Energy: Home Energy Audit

Introduction

Energy Transfers and the First Law of Thermodynamics

In the 1800's, scientists found, empirically, that rules exist that determine how energy can be transferred. The first of these rules is called the First Law of Thermodynamics. This law is usually stated as, "Energy can neither be created nor destroyed; it can only be transferred from one form to another." This often leads to the re-titling of this law as the Conservation of Energy Principle since it says that energy must be conserved.

This statement of the First Law does not say anything about how energy can be transferred, though. It turns out that there are only two ways. This was discovered in 1850 by the English scientist James Joule, who found that heat and work are equivalent methods for changing the energy of an object. In his experimental work, Joule was able to show that he could increase the thermal energy of a pot of water by either placing it over a flame (adding heat), or by stirring it with a paddle (doing work). For this and other important work in this area, the SI unit of energy is called a joule ($1\ J = 1\ kg\ m^2/sec^2$). Using this, we can re-write the First Law mathematically as

$$\Delta E = W + Q$$

where ΔE is the change in the energy of an object, W is the work done on the object, and Q is the heat added to an object. In laymen's terms, this means that the only way to change the energy of an object is to exchange either work or heat with it.

Energy History

The discovery of the laws of thermodynamics was extremely important, as our need to understand energy is fueled by the overwhelming use of energy in human society. From the earliest days, humankind has recognized the need to use energy to condition the environment around it. Wood was needed to heat homes and to cook food. Beasts of burden were needed to plow fields and to provide transportation. When either of these commodities became scarce, hardship prevailed, and solutions were sought. In ancient Rome, for example, the lack of available firewood led to the passing of laws that made it illegal to build a house or structure that would block another person's home from getting sunlight, as this was the primary method of heating homes without fire.

In the 20th century, fossil fuels (oil in particular) reigned supreme as the energy of choice. Their ubiquitous nature created historically low prices for energy. This led to a substantial increase in the number of mechanized tools used by the average citizen. By the year 2020, the U.S. had a population of about 330 million people that were driving over 285 million passenger vehicles. Almost every home in America has a television, some type of range or stove, and a refrigerator. About 3/4 of all households have their own washer, dryer, and air conditioner. Of course, this cheap price does not come without some political and economic consequences. Energy, and oil in particular, have played a very important role in the economy and politics throughout the last 150 years, affecting everything from the entry of U.S. into World War II to the rampant inflation of the 1970's to the current de-stabilized situation in the Middle East.

Energy Use in the U.S.

This modern dependence on many appliances of convenience requires a lot of energy. Our current energy per capita use is over 305 million BTU's of energy. Put another way, this means that the average U.S. citizen would be responsible for using more than 50 barrels of crude oil each year, if all of the energy used in America came from oil. The only other country in the Western World that was even close to this is Canada, which has almost the same amount of usage. Most of the Western world uses 200 million BTU's of energy or less. Although we make up only about 4% of the world's population, we account for more than 16% of all of its energy consumption. In comparison, many economically-emerging countries, such as Ethiopia, use less than 1 million BTU's per person.

The majority of the United States' energy (81%) is supplied by fossil fuels. Crude oil accounts for the largest share of this (37%), followed by natural gas (31%) and coal (13%). The remaining energy comes mostly from: nuclear energy (8%); renewable energy sources such as hydropower, wind, and solar (6%); and biomass energy (5%).

Of the energy used in the U.S., about 37% of it is used for transportation, 35% for industrial processes (mining, milling, etc.), and 28% of it is used to power homes and offices.

While most of us cannot directly affect the amount of energy used for industrial processes, we can do something about our residential and transportation energy use. The figures above mean that about 101 million Btu's are used each year just to run our households (this does not include the energy that was lost in producing and transporting this energy, which accounts for an additional 71 million Btu's). The majority of this energy use is to heat and cool our homes (55%). In this week's lab, we are going to begin to study ways to reduce our home energy usage, primarily through reducing our demand for heating and cooling.

Measuring your home

In this week's lab, we are going to prepare for the energy analysis that we are going to perform in two weeks by measuring the surface areas of our homes that are exposed to outside temperatures. We are also going to note what materials were used in the construction of our dwelling. This will allow us in week three of this module to estimate the amount of energy that is being lost in our homes due to conduction. This type of heat transfer depends upon the type of materials used for construction, the amount of surface area through which heat is transferred, and the temperature difference across the material. As we will see in next week's lab, the type of material can drastically change the amount of heat that is conducted from a hot to a cold region. Plywood, by itself, provides little resistance to the flow of heat; plywood, combined with fiberglass and polystyrene insulation, can provide a significant barrier to conduction and allow large temperature differences to be maintained between hot and cold regions. While we are making these measurements of the exterior surfaces of our home, we will also be gathering some basic information about some energy-using devices in our home, such as the refrigeration, cooking, and water heating systems. These systems are responsible for most of the energy used in the home outside of the heating and air-conditioning systems. These are also systems for there can be a wide range of energy efficiency between various makes and models.

Instructions

1. Prepare a drawing of your dwelling. This does not need to be an intricate blueprint of your dwelling (although it helps if you already have one), but a simple illustration of it that will allow for all external surface measurements to be shown. Indicate north on the illustration.
2. On your drawing, please signify the measurements of all exterior, heat-dissipating surfaces. These will be surfaces that lead from an air-conditioned and heated room to either the exterior of the house or to rooms (ex garage) that are not heated or air-conditioned. **NOTE: These measurements do not need to be made from the outside of the home; measurements made from the inside of the house will be sufficient)**
3. While you are measuring the exterior components of your home, note the materials from which they are constructed. For instance, is your exterior door constructed of 1 1/2 inch solid wood, or is it 1 3/4 steel with foam insulation? Enter this information on your Data Sheet (Exterior Surface Type section) as to type of material of each exterior surface (Interior surfaces are irrelevant for calculating heat transfer since internal heat transfers do not affect the amount of energy lost or gained to your home). Some homes will have more than one surface type for each exterior surface. For instance, a house might have single and double paned windows. If so, make sure that both types of surfaces are entered onto the sheet.
4. Using the measurements from your drawing, calculate the area of each exterior surface in your home and enter the data on the Data Sheet provided. Round off all dimensions to the square foot and enter the data into the appropriate slot for each surface type. If you have more than one surface type for each component, remember to the different areas for each type (ex. if you have 10 square feet of single paned windows and 20 square feet of double paned windows, be sure to put the appropriate amount in each slot). If you are unsure of how to calculate areas of external surfaces, look at the example audit at the end of this file after the data sheet.
5. For each surface type, check the list of surface types and fill in the value for the appropriate R factor (Ex. single pane window, R: .9).
6. From your drawing, calculate the square footage of the livable space and write this value in the appropriate slot on your Data Sheet. If you have not done so already, measure/estimate the average height of the ceilings in that living space, and place the value in the slot below this.
7. Check the accuracy of thermostats on your heating and air conditioning unit. While you might think that you have it set at 70 degrees, it might actually be maintaining a temperature of 72. This can be checking by placing an accurate thermometer near the thermostat and noting any differences between the readings. Noting any differences, record the temperature settings for both the air conditioner and heater during the year.
8. The final audit will require certain information about the appliances in your home. You will need to know what type of heating and cooling system your home has, as well as the types of major appliances. For heaters and air conditioners, describe the energy source (electrical, natural gas, wood, etc.) and tell whether the system is centralized (ductwork takes the air to all parts of the home) or not. For the other appliances, check the line next to the type if you have it. For electrical stoves and dryers, we are also going to need to know the wattage of the appliances. If you cannot find this information on the inside door of the appliance, please note this on your data sheet.
9. From your utility company(ies), find out the cost per unit energy for your energy source(s). For some companies, this information will be printed on their bill (Ex. $.75/therm on a natural gas bill or $.08/kWhr on an electric bill). For other companies, this information can be

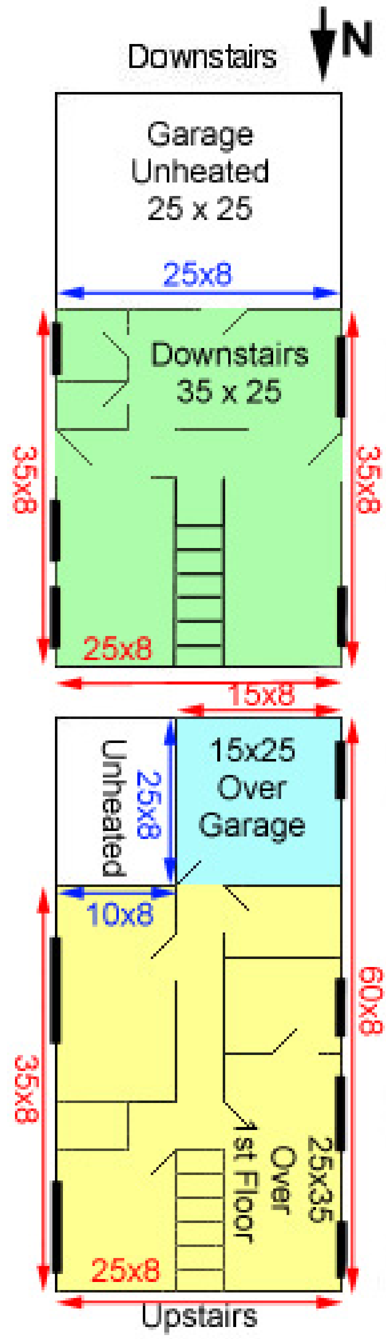
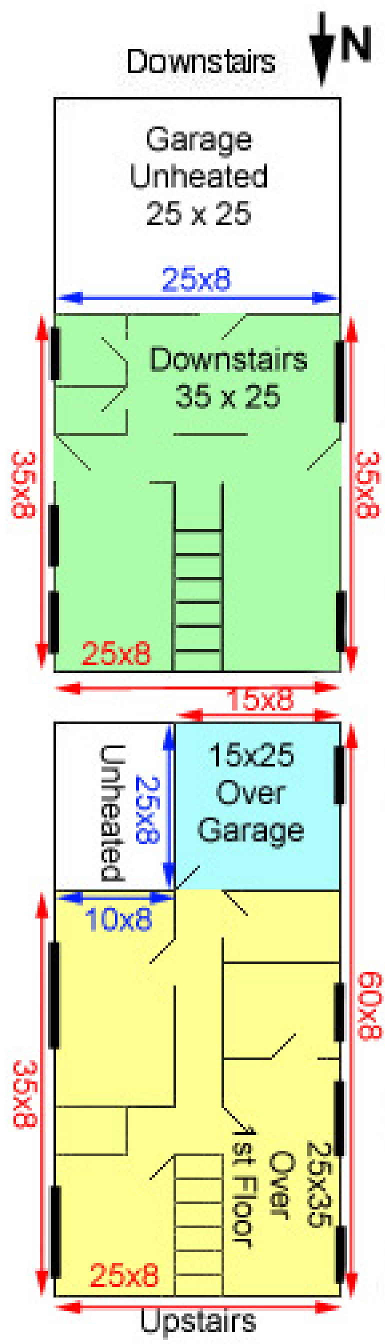


Fig. 3: Sample house drawing

extracted from the bill by dividing the total cost of the energy by the amount of energy that was used. If this information is not on your bill, or if you do not have a bill to check, call the companies that supply you with energy and ask the rate that they are billing you.

Example



The floor plan at the left is of a wood-sided house built upon a cement slab. It is two stories tall with insulated walls and twelve inches of blown fiberglass insulation in the attic. The house is 5 years old, and has been well maintained. The garage, while sealed with doors, is not heated or cooled. The main living space occupies a 25'x35' space both upstairs and downstairs (yellow and green areas), with an additional 15'x25' room (blue area) on the second floor that is over the garage. Windows are as marked on the floor plan and are all 1/4" double pane. The three exterior doors are standard 3'x7' insulated-core steel doors.

The Data Sheet for this house looks like the following:

Type of structure: _X_ House ______ Apartment/Duplex ______Mobile Home
Number of stories _2__

Exterior Surface Types

	First Type	Second Type (if needed)
Windows	1/4" double paned	
Walls	Wood with 3 1/2" fiberglass and 1" foam	Sheetrock with 3 1/2" fiberglass
Doors	1 3/4" Pella	
Roof/Ceiling	12" fiberglass (blown)	
Ground Floor	Concrete slab	6" fiberglass over closed unheated space

Exterior Surface Types	Area	R-factor	Area	R-Factor
Windows	210	1.7		
Walls	1588	20	459	12
Doors	63	13		
Roof/Ceiling	1250	43		
Ground Floor	875	11	375	43

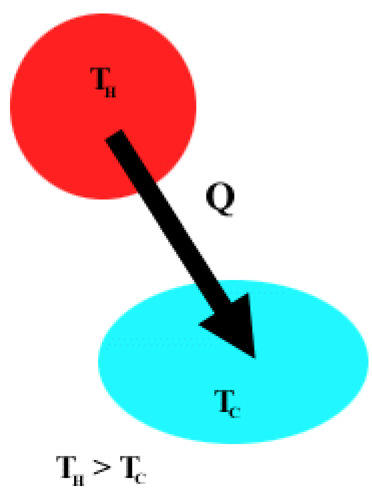
Total area of heated and air conditioned space: _2125__ sq. ft.
Average height of ceilings: _8__ ft.
Average indoor winter temperature (^{o}F): _69________
Average indoor summer temperature (^{o}F): __74____
Number of air exchanges per hour: __1___

Appliances

Heater Type: Central Natural Gas with insulated ducts___
Air Conditioning Type: __Central Electric with insulated ducts _
Refrigerator/Freezer Combo: _1__
Gas Hot Water Heaters: _1_
Gas Stove/Oven: _1_
Electric Clothes Dryer: _1_ If yes: _2000__ Watts

Confusion About Heat and Temperature

Even though it has been over 150 years since the First Law of Thermodynamics was discovered, we still find that heat is misunderstood. For example, the many environmental science textbooks define heat as "the total kinetic energy of atoms or molecules in a substance not associated with bulk motion of the substance." **THIS IS WRONG!** What these books are describing is the thermal energy of a system. This is a common misconception. While heat is energy, it is not a containable form of energy since, by its very definition, heat is energy that is transferred. In particular, heat is **the energy transferred between objects of different temperature**. The misunderstanding comes from the fact that we often talk about heat leaving or entering an object, which gives people the idea that the object must contain heat. But this is not the case. Once heat enters an object, it increases the internal energy of an object, which is the same result that doing work on the object would produce. The object does not contain the heat or the work; it merely changes its energy because of them.

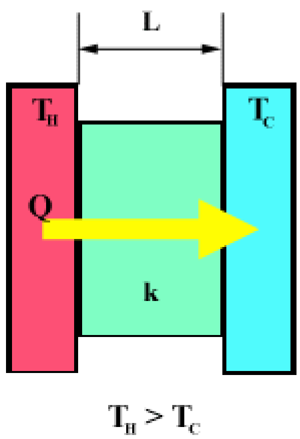


This increase in internal energy can cause numerous things to occur to the object. One of the more common things that it causes is for the temperature of the object to increase. However, it can cause other things to occur that do not involve any change in temperature, such as a change of state (ex. water changing into steam). The fact that one of the most common experiences is that the temperature changes leads to another erroneous definition. Many books also define temperature as "a measure of the speed of motion of a typical atom or molecule in a substance." Again, this is wrong. While it may be true for an ideal gas, it does not apply to all objects. The best definition for temperature is **the property that two objects have in common when no heat is transferred between them when placed in thermal contact**. The observant reader is going to note a certain circuitousness about these definitions for heat and temperature. But, these are the only definitions that truly make sense. The best way to illustrate this is to examine what happens when you measure the temperature of a glass of water with a mercury or alcohol thermometer. Upon entering the water, the thermometer does not instantly register the correct temperature. Instead, it takes several seconds for the liquid in the thermometer to settle to the correct reading. During this time, heat is being exchanged between the water and the liquid in the thermometer. As it does so, the temperature of the liquid in the thermometer changes, becoming closer to that of the water. This change in temperature of the alcohol or mercury results in its volume changing, which is what changes the level of the fluid in the thermometer. Once the temperature of the fluid has reached that of the water in the glass, heat stops being transferred between them, and the volume of the fluid stops changing.

Thus, the thermometer is not measuring the average speed of the molecules in the water. The only thing that is being measured is the volume of the liquid in the thermometer. Somebody (or some machine) calibrated the volume of the fluid in the thermometer to a temperature scale that is painted onto its side. Because of this, we are able to read a value for the temperature by merely measuring the height of the liquid in the thermometer. The temperature that we read, though, only tells us which way that heat will flow if the object is put into thermal contact with another object.

Conduction

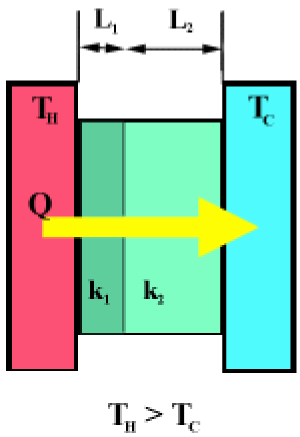
As we have previously stated, homeowners, on average, spend almost 50% of their energy budget for heating and cooling. The reason for this is because heat is constantly transferring through all of the exterior surfaces of the home. The most predominant type of heat transfer for the majority of homes is known as conduction, which occurs when two regions of different temperature are put into direct contact, but are not allowed to mix. As an example, the inside temperature of a home in the winter is hotter than the exterior temperature if the home is being heated. The walls, doors, and windows are all conducting heat to the outside since they are in direct contact with both reservoirs of air.



The rate at which heat gets transferred depends upon (1) the thickness of the material L, (2) the thermal conductivity k (this depends on the composition of the material), (3) surface area of the material A, and 4) the temperature difference between the reservoirs. In particular (see Fig. 2), the rate of heat transfer = A k $(T_H - T_C)/L$. This equation shows that the thicker the material separating the two reservoirs (L larger), the smaller the surface area that is contact (A larger), or the smaller the temperature difference, the slower the rate of heat transfer through the substance. When it comes to heating and cooling our homes, this is exactly what we will need to strive for in order to reduce our energy bills.

In our homes, the exterior surfaces are usually comprised of more than one type of material. For instance, a wall can be composed of 3 1/2 inches of fiberglass insulation which is covered by 1/2 inches of sheetrock on the inside and plywood and brick on the exterior. When two or more different materials are between the hot and cold reservoirs, the equation on the previous page can become quite messy since there will be various thermal conductivities and thicknesses with which to deal.

The equation is greatly simplified if we consider the R-value of objects instead of their thermal conductivity. This is a measure of how well the material resists the flow of heat through it, and it combines the thermal conductivity and thickness into one term (R-value = thickness/thermal conductivity = L/k). While the common units for the R-value are ft^2 hr ^oF/Btu, these are often not quoted. If you visit any hardware store, you are likely to just see the R-value of a substance to just be quoted as a number, as in "Fiberglass R-value = 13."



From the previous page, we can see that the equation for conductive heat transfer through a single substance is given by

rate of heat transfer = A (T_H-T_C) k/L = A (T_H-T_C)/R

If there are multiple materials that comprise the surface (see Fig. 3), then the equation becomes

rate of heat transfer = A (T_H-T_C)/R_T

where R_T = sum of all of the individual R-values. As an example, in the wall that we proposed above, the R-value for the fiberglass is 13, for the plywood and brick is 4, and for the sheetrock is 0.5. Therefore the total R-value for the wall is 17.5, which is what would be placed in the denominator of the heat transfer equation.

R-Factors for Common Materials

After you have finished making the drawing of your dwelling with the measurements of the exterior surfaces, it is time to determine what is the R-factor of all of the exterior surfaces. The R-factor of a surface determines how quickly heat is conducted across it. The values below are some of the more common R-factors for surfaces found on homes in the U.S. **NOTE:** If your exterior surface leads into an enclosed area that is sealed, but is not heated or air-conditioned (ex. a door that leads to a closed garage), then multiply the R-factors below by 1.5 in order to get a better estimate of the factor. If the enclosed area happens to be earth-sheltered (ex. a basement that is not heat or cooled), then multiply the R-factors by 2.0.

Exterior Doors (Excluding sliding glass doors)
Calculate glass area of door as window

Wood Door	**Factor**
1 1/4" no storm door	2.4
1 1/4" with 1" storm door	3.8
1 1/2" no storm door	2.7
1 1/2" with 1" storm door	4.3
1 2/3" solid core door	3.1
Steel with Foam Core Door	
1 3/4" Pella	13
1 3/4" Therma-Tru	16

Roof/Ceiling

Material	**Factor**
No insulation	3.3
3 1/2" fiberglass	13
6" fiberglass	20
6" cellulose	23
12" fiberglass	43
12" cellulose	46
14" cellulose	54

Exterior Walls with Siding

Concrete block (8")	**Factor**
(a.) Concrete block (8")	2.0
with Vermiculite insulated cores	13
with foam insulated cores	20
with 4" on un-insulated stud wall	4.3
with 4" insulated stud wall	14
with 1" air space and 1/2" drywall	2.7
Brick (4")	
with 4" un-insulated stud wall	4
with 4" insulated stud wall	14
Wooden Logs	
Logs (6")	8.3
Logs (8")	11
Wooden Frame	
Un-insulated with 2" x 4" construction	4.6
with 1 1/2" fiberglass	9
with 3 1/2" fiberglass; studs 16" o.c.	12
with 3 1/2" fiberglass and 1" foam	20
with 6" fiberglass; studs 24" o.c.	19
with 6" fiberglass and 1" foam	26
with 6" cellulose	22
with 6" cellulose and 1" foam	28

Floor

Over unheated basement or crawl space vented to outside	**Factor**
Un-insulated floor	4.3
6" fiberglass floor insulation	25
Over sealed, unheated, completely underground basement	
Un-insulated floor	8
with 1" foam on basement walls	19
with 3 1/2 fiberglass on basement walls	20
Insulated floor, 6" fiberglass	43
Concrete Slab	
No insulation	11
1" foam perimeter insulation	46
2" foam perimeter insulation	65

Windows and Sliding Glass Doors:

Glass	Factor	Low Emissivity	Drapes	Quilts
Single pane	0.9	1.1	1.4	3.2
Single w/storm window	2.0		2.5	4.2
Double pane, 1/4" air space	1.7		2.2	4.0
1/2" air space	2.0	2.99	2.5	4.3
Triple pane, 1/4" air space	2.6		3.0	4.8
Triple pane, 1/2" air space	3.2	3.7	3.7	5.5

Home Audit Tips

1. Unless you live in a very unusual structure, the walls of your dwelling should be 3 1/2 inch studded walls. The biggest question you should have is whether your walls are insulated. If you do not know, there are a few ways to find out. If you dwelling was built since 1980, the odds are that it is insulated with fiberglass insulation. If your home was built before this, then the answer is not so easy. You could determine if there is insulation in the walls by cutting or smashing a hole in the wall to see. However, this is not recommended. There are probably holes in your exterior wall already. Remove the faceplate from either an outlet or a light switch that are on an exterior wall. Be very careful NOT to stick anything into the socket or switch. Once the plate is off (make sure that it does not rip the paint or paper off of the wall), you should be able to see around the side of the outlet box to see if there is any insulation in the wall.
2. If the ceilings in your home are horizontal, then the area of the ceiling is the same as the area of the floor. Therefore, there is no need to get on a ladder to measure the area of your ceiling. If you have vaulted ceilings, the task of measuring the area of your ceiling is slightly more difficult. You can try to measure the distance along the vault if your tape measurer is rigid enough to allow this. If you cannot measure the distance this way, you will need to use a little geometry to aid you. Measure the height (vertical distance) of the ceiling at its highest and lowest points. Then measure the horizontal distance from the highest to the lowest points. You can now use the Pythagorean Theorem to calculate the distance. Square the difference in the vertical distance between the highest and lowest points. Square the horizontal distance between the two points. Now, add the squares together and take the square root of the sum. This will give you the distance along the vault.
3. If your ceiling is neither horizontal nor vaulted (ex. bi-level or tri-level), then you will need to measure or estimate all horizontal and vertical surface areas and sum them together.
4. The wattage information for your electric stove, oven, or dryer should be found on tags somewhere on the device. On these devices, this is usually on a metal tag either on the side of the door or in the door opening. If it is not, then it is probably on the backside of the device. If it possible to easily get to the backside of the device, please do so. If it is not easy, then write "Could not find" on your sheet. When we get to the calculator section of the audit in two weeks, you should just use the average values that the calculator gives you as a default.

Name: **Professor:**

Structure Data

Type of structure: _____ House ______ Apartment/Duplex ______Mobile Home
Number of stories _____

Exterior Surface Types

	First Type	Second Type (if needed)	Third Type (if needed)
Windows:	______________	______________	______________
Walls:	______________	______________	______________
Doors:	______________	______________	______________
Roof/Ceiling:	______________	______________	______________
Ground Floor:	______________	______________	______________

Ext. Surface Type	**Area**	**R-Factor**	**Area**	**R-Factor**	**Area**	**R-Factor**
Windows						
Doors						
Walls						
Roof/Ceiling						
Ground Floor						

Total area of heated and air conditioned space: ___________ sq. ft.
Average height of ceilings: ____________ ft.
Average indoor winter temperature (^{o}F): _________
Average indoor summer temperature (^{o}F): _________
Number of air exchanges per hour: _________

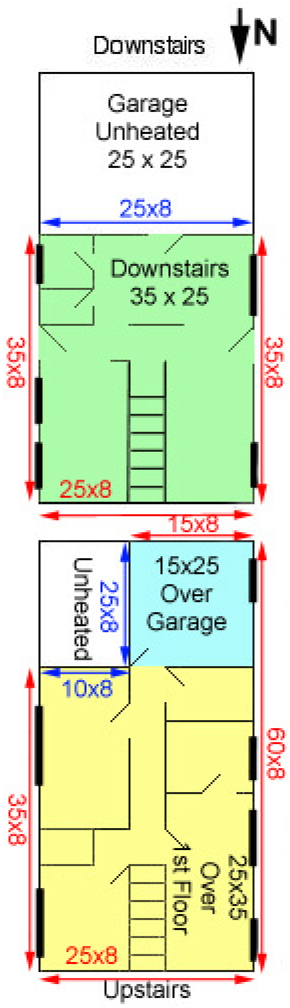
Appliances

Heater Type: ___________________________ Air Conditioning Type: _____________________
Refrigerators:____ Freezers:____ Refrigerator/Freezer Combo:_____
Electric Hot Water Heaters:____ Gas Hot Water Heaters:____
Electric Stove/Oven:____ If yes:______ Watts Gas Stove/Oven:____
Electric Clothes Dryer:____ If yes:______ Watts Gas Clothes Dryer:____

Energy Cost

Energy Source	**Cost**
Electricity	$___/kwh
Natural Gas	$___/therm
LP gas	$___/gal
Wood (cord = 128 ft^3)	$___/cord

Calculating Areas: Example



As long as our floor plan drawing has enough detail, calculating the various areas that are needed for this audit is not too difficult. The picture at the left is the floor plan that we had on the previous page, with exterior measurements of the wall specified in greater detail (for the measurements of the windows, please refer back to previous page). The wall measurements that are in red are those for the surfaces that are wood sided with 3 1/2" of fiberglass insulation and 1" of foam; the measurements in blue are for those measurements that are sheetrock with 3 1/2" of fiberglass insulation. The area in green is the downstairs floor area; it has no exterior ceiling since the upstairs rooms are above it. The area in yellow and blue is the upstairs ceiling area, while the blue area is also the upstairs floor area (6" fiberglass over an unheated enclosed space); the yellow area has no exterior floor since the downstairs rooms are below it.

The calculation of the floor and ceiling areas are quite simple and straightforward. The area of floor that is concrete slab is that of the green area (25'x35' = 875 sq. ft.). The area of floor that is 6" fiberglass over an unheated enclosed space is that of the blue area (15'x25' = 375 sq. ft.). The area of the ceiling is the sum of the yellow and blue areas (25'x35' + 15'x25' = 1250 sq. ft.).

The calculation of the areas of the doors and windows is similarly straightforward. There are 8 double pane windows that are 3'x5' and 3 double pane windows that are 6'x5'. Thus, the area of windows is 8x3'x5' + 3x6'x5' = 210 sq. ft. There are 3 steel doors with 1 3/4" foam insulation that go to the exterior of the house that are all 3'x7'. Thus, the area of the doors is 3x3'x7' = 63 sq. ft.

The hardest calculations are for the walls. The reason for this is that the doors and the windows also reside in the walls. Thus, we cannot just multiply the height of the walls times the length of the walls; we must subtract the area of the doors and windows from this result. For the wood siding with 3 1/2" fiberglass and 1" foam insulation, we notice that all of the windows and two of the doors reside within this surface. Thus, we have:

Upstairs: 15'x8' + 60'x8' + 25'x8' + 35'x8' = 1080 sq. ft.
Downstairs: 35'x8' + 25'x8' + 35'x8' = 760 sq. ft.

Wall area = Upstairs + Downstairs - All windows - area of 2 doors = 1080 sq. ft. + 760 sq. ft. - 210 sq. ft. - 42 sq. ft. = 1588 sq. ft.

For the sheetrock with 3 1/2" fiberglass insulation, we note that only one exterior door resides in this surface. Thus:

Upstairs: 10'x8' + 25'x8' = 280 sq. ft.
Downstairs: 25'x8' = 200 sq. ft.

Wall area = Upstairs + Downstairs - area of one door = 280 sq. ft. + 200 sq. ft. - 21 sq. ft. = 459 sq. ft.