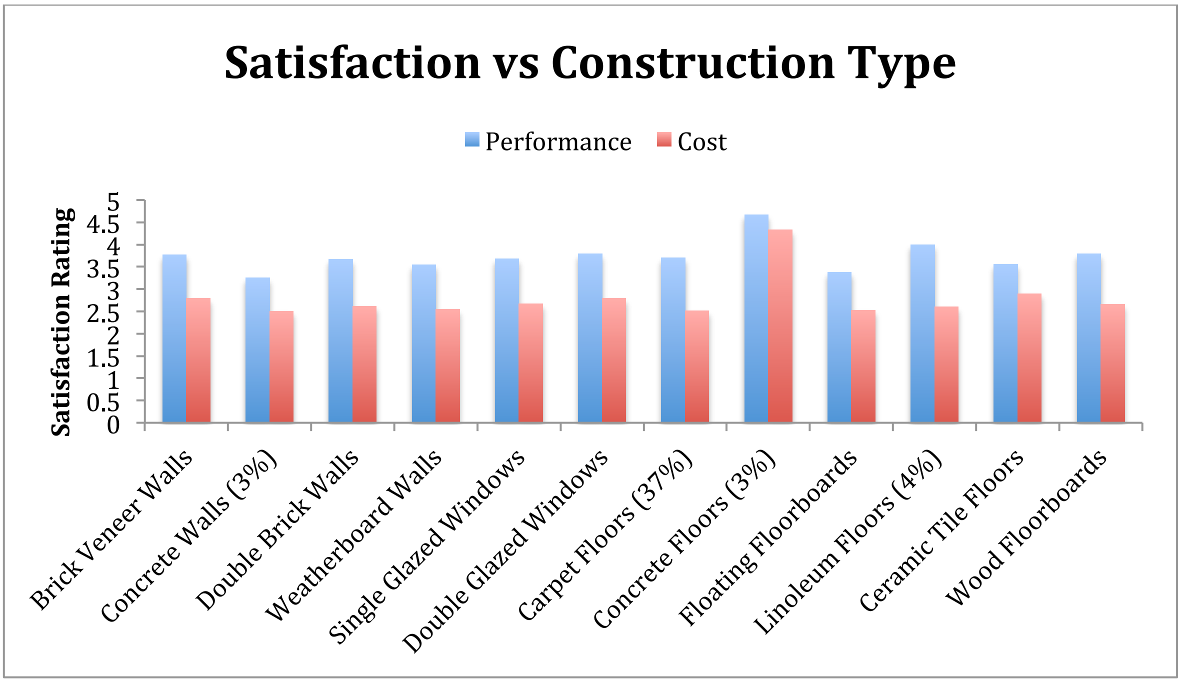

Figure 1. User satisfaction ratings with respect to construction type.

We can see from the figure 1 that when considering construction type, the performance of the system is correlated with the cost satisfaction. This indicates that construction type has an influence on both the cost and performance of the system. This may be because the insulative properties of the construction materials used directly affect how long heat is retained within the home, which makes a heating system appear to perform better, and also reduces energy expenditure. This is a reflection of the fact that as the thermal conductivity, or U-value, of the construction materials increases, so does the energy usage of the home (*Petersen et. al, 1981*).

While the cost satisfaction for linoleum flooring doesn't necessarily correlate with performance satisfaction, it should be noted that sample size for this type was very small, so this figure may not be an accurate reflection of the performance of these materials.

Apart from high running costs, the major complaints across the entire sample were an uneven heat distribution for multi-story houses, the inability to heat the entire home for technologies such as burners or reverse cycle systems, the inability to set different temperatures in different rooms, also known as zoning, and other control issues, such as a fluctuation in temperature and placement or accuracy of thermostat.

3. Human Factors

Beyond basic survival needs, a heating system is designed specifically for human comfort. It is therefor an essential requirement of such a system to consider human factors in any design improvements.

There have been a number of studies into predicting the neutral temperature for human thermal comfort, and a number of models have been proposed. Since perceived temperature is influenced by recent temperature history, such models must take into account not only the external temperature, but also previous days' external temperatures.

One such model is proposed in a study by Peeters et. al (*2009*), and derives the mathematical model for neutral temperature in rooms where office-like activities are undertaken as:

$$T_n = 0.06T_{e,ref} + 20.4°C \quad for \quad T_{e,ref} < 12.5°C$$

$$T_n = 0.36T_{e,ref} + 16.63°C \quad for \quad T_{e,ref} \geq 12.5°C$$

Where $T_{e,ref}$ is defined as:

$$T_{e,ref} = \frac{T_{today} + 0.8T_{today-1} + 0.4T_{today-2} + 0.2T_{today-3}}{2.4}$$

Where T_{today} is the arithmetic average of the maximum and minimum external temperatures of the current day, and $T_{today-n}$ is the arithmetic average of maximum and minimum external temperatures of preceding days.

If we apply this model to Canberra temperature data provided by the Australian Bureau of Meteorology (BOM) for the months of June, July, and August 2015, we find that the average neutral temperatures are 20.81°C, 20.73°C, and 20.81°C respectively.

During sleep, when residents have added thermal protection, the ideal neutral temperature is lower. The world health organisation advises a lower bound on sleeping temperatures of 16°C, as resistance to respiratory infection reduces below this temperature (*Collins, 1986*).

Acceptable temperature variation is another human comfort factor to consider. It is difficult to maintain neutral temperatures consistently, since a household is a dynamic system. Influencing variables of the system include external temperature, internal heat gains, and ventilation rates, all of which can are often constantly changing *(Peeters et. al, 2009)*. In addition, many forced air heating systems, particularly older systems, use only a single stage fan, so can only pump heated air into a room at a certain rate. This type of system must cycle on and off to maintain an average temperature, which the user sets. These systems inherently involve temperature fluctuations, and it is shown by Peeters et. al that there is a limit to the variation in temperature beyond which a person will feel uncomfortable. The formula derived in Peeters' study for the maximum allowable temperature variation is given as:

$$T_{upper} = T_n + \alpha w$$

$$T_{lower} = T_n - w(1 - \alpha)$$

Where w is the is the width of the comfort band, which is agreed to be 5°C as shown by a number of independent studies *(de Dear and Brager, 1998, van der Linden, 2006, Oseland, 1994)*, and α is a constant that accounts for the fact that humans are more sensitive to colder temperatures than hotter temperatures. In the study α is calculated to be 0.7 *(Peeters et. al, 2009)*.

Using these values, the average ideal temperature variation for the months of Jun, July, and August, 2015, is calculated to be 19.28°C to 24.28°C, with the ideal neutral temperature at 20.78°C. The neutral temperature agrees with the survey results from the previous section.

Since most people set their thermostat close to the recommended lower bound, there is no real opportunity to reduce energy expenditure by reducing thermostat temperature.

A number of other behavioral factors also influence the energy usage for heating of a home. For example, thermostat type plays a significant role in the amount of energy used. For energy conscious households, systems that require active involvement tend to lead to a reduction in energy cost, where as energy-complacent households tend to conserve more energy with a system that requires less active involvement (*Santin, 2011*).

In general, programmable thermostats tend to lead to greater energy usage, because they are set for time-periods when the home might be occupied, as opposed to manual thermostats, which are set when the home is definitely occupied (*Santin, 2011*). However, in the survey in the previous section, many of the respondents indicated that the programmability of the thermostat was the strongest aspect of their system, reporting that being able to wake up to a warm home was an important feature of the system.

A potential solution to this compromise would be to have a Wifi connected system that connects to a user's smartphone and is able to detect when the occupants are at home in the early morning before the wake-up period, only switching on when the home is occupied. Such a system could also potentially use a smartphone's GPS capabilities to track speed and position, then switching the heating on only when an occupant is approaching home.

4. Energy Factors

To estimate the energy flow of a residential forced air heating (FAH) system, a case study was performed, applying a simplistic thermodynamic analysis to a residential house in Canberra. The characteristics of the house can be seen in table 2.

Table 2 Case Study House Characteristics.

House Type	Single Story Freestanding House
Heating Type	Ducted Gas (FAH)
Heat System Output	20kW
External Wall Construction	Brick Veneer
Window Type	Single Glaze
Insulation Configuration	Roof Only
Floors	Floating Floorboards in Living Area, Tiles in Hallway, Carpet in Bedrooms
Base	Concrete Slab
Window Area	21.56m^2
Floor Area	79.75m^2

The heating system used has a maximum gas input 33.33kJ/s and a maximum heat output of 20kW, giving an efficiency of 60% (*Brivis, 2013*) after flue losses.

Additional losses occur through the distribution ducts, and can range from 25-40% in a roof cavity installed venting system, depending on the condition of the ducts. Assuming an insulation value of R-4, and 15% air leakages, a fair estimate is 30% heat losses through duct walls (*Andrews, 2001*).

The heat losses in Watts, H, from the household to the external environment can be found using the following equations:

$$H = H_t + H_v + H_i \qquad (1)$$

H_t = heat loss due to heat transmission through external surfaces, H_v = heat loss caused by ventilation, H_i = heat loss caused by infiltration. The house is not ventilated, so only H_t and H_i apply, which are given as:

$$H_t = AU(t_i - t_o)$$

$$H_i = c_p \rho n V(t_i - t_o)$$

Where A = exposed surface area, U = overall heat transmission coefficient of the wall (W/m^2K), t_i = inside air temperature, t_o= outside air temperature, c_p = specific heat capacity of air (J/kgK), ρ = density of air (kg/m^3), n = number of air exchanges per second (assumed to be 1.4x10^-4/s), and V = total volume of the house (m^3) (*The Engineering Toolbox, n.d*).

An online calculator was used to find the U-value of each material (*Eco,Who, n.d*), and other thermal properties were researched or calculated from thermodynamic principals. Using the given house's dimensions with these values, the Sankey Diagram in figure 2 was generated to show the energy flow during heating.

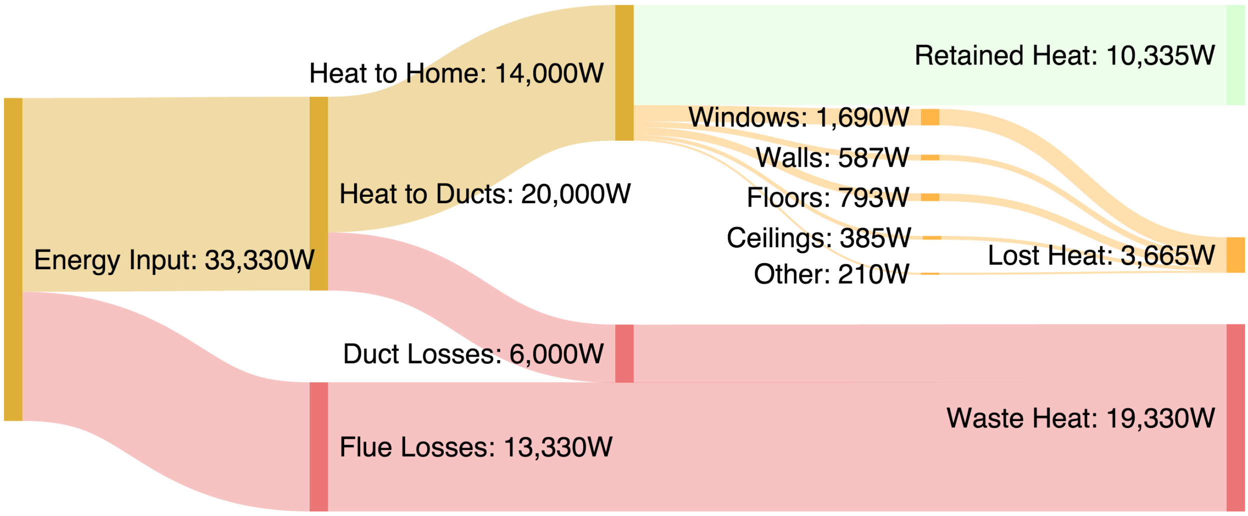

Figure 2. Sankey diagram of household space heating energy flow during operation

In the thermodynamic model used, the system was assumed to be operating at night, and that all heated rooms were at an average of 21°C, with an external temperature of 7°C, and a utility room (unheated) temperature of 16°C. An average soil temperature of 13°C was based on data from the Bureau of Meteorology *(Australian Bureau of Meteorology, 2015).*

As well as duct losses, we can see that a significant amount of energy is immediately lost through flue losses. A portion of this heat could be recovered using a heat pump. If an exhaust gas temperature of 55°C is assumed, and an indoor temperature of 21°C, the maximum theoretical efficiency of the heat pump can be calculated using the following formula:

$$\gamma = \frac{T_H}{T_H - T_C} = \frac{328.15°K}{328.15°K - 294.15°K} = 9.65\%$$

In reality, thermodynamic inefficiencies within the system would result in a slightly lower efficiency. A study on optimisation of a cogeneration power plant reports a flue heat recovery efficiency of 7% (*Blarke and Dotzauer, 2011*), which can be assumed to be similar for a home flue recovery system. This would allow an additional 650W to be redirected to the household after duct losses.

We can also see from figure 3 that nearly 50% of the energy lost from the heated space is lost through the windows, and 40% through the floors and external walls. Very little purchased gas energy actually goes into heating the home after these losses. It is clear that one of the greatest opportunities to reduce energy use is to improve the insulation of the home, thereby reducing the amount of energy required to heat the space from one temperature to another.

There are several solutions to improve household heat retention, which include fitting double-glazed windows, installing wall insulation, carpeting uncarpeted areas of the home (where appropriate), and hanging close-fitting roller blinds in all windows.

The most effective solution is to retrofit double glazed windows into all window openings. While expensive, this has the potential to decrease thermal conductivity to as low as 2.7 W/m^2K, from the current value of 4.8 W/m^2K (*Pilkington UK Ltd., n.d.*), nearly halving heat losses through windows.

A less effective, but still significant solution is to fit all window openings with roller blinds, which have the potential to reduce heat losses by up to 28% compared to single pane windows (*Clark, 2009*). A conservative estimate would be 20% reduction in U-value.

Wall insulation, if using R3 insulation bats, would result in a reduced U-value of 0.271kW/m^2K. Again, this effectively cuts losses through the walls by more than half.

The final proposed solution is to increase the insulative properties of the floor by using carpet in the main living areas, which are currently a combination of floating floorboards and tiles. This modification will reduce the thermal conductance through the floor from around 1 W/m^2K to 0.3 W/m^2K (*Cyberphysics, n.d.*), cutting heat losses through this floor area by 70%.

To analyse the effect of these modifications on annual energy expenditure, it is necessary to introduce the concept of average annual heating degree-days. This is the summation of the number of degrees that the average daily temperature is below the desired comfort level for the entire year. For example, if the average temperature on a given day is 2 degrees lower than the desired comfort temperature, this equates to 2 heating degree-days.

In addition, the first law of thermodynamics is employed, which states that for a closed system, heat entering the system must equal the heat leaving the system for the temperature to remain constant. Therefor by calculating the heat lost from the system during heated periods, we can calculate the required input energy to maintain comfort levels.

With a base comfort temperature of 21°C during waking hours, and using temperature data from the Australian Bureau of Meteorology, the number of heating degree-days for Canberra in 2014 was 2545 (*Australian Bureau of Meteorology, 2015*). For sleeping periods, a base comfort temperature of 16°C is used, resulting in 1303 heating degree-days.

Using equation (1), the heat loss per heating degree-day is calculated, accounting for the fact that ideal comfort temperatures are only maintained for part of the day. This gives the energy loss per day with a one degree difference between the average inside and outside temperatures. Thus, to calculate total annual energy requirements, the heat loss per degree-day is multiplied by the number of degree-days in the year, taking into account the number of hours per day heating is required. This methodology is adapted from that used by R. Nave of Georgia State University (*n.d.*).

Table 3 shows the resulting reduction in annual energy requirements for each proposed modification, taking into account the furnace efficiency.

Table 3. Comparison of annual energy requirements with each modification

	Unmodified	Double Glazing	Wall Insulation	Roller Blinds	Carpet	All	All But Windows
Annual Energy (GJ/year)	70.4	58.9	65.3	63.1	54.3	33.4	42.0

The cost of each solution and combination thereof is assessed later in this report, and compared against the resulting energy savings incurred.

5. Dynamics and Controlling Factors

When considering the dynamics of a FAH system the major controlling factor is the thermostat, which receives input from the user. This type of system can be described as a basic feedback loop as shown in figure 3.

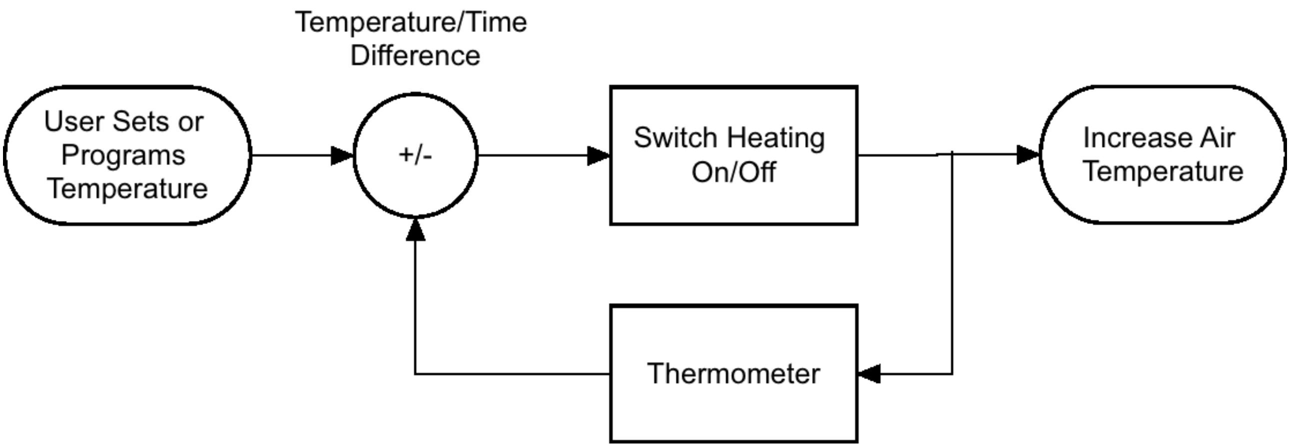

Figure 3. Basic feedback control loop for thermostat controlled heating system.

There are, in fact, a number of controlled feedback loops occurring. One within the thermostat controller itself that takes a user input, measures household temperature and initiates the heating cycle, and another in the actual heating unit that takes input from the controller to switch on or off, and a third that measures the temperature of the furnace, and initiates fan operation once the furnace is hot enough. These last two are subsystems of the heaters switching system.

Most modern heating controllers offer programmable heating patterns, which add an additional sensor channel to the system in the form of a clock. However as noted previously, it has been observed that programmable thermostats actually tend to increase energy consumption when compared to manual thermostats. With a programmable thermostat, the lack of user input generated by user complacency results in unnecessary energy expenditure. The solution to this would be to incorporate a 'smart' thermostat, removing the need for the user to program the schedule.

One such system currently on the market is the Google Nest Learning Thermostat. This product incorporates multiple temperature sensors, motion and light sensors, a humidity sensor, and Wifi connectivity. It is controllable through a web-server from any mobile device so can be managed remotely (*Crawford and Johnson, n.d*). Whilst the basic feedback loops is similar, there are additional sensor channels and a history monitor to learn and predict the user's behavioral patterns and heating preferences. The system uses this information to program the most energy efficient heating schedule for the user's needs, heating the home only when it is occupied, lowering thermostat temperatures during daily peak external temperatures, and scheduling preferred heating patterns throughout the week.

Nest Labs claims that across 3 case studies of homes using the Nest, energy savings for heating were found to be similar at around 10-12% (*Nest Labs, 2015*). A study of a similar technology, called the Neurothermostat, applies theoretical analysis and modeling using test data and real world occupancy behavior data to predict the savings of such a system. This study predicts savings of around 36% (*Mozer et. al, 1997*). While the Neurothermostat offers a much greater efficiency, these results are modeled by a simulation, so are perhaps not as reliable as the Nest Labs case study. However, it's reasonable to suggest that an energy savings of 15% is achievable if such a system were introduced to the case study home.

As an addition to this type of system design, it is suggested that the system utilize the Wifi connectivity of the smart thermostat to monitor the movement patterns of the occupants via their mobile devices or an optional GPS tracker to predict when the occupants are returning home. This would have the added benefit of being able to account for anomalies in regular behavioral patterns. For example, if on a certain evening the adaptive learning algorithm predicts the user to return home at a certain time, but the user is in fact returning later, the thermostat could refrain from switching the heating on until such time that the user is within 5km of home. This is estimated to save an additional 1-2% energy. The implementation of this system could be incorporated into the mobile app that is already available for the Nest, and so can be absorbed into the capital costs.

Another control system improvement that can reduce energy consumption is a multistage furnace with zoning capabilities. Such a system could heat the home to the desired temperature, and then maintain it with a lower airflow rate, giving a very narrow temperature band and minimizing furnace efficiency.

A narrow temperature variation band would allow the used to set a lower thermostat temperature, resulting in less energy usage overall. The reduction in cycling frequency would also mean that the heater system spends less time in start-up and shut-down periods, and more time operating at maximum efficiency. The zoning ability would allow the user to heat only those rooms that are occupied, reducing the overall heating requirements of the home.

Such an improvement would require a completely new heating system to be installed, where as this report is focused on improving the existing system, and so the cost and energy implications of such a system will not be analyzed further in this report.

6. Cost Factors

Residential ducted heating heating systems require high-energy inputs to maintain comfortable ambient temperature levels, which contribute the majority to life-cycle costs of the system. Analysing energy prices can provide insight into the potential lifecycle cost savings that could result from implementing the recommended solutions.

According to a number of studies, liquefied natural gas (LNG) supply prices for Sydney are set to spike with in the next 5 years (*Lewis, 2014, Department of Industry and Bureau of Resources and Energy Economics, 2013*). In general however, gas prices have been increasing over the last 25 years exponentially.

Figure 4 shows the relative increase in natural gas prices since 1990/1991.

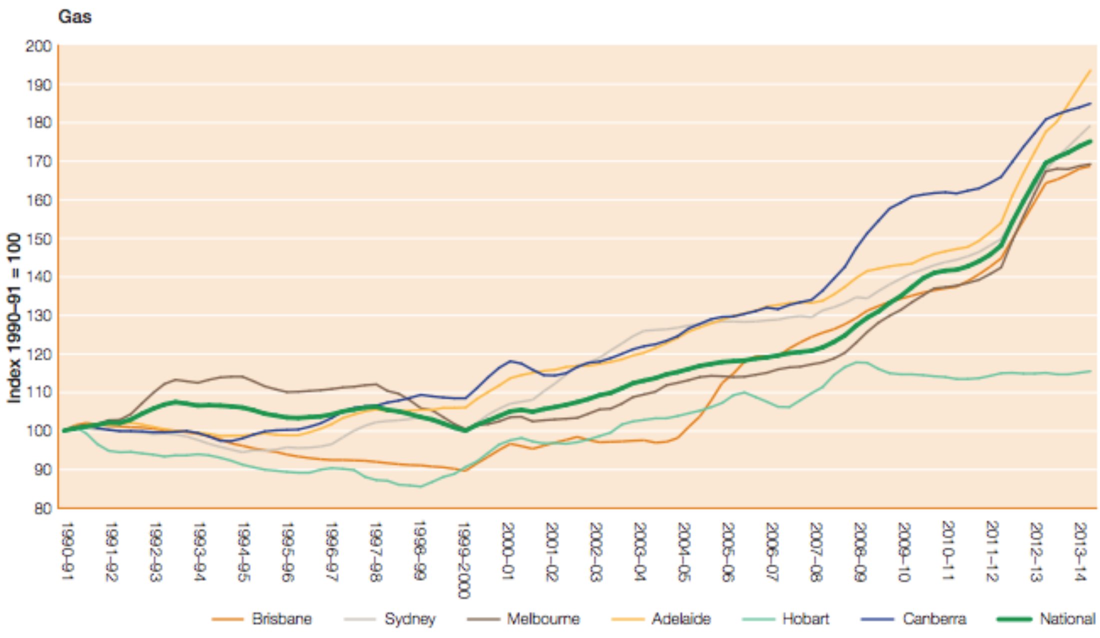

Figure 4. Natural gas price trends 1990-2014 for Australian capital cities (AER, 2014)

Extrapolating the trend line to 2040 gives an energy cost of $0.0712/MJ, which is 265% higher than current the current cost of $0.0285/MJ. This figure is considered to be a reasonable estimation when compared to other predictive studies, such as those on the US energy market, which predict an LNG cost increase of as much as 300% in an extreme case scenario (*EIA, 2015*).

To calculated a payback period for each solution, we analyse heating requirements of each solution as shown in the previous energy analysis, and calculate the lifetime costs of running the system based on average LNG prices over the next 25 years. Initial capital investment costs are based on market research. Table 4 below shows the cost implications of each solution.

Table 4. Cost breakdown of thermal insulation solutions

Modification	Capital Cost*	Operational Cost	Savings	Payback Time
Current Model	$0	$3,270/year	-	-
Double Glazing	$11,210	$2,740/year	$530/year	21 years
Wall Insulation	$800	$3,040/year	$320/year	4 years
Roller Blinds	$600	$2,940/year	$330/year	2 years
Carpet	$3,020	$2,530/year	$740/year	4 years
Smart Thermostat	$340	$2,590/year	$680/year	0.5 years
All	$17,750	$1,260/year	$2,010/year	9 years
All but Double Glazing	$4,760	$1,580/year	$1,690/year	3 years

**A table of quote sources can be found in the appendix of this report.*

Figure 4 visualizes these results.

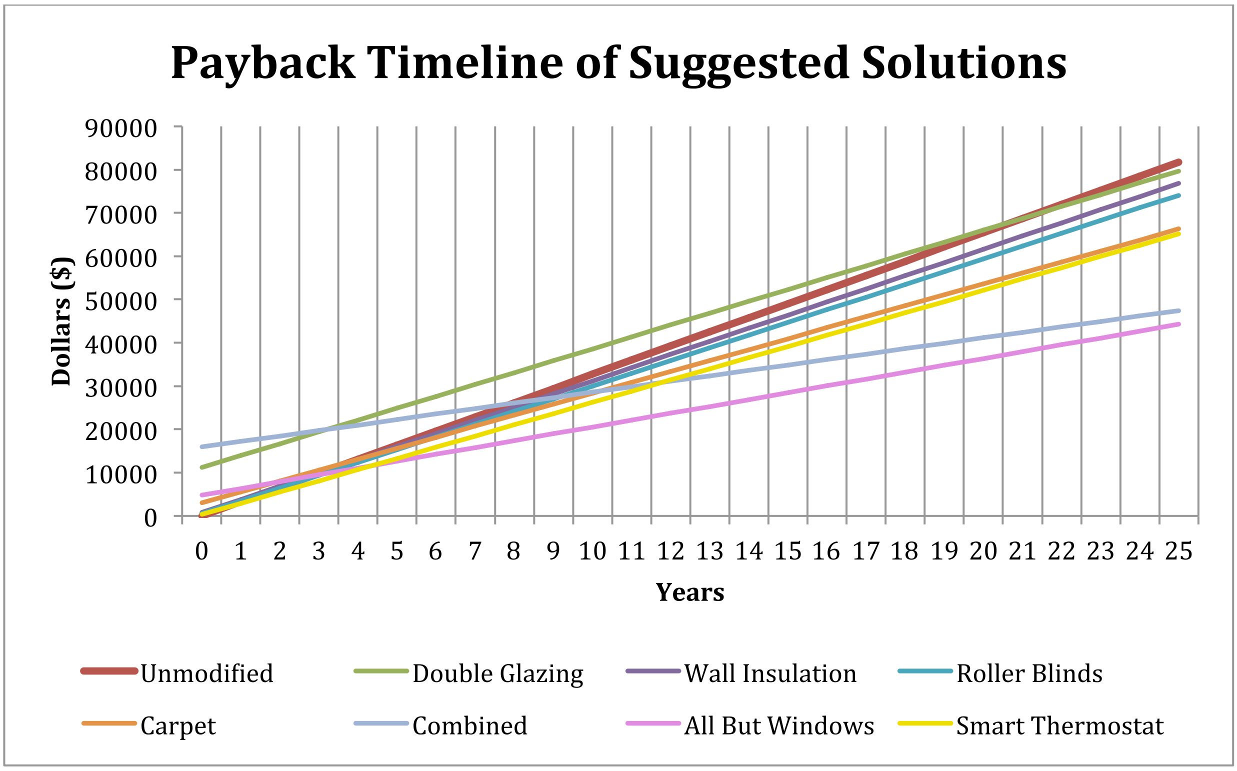

Figure 4. Graph of payback timelines of each solution

From the graph, it is clear that this is the most effective solution to maximise heat retention and lower energy usage and cost is to implement all suggested modifications except for double glazed windows. While the annual savings are greater if double glazing is included, meaning that eventually this option will be more cost effective, the payback period is too long, exceeding the lifetime of the project, due to the high capital cost of double glazing.

The suggested solutions without double glazed windows has a payback period of just 3 years, with an annual savings of $1,690/year.

It should be noted that the energy requirements are based on the same living configuration over the 25 years. Savings are likely to increase even further when compared with an unmodified system as energy consumption of the household goes up with an increase in family size and perhaps more energy-hungry technologies in future.

It should also be noted that the double-glazing solution considers retrofitting all windows in the house. This solution should be scrutinized further by modelling a system where only the main living areas feature double-glazed windows.

7. Time Factors

Queue theory can be employed to calculate the time required to heat the home from an arbitrary temperature of say 15°C.

The heat rate of the energy into the household, $\dot{Q}_{in}$, is considered to be the service rate, while the heat rate of energy lost from the house to the outside through external walls, $\dot{Q}_{out}$, could be considered the arrival rate, and heat required, Q_{req}, at the time heating is switched on is the number already waiting in queue. For example:

$$t = \frac{Q_{req}}{\dot{Q}_{in} - \dot{Q}_{out}}$$

While this is a very simplistic model of the thermodynamic behavior of the system, this model could be used to estimate the heating time and the energy consumption of the household.

To begin, thermodynamic theory can be used to calculate the heat demand based on increasing the household 15°C to 23°C (adding 2.5°C the ideal neutral temperature to account for the fluctuation of temperature around this).

With draft excluders under all external doors, we can assume zero airflow in or out. Since the system is closed, the heat required, Q_{req}, to raise the temperature from 15°C to 23°C can be found with a simple energy balance:

$$\Delta E = \Delta U + \Delta KE + \Delta PE = Q_{req} - W$$

Since the house is stationary, $\Delta KE = \Delta PE = 0$, and since the walls are considered to be rigid, the system doesn't transfer any energy to it's surroundings through work, so $W = 0$. Under the assumptions of an ideal gas, with constant specific heat capacity, the above equation reduces to:

$$Q_{req} = mc_v(T_2 - T_1)$$

Where m is the mass of the air in the system, c_v is the specific heat capacity of the air, and T_1 and T_2 represent the initial and final temperatures of the air. Given the initial conditions of pressure and temperature equal to 1atm and $285.15°K$ respectively, and the volume of air in the home, the mass of air in the system can be found to be 234.5kg, and the specific heat capacity for air at constant volume and at ambient temperature is given in literature as 0.718kJ/kg.K. Using these values, the total heat required to heat the entire house from 15°C to 23.5°C is calculated to be 1.43MJ.

Calculating the losses through external surfaces as in the energy flow analysis, using an average inside temperature of 19.25°C, the net heat energy flow rate into the system is 10,789W (kJ/s), resulting in a heating time of 2.21 minutes. Once heating is switched off, heat is lost from the system at a rate of 3666W until 18.5°C is reached (lower limit of neutral temperature band), with the system losing 841kJ in this time. At this rate, it takes 3.8 minutes before the heating cycle starts again. Each further heating cycle will require less energy to heat the home to the required temperature (841kJ), and each further heating period is calculated to take 1.36 minutes, using the net heat rate from the energy analysis.

By comparison, if the recommended solution was to be implemented, the net heat-rate retained for space heating would increase from 10,789W to 11,917W, resulting in a heating time of 2.00 minutes, or around 13 seconds less. The cool down time with the modifications is much greater, with a calculated cool down period of 5.9 minutes, which is 50% longer than the unmodified system. Each further heating period is calculated to take 1.2 minutes.

As expected, the added insulation results in heat being retained within the home for much longer, giving a more gradual temperature variation and a much lower energy requirement in a given period of time.

To quantify this in terms of energy consumption, after the initial heating period, the unmodified cycle repeats every 5.16 minutes, and the modified cycle repeats every 7.1 minutes. Factoring in an energy consumption of 33.33kW, over any given hour of system operation, the unmodified system uses 29.1MJ, and the improved system uses 20.3MJ, giving a energy reduction of 30.3%. This is reasonably consistent with the comparison drawn in the previous energy analysis of this report, which was a %40.3 reduction.

While this reduction is lower than predicted in the energy calculation, there are expected to be discrepancies due to time-based calculations using a fixed external temperature that is lower than the average used in the energy analysis.

It should also be noted that these times don't take into account the time it takes to circulate the air to distribute heat evenly, and so in reality we expect longer heating times.

8. Material Factors

To assess the environmental impacts of the proposed solution, a materials audit is performed, with the embodied energy and carbon of the total materials required for each modification being estimated based on amount of material used and the researched embodied energy and carbon figures of each type of material. Table 5 below lists the main materials required for the suggested modifications, and the estimated mass of each, with the resulting absolute embodied internal energy and carbon is shown.

Table 5. Embodied Energy and Carbon of Construction Materials (Hammond & Jones, 2008)

Design Solution	Material	EE (MJ/kg)	EC (kgCO2/kg)	Estimated Requirement	Total EE (GJ)	Total EC (kgCO2)
Double Glazing	**Glass**	15.00	0.85	250kg	3.75	212.5
Wall Insulation	**Fibreglass Wool**	28.00	1.35	324kg	9.07	437.4
Carpet Installation	**General Carpet**	74.4 (186.4/m^2)	3.89 (9.76/m^2)	50.4m^2	9.39	491.7
Carpet Installation	**Wool Carpet**	106 (84/m^2)	5.48	50kg (50.4m^2)	4.23	274
Roller Blinds	**General Plastic**	80.5	2.53	62kg	5.03	157.9
Roller Blinds	**Cotton, Fabric**	143	6.78	38kg	5.43	257.6
Roller Blinds	**Wool Fabric**	3.00	0.15	33kg	0.0986	4.93
Total	**-**	-	-	-	22.2	1562

Estimates for mass requirements were based on density data for each material found in online literature and the window and floor dimensions of the household. The total embodied energy and carbon figures assume wool is used for the roller blinds instead of cotton.

From the table we can see that cotton roller blinds have the highest embodied energy due to the need for plastics and cotton, and also quite a high quantity of embodied carbon. In addition, compared to other solutions, the roller blinds are the least effective for saving energy. As such, care should be taken about the type of material used to make the blinds, so that the energy savings incurred can justify the environmental costs. If a wool fabric were used instead of cotton fabric, it would halve the embodied energy of the roller blinds making for a more environmentally friendly solution.

Another big opportunity to reduce environmental impacts is to consider carpet selection. By selecting wool carpet over general carpet, which is usually a nylon blend, the embodied energy could be halved.

However, since improvements of the system are designed to save on household energy expenditure, the quantity of energy saved over the lifetime far outweighs the embodied energy of the product regardless of the solution. Indeed, we can see that the energy savings accrued after just one year, as calculated in the energy analysis, already exceed the lifetime embodied energy of the materials used.

Double-glazing is clearly a much more environmentally friendly solution than carpets and insulation, though the high capital cost could make it an unattractive choice for the user, depending on their salary. As such, it remains as a possible solution, but not the recommended cost effective solution.

9. Conclusion

This paper has presented a comprehensive analysis of a natural gas powered forced air heating system in a residential building with the express purpose of maximising energy efficiency and reducing energy expenditure for the household.

It applied a number of systems engineering methodologies in cohesion with thermodynamic analysis to assess the energy losses and highlight potential inefficiencies and downfalls of the system, offering a number of possible solutions to resolve them, and providing research based evidence to support the conclusions.

From theoretical modelling and public survey, it was seen that most people set their thermostats to the ideal neutral comfort temperature. It was also seen that there is a lower bound recommended thermostat settings before occupant health is compromised. Since most people set their thermostat towards this lower bound, there is no real opportunity to reduce energy expenditure by reducing thermostat temperature.

It was found that for the household studied, a great improvement in energy efficiency could be realized by installing more insulating materials. In particular, it is recommended that walls be fitted with insulation, floors be carpeted where appropriate, and windows have fitted roller blinds installed. A smart thermostat, such as the Nest, will further cut energy usage.

With these improvements, it is proposed that the annual energy consumption used for heating of the household could be reduced by as much as 40%. The cost analysis, when considering a span of 25 years and the rising prices of natural gas in that time, indicates a potential annual savings of $1,690/year, a payback period of 4 years, and a capital cost of $6,540.

In addition to the recommendations suggested, possible future improvements include the addition of a multistage heating system with zoning capabilities to minimise unnecessary energy use, and incorporating a flue heat recovery system to maximise heat into the home.

In summary, residential buildings are dynamic systems with many influencing variables contributing to the thermal characteristics of the household. As such, each house should be analysed rigorously to determine the most appropriate solutions to reducing energy expenditure on heating. However, the methodologies described in this report can be applied to most household situations to identify the most cost effective energy saving solutions where space heating is concerned, as well as assess the environmental impact of implementing such solutions.

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11. Appendix

11.1 Survey Questions Asked for Preliminary Research

A few short questions on your household heating...

* Required

What sort of heating system do you use for your main heating needs? *

Select one

- ○ Ducted Gas
- ○ Ducted Electric
- ○ Reverse Cycle Electric
- ○ Radiator (aka Hydronic)
- ○ Portable Electric
- ○ Slow Combustion Wood Burner
- ○ Closed Gas Burner
- ○ Open Fireplace
- ○ Don't Know
- ○ Other:

If using a thermostat controlled system, what temperature is your heating usually set to when you are at home?

Answer in degrees Celsius

What is the best thing about your heating system? *

Answer in one sentence.

What is the worst thing about your heating system? *

Answer in one sentence

How satisfied are you with the your heater's performance in winter? *

	1	2	3	4	5	
Very Unsatisfied						Very Satisfied

How satisfied are you with the cost of running your heating system? *

	1	2	3	4	5	
Very Unsatisfied						Very Satisfied

What are the external walls of your house made of? *

- ○ Double Brick
- ○ Brick Veneer
- ○ Weatherboard / Wood Cladding
- ○ Breeze Blocks
- ○ Concrete
- ○ Wood / Logs
- ○ Don't Know
- ○ Other:

Does your home have additional insulation? *
Such as insulation bats

- Walls and Roof
- Roof Only
- Walls Only
- No Additional Insulation
- Don't Know
- Other:

What type of windows do you have? *

- Single Glazed
- Double Glazed
- Triple Glazed
- Don't Know

What type of floors are in your main living area? *

- Wood Floorboards
- Tiles
- Carpet
- Floating Floorboards
- Linoleum
- Other:

Final Question! What type of base does your home rest on? *

- Concrete Slab / Poured Concrete
- Raised Perimeter Foundations
- Treated Timber
- Don't Know
- Other:

11.2 Cost Analysis Quotes

Table A-1. Quotes used for cost analysis.

Item	Cost	Quote Source	Notes
Double Glazed Windows	$12,900	CannyLiving.com	Online quote calculator based on window dimensions. Installation included.
	$500/m^2	bunnings.com.au	Average of cost per window area over a range of products was used. Installation not included, price is doubled to include installation cost.
	$330/m^2	diydoubleglaze.com.au	Installation not included, price is doubled to include installation cost.
Wall Insulation	$14.50/m^2	Australian-government-insulation-rebates.com	Price for complex installation

	$7.40/m²	Homeimprovementpages.com.au	Includes installation
	$10.30/m²	Insulationaustralia.com.au	Includes installation
Carpet	$60/m²	Stainmaster.com.au	
	$2,750	Carpetcourt.com.au	
Roller Blinds	$600	Bunnings.com.au	Based off nearest fit
	$60-70 per blind	Homeimprovementpages.com.au	9 blinds total.
Smart Thermostat	$340	Nest.com	Exchange rate of US$0.73/AU$1.00

11.3 MATLAB Code used for energy, cost, and time calculations:

```
% Thermal conductivity values

Uwall = 0.27; %0.621 Original ---- %0.27 Insulated
Uwindow = 0.72*4.7; %4.7 Original ---- %0.72*4.7 Roller Blinds ---- %2.7 Double
Glazing
Uglassdoor = 0.72*5.7; %5.7 Original ---- %0.72*5.7 Roller Blinds ---- %2.7
Double Glazing
Uwooddoor = 3.7;
Uceiling = 0.3;
Ufloor = 0.3; %1.075 Original ---- %0.3 Carpeted
UfloorC = 0.3;
UutilityWall = 0.794;

% Surface Areas
Awall = 67.5;
Awindow = 21.56;
Aglassdoor = 3.4;
AutilityWall = 12.678;
Afloor = 50.38;
AfloorC = 29.37;
Aceil = Afloor+AfloorC;
Autilitydoor = 0.9*2*2;
Afrontdoor = 0.9*2;

% Temperatures
Tin = 21+273.15;
Tutility=Tin-5;
Tout = 7+273.15;
Tearth = 8.4+273.15;

% Ifiltration variables
cp = 1.005*10^-3;
ro = 1.205;
n = 1.4*10^-4;
V=2.4*Afloor;

% Heat Loss through various surfaces at comfort temperature and specified
% external temperature. Used for time analysis.
Htwall = Awall*Uwall*(Tin-Tout);
HtutilityWall = AutilityWall*UutilityWall*(Tin-Tutility);
Htwindow = Awindow*Uwindow*(Tin-Tout);
Htceil = 1.15*Aceil*Uceiling*(Tin-Tout);
Htfloor = Afloor*Ufloor*(Tin-Tearth);
HtfloorC=AfloorC*UfloorC*(Tin-Tearth);
Htglassdoor = Aglassdoor*Uglassdoor*(Tin-Tout);
Htutilitydoor = Autilitydoor*Uwooddoor*(Tin-Tutility);
Htfrontdoor = Afrontdoor*Uwooddoor*(Tin-Tout);
```

```
Hi = cp*ro*n*V*(Tin-Tout); %infiltration

HtTotal =
Htwall+HtutilityWall+Htwindow+Htceil+Htfloor+HtfloorC+Htglassdoor+Htfrontdoor+Ht
utilitydoor+Hi;

% Heat Loss per degree difference. Used for energy and cost analysis.
HtwallDD = Awall*Uwall*(1);
HtutilityWallDD = AutilityWall*UutilityWall*(1);
HtwindowDD = Awindow*Uwindow*(1);
HtceilDD = 1.15*Aceil*Uceiling*(1);
HtfloorDD = Afloor*Ufloor*(Tin-Tearth);
HtfloorCDD= AfloorC*UfloorC*(Tin-Tearth);
HtfloorDDSleep = Afloor*Ufloor*((16+273.15)-Tearth);
HtfloorCDDSleep=AfloorC*UfloorC*((16+273.15)-Tearth);
HtglassdoorDD = Aglassdoor*Uglassdoor*(1);
HtutilitydoorDD = Autilitydoor*Uwooddoor*(1);
HtfrontdoorDD = Afrontdoor*Uwooddoor*(1);

HiDD = cp*ro*n*V*(Tin-1); %Infiltration

HtTotalDD =
HtwallDD+HtutilityWallDD+HtwindowDD+HtceilDD+HtglassdoorDD+HtfrontdoorDD+HiDD;


%Calculated percentage losses
ptwall = Htwall/HtTotal;
ptutilitywall = HtutilityWall/HtTotal;
ptwindow = Htwindow/HtTotal;
ptciel = Htceil/HtTotal;
ptfloor = (Htfloor+HtfloorC)/HtTotal;
ptglassdoor = Htglassdoor/HtTotal;
ptutilitydoor = Htutilitydoor/HtTotal;
ptfrontdoor = Htfrontdoor/HtTotal;
ptHi = Hi/HtTotal;

%Data for table for easy viewing
vals = [Htwall, ptwall;
    HtutilityWall, ptutilitywall;
    Htwindow+Htglassdoor, ptwindow+ptglassdoor;
    Htceil, ptciel;
    Htfloor+HtfloorC, ptfloor;

    Htutilitydoor, ptutilitydoor;
    Htfrontdoor, ptfrontdoor;
    Hi, ptHi;
    HtTotal, 100];

HeatLoss = vals(:,1);
Percentage = vals(:,2);

%Create Table
T = table(HeatLoss,
Percentage,'RowNames',{'walls';'utilitywalls';'windows';'ceiling';'floors';'util
itydoors';'frontdoor';'infiltration';'Total'});


%Calculate degree day losses by multipying time duration (factoring in
%weekends)
degreeDayLossWake=(HtTotalDD)*9.7142857*3600; %average number of waking hours
per day is 9.714
degreeDayLossSleep=(HtTotalDD)*8.57142857*3600; %average number of sleeping
```

```
hours per day is 8.571

degreeDaysWake=2545;
degreeDaysSleep=1303;

% Annual Losses (Soil temperature is considered to remain reasonably
% constant, so floor losses are calcualted seperately and are constant
% during periods of heating.
annualLoss=degreeDaysWake*degreeDayLossWake+degreeDaysSleep*degreeDayLossSleep+(
HtfloorDD+HtfloorCDD)*9.7142857*3600*365+(HtfloorDDSleep+HtfloorCDDSleep)*8.571*
3600*365;

%annualLoss=annualLoss*0.84;

furnaceEfficiency=0.6;

annualReq = annualLoss/furnaceEfficiency;

gasCost=0.0465; %predicted average over next 25 years

annualCost=gasCost*(annualReq*10^-6);
```

Walls insulation quotes
http://www.australian-government-insulation-rebates.com/Products/bestinsulation.html
http://www.homeimprovementpages.com.au/article_variation/how_much_does_it_cost_to_install_insulation?v=5&enable_hui_body=1&style=hui_look&footer_style=hui_hybrid
http://www.insulationaustralia.com.au/get-a-quote/pricing/

**Quote from CannyLiving (CannyLiving, n.d.), **Quote from Bunnings (Bunnings, n.d.), ***Quote from Stainmaster (Stainmaster, n.d.)*.