Applications of Sustainable Technology to Retrofits in Urban Areas

by
Paki Taylor

B.Arch.
Cornell University, 1996

Submitted to the Department of Architecture and Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Architecture Studies
and
Master of Science in Mechanical Engineering

at the
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Signature of Author:______________________
Department of Architecture
May 24, 2001

Certified by:______________________
Leon Glicksman
Professor of Building Technology and Mechanical Engineering

Accepted by ______________________
Roy J. Strickland
Chairman, Departmental Committee on Graduate Studies
Architecture

Accepted by:______________________
Ain A. Sonin
Chairman, Departmental Committee on Graduate Studies
Mechanical Engineering

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Leon R. Glicksman

Professor of Building Technology and Mechanical Engineering

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ABSTRACT

Energy Losses from old buildings comprise a significant percentage of the total residential energy consumption in the United States. Retrofitting buildings for conservation can greatly decrease the present energy demand and help prevent an eventual depletion of the world's natural resources. This investigation analyzes energy efficient measures applicable to retrofits in residential buildings in New England. The project estimates the likely performance of the latest sustainable technology and rates them according to cost-effectiveness for an average homeowner.

Various retrofit measures and applications of sustainable technology are assessed according to relative importance and net savings. Improvements include a building envelope upgrade, an installation of a ground source heat pump and renewable energy systems. The analysis determines the energy savings relative to two base case models: a Cambridge Code and 1920s standard. The retrofit measures are analyzed at present and future energy rates.

Thesis Supervisor: Leon Glicksman
Title: Professor of Building Technology and Mechanical Engineering

Acknowledgements

I would like to thank Professor Leon Glicksman for his insightful comments, patience and guidance during this investigation. His commentary helped me to stay focused on the most important issues at hand. Under his leadership, the Building Technology Program addresses concerns at the forefront of the building industry.

I would also like to thank Diane Cotman for having provided me with most of the documentation and information on the Cambridge House for Sustainability as well as the project engineers (Ambrose, in particular). The House encompasses many complicated issues that cannot be addressed, comprehensively, in one thesis. With the information provided, I was able to gain an entry into the many dimensions of sustainability.

I also thank my mom for her love and support. All of this would not have been possible without you.

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Chapter 1 Statistics and Trends in Retrofitting

1.0 Purpose of Investigation

The need for energy conservation is of increasing concern to the builders, planners, architects and engineers of today. Buildings have a substantial environmental impact consuming one third of all energy in the United States. Consequently, they contribute to the eventual depletion of the earth's oil reserves, and global warming. As energy prices rise, residential energy consumption will become a major concern to the average homeowner and occupant.

Many of the poorest energy efficient buildings are built between 1941 and 1970[1]. These buildings were constructed during a period of low and stable energy prices. During that time, there was very little emphasis on conservation techniques. With an average life expectancy of 50 years, existing structures have a significant effect on the outcome of energy conservation because they comprise a large portion of the current building stock. 54% of the 80 million households in 1980 were constructed before 1960[2], under less efficient energy codes. 28% of those residences were constructed in 1939 or before. According to a SERI solar conservation study, the space heating and cooling of the existing residences in 1980 occupied 58% of the annual residential energy consumption. In 1997, the Residential Consumption survey showed that buildings constructed before 1970 comprised 66% of the total energy used for space heating and electric air conditioning. However, aggressive retrofitting of these buildings can reduce residential energy consumption by as much as 72%[3].

The purpose of this thesis is to study retrofitting options and the application of sustainable technology to residential buildings in urban areas. Given the many possibilities of retrofit designs, the following investigation will cite a demonstration project in Cambridge, Massachusetts as a case study for the New England region. The study will evaluate the design decisions made by the project engineers based solely on energy efficiency and cost-effectiveness. The analysis is intended to provide insight on the performance of sustainable technology and their potentially widespread use in the future.

Although not all of the sustainable technology in the house is cost-effective at present energy rates, the project can educate a community on alternatives to conventional systems. As the demand for power continues to rise in the U.S, the retrofitting of existing buildings is a more economical solution to the construction of more power plants. At higher energy rates, sustainable technology will become a viable solution to a potential energy crisis.

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[1] National Trust for Historic Preservation, New Energy from Old Buildings, Preservation Press, Washington, D.C., 1981

[2] U.S Department of Energy, Consumption and Expenditures, April 1980 through March 1981, Residential Energy Consumption Survey, September, 1982

[3] The Seri Solar Conservation Study, A New Prosperity, Building a Sustainable Energy Future, Brick House Publishing, Andover, Massachusetts, 1981

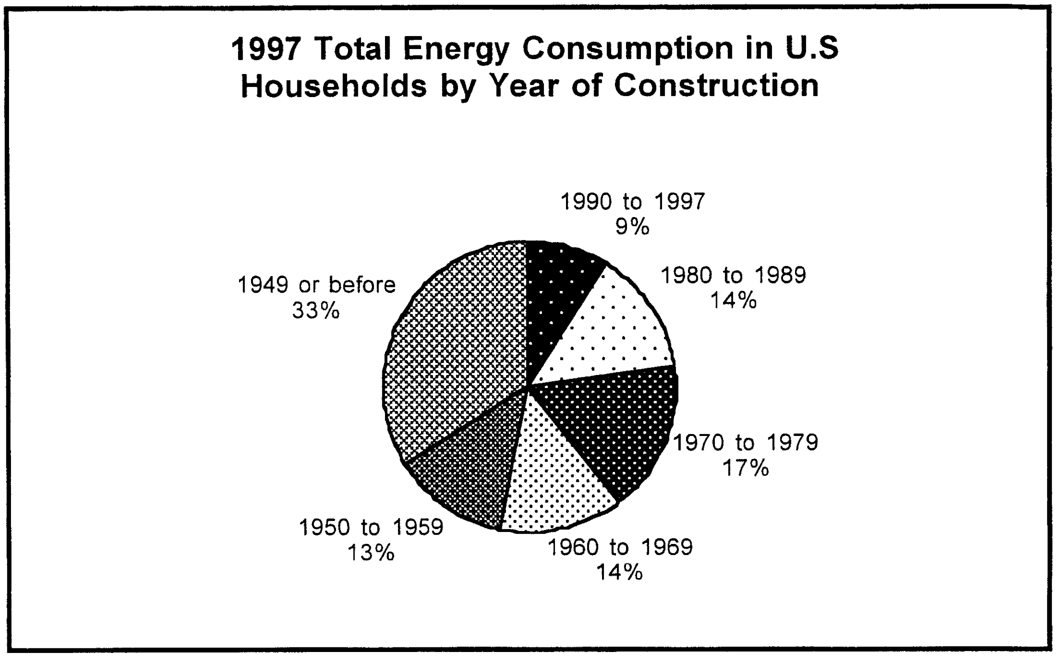

Figure 1.1

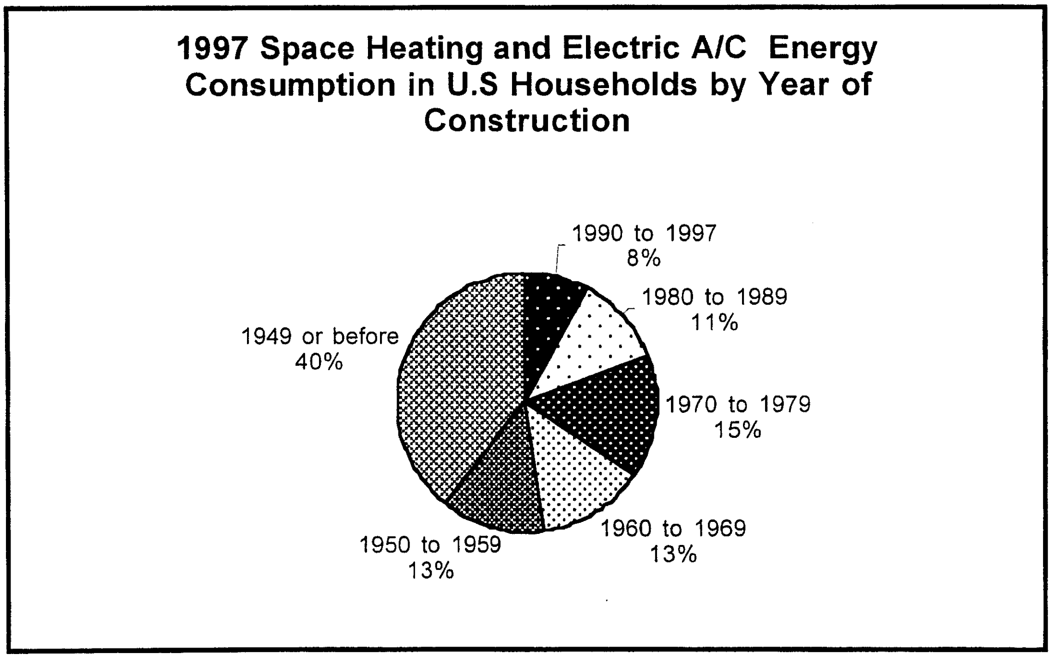

Figure 1.2

Statistics from the 1997 Residential Energy Consumption Survey, U.S Department of Energy

1.1 Procedure

The remainder of chapter 1 of this report cites statistics on retrofit activities performed by homeowners from 1970 to 1990 and 1997. Most of this information was obtained from the 1990 and 1997 Residential Energy Consumption Survey, and a report written by the Lawrence Berkeley Laboratory. The statistics indicate the likely energy efficient measures performed by the average consumer. This chapter demonstrates that most homeowners renovate for repair and remodeling concerns and to meet code standards imposed by government regulation. Only a few have energy efficiency in mind.

The second chapter is a general discussion on the different types of energy saving technology applicable to retrofits, such as heat pumps, insulation, window replacement, radiant systems and solar technology. The chapter describes how the systems work, and some installation techniques practiced by industry. Most of these measures were performed in the Cambridge Sustainable Demonstration Project. However, not all of them are cost-effective at present energy rates.

Chapter three focuses specifically on the demonstration project. The chapter cites the house and describes the house characteristics and energy features. In later chapters, the various measures are rated according to performance and cost-effectiveness. The analysis demonstrates that a homeowner obtains the most energy savings by reducing air infiltration (with an investment in the Blower Door Program) and insulating doors. These investments provide the most savings over the long term. However, heat pumps, photovoltaic systems and radiant heating systems were the least reasonable and cost-effective in colder climates.

Although the analysis of the cost-effective measures in this report is based solely on energy efficiency, the project incorporated many aspects of sustainability such as embodied energy, environmental impact, waste and water resource management. Given the complexity of the above issues, *this report focuses only on the reduction of operational energy*, which is an important aspect of the house.

The process outlined in the investigation entails the following methodology:

1. To explore energy saving options for retrofitting
2. To list energy features and to describe how they work.
3. To compare the heating and cooling loads of a house built according to Cambridge code, 1920s code and the new improvements made by the project engineers of the sustainability team
4. To determine the yearly power consumption of hot water and electricity for a multi-family dwelling
5. To analyze the initial cost of each feature compared to the energy savings

6. To determine which ones provide the most saving
7. To suggest an alternative retrofit design based on cost-effectiveness.

1.2 Current Trends in Retrofitting[1]

The oil embargo in the 1970s stimulated the drive to retrofit homes. Federal and local governments established several policies, such as tax credits, grants, and weatherization programs. Increased funds for research and development accelerated the advancement and the improvement of new solar/sustainable technology. Several guidelines and building codes were established to increase the thermal performance of the building envelopes. Many of these standards encouraged an increase in the efficiency of the building envelope by reducing infiltration, adding insulation and window replacement.

Sources of information on retrofit activity are widely varied, and there is no single document that provides a complete picture on the relative success or the rate of application of energy conservation measures. The Lawrence Berkeley laboratories have studied the following areas of retrofit activity:

1. Installation of ceiling/wall insulation
2. Window Replacement
3. Furnace Replacement
4. Reduction of Infiltration
5. Installation of Efficient Water Heater Technology

1. Installation of ceiling/wall insulation

According to a report entitled, "Progress in Residential Retrofit", published by the Lawrence Berkeley laboratory in 1993, 83% to 89% of households had ceiling insulation. It was estimated from three sources (Residential Energy Consumption Survey (RECS), Owens-Corning Fiberglass Corporation, and Residential Appliance Saturation Survey (RASSes)) that proprietors installed ceiling insulation at a rate of approximately 4% to 6% per year.

The 1990 Residential Energy Consumption Survey showed that 81% of households claim to have some level of wall insulation (the studies were based on the reports of several homeowners who were unsure of the amount of insulation in the walls of their home. As a result, the data collected was not exact). Approximately 25% of the houses with wall insulation had an R-value of 19 $ft^2 °F$ h /Btu, an insulation value that exceeds some energy code requirements in the

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[1] All of the information in this section on the current trends in retrofitting was obtained from the following report: Alan Meier, Brian Pon, Marilyn Brown, Linda Berry, "Progress in Residential Retrofit", Lawrence Berkeley Laboratory, December, 1993

U.S for frame walls. 18% of these households are super-insulated with an r-value of 38 $ft^{2o}F$ h/ Btu. A standard home may have wall insulation with an r-value equivalent to 11 $ft^{2o}F$ h/ Btu.

Based on an Owen-Corning study, the re-insulation activity in households was at a low rate in 1974. However, from 1974 to 1978, there was a sharp increase in re-insulation activity from 2 million to 6 million households per year. From 1978 to 1990, re-insulation improvements slowly decreased and stabilized around 3 million households per year, indicating that it had reached a saturation level. (Figure 1.3)

Retrofits for floor, basement and duct insulation were typically installed during basement renovations, exterior landscaping and other projects unrelated to energy conservation. According to a RECS (Residential Energy Consumption Survey) and RASSes (Residential Appliance Saturation Surveys) study, 14% to 27% of households had some floor insulation, 15% had basement insulation and 20% to 32% had duct insulation.

2. Window Replacement

Heat loss through windows can account for more than a one quarter of the annual heating cost. Based on the Lawrence Berkeley Laboratory report[1], there were approximately one billion windows in the nation in 1990 and 70% of the windows were single-pane. Double, triple, glazed, storm, and low-e windows can significantly reduce energy loss. However, the high cost of window replacement makes such a venture not very cost-effective. The report indicated that in 10% of single-family homes, 50% - 99% of the windows were covered with storm windows. RASSes determined that approximately half of the total number of households surveyed had storm windows. In the 1970s, after the oil embargo, there was an increase in the sale of storm windows. Since then, the sales have steadily declined. (See figure 1.5)

Because of current energy standards, new homes are more likely to have double-glazing than older homes. The installation of double-glazed or even triple-glazing with low-e coating is more cost-effective for new homes because contractors can purchase the materials directly from manufactures at whole sale costs. In addition, the relative cost of a high performance window versus a regular single-glazed window is small and does not greatly increase the construction cost in new buildings. Therefore, the owner may opt to install better windows in newer facilities.

The overall sales of high performance windows (i.e. double-pane with low-e and triple pane) are lower than storm windows. Nonetheless, they have steadily increased since 1986. Half of the annual sales are installed in new buildings and the other half in existing buildings. Approximately, 16 million windows are replaced each year and 90% are double-pane or better. However, most often these windows are replaced due to repair and remodeling rather than energy conservation concerns. (See figure 1.4)

3. Furnace Replacement

An uninsulated distribution system (ducts and pipes) can account for 28% of the overall heat loss in a building. Losses occur for the following reasons: faulty installation, open joints, ruptures and punctures of ducts, and the failure to properly connect return air. The upgrade of an old furnace can significantly reduce the space heating energy bill of a residence. An old furnace can have an efficiency that is 25% lower than a modern furnace.

Since 1975, the sale of furnaces with efficiencies below 65% has decreased steadily over the years. However, the sale of furnaces with efficiencies of 80% or greater have increased. This is due primarily to the standards imposed by the government. Trends in the sale of furnaces indicate that consumers will either purchase equipment with an efficiency in the range of 65% - 71% or equipment that has an efficiency of 80% or greater. (Figure 1.6)

3. Reduction of infiltration

One third of energy loss can occur through air infiltration. Existing dwellings in the United States are ventilated primarily through leaks in the building envelope (exfiltration /infiltration) rather than whole mechanical ventilation systems. Home-weatherization, the simple caulking and weather-stripping of frame walls and windows, can significantly reduce air leakage. The Blower Door Program, a service where professionals are hired to tighten the house, is very effective in reducing air infiltration. These programs are not well known among the public or simply not utilized. As a result, only 1% of households in the United States has employed blower door diagnostic technology. Interestingly, low-income weatherization agencies funded by the government have been leaders in the use of blower door. Under the DOE Weatherization Assistance Program, 18% of the participating households used the blower-door diagnostic technique.

5. Installation of Efficient Water Heater Technology

In 1997, water heating accounted for 19% of the total energy consumption in U.S households. Some water saving energy measures include, water-efficient appliances, flow restrictors, temperature reduction, fuel switching (from electricity to gas), and pipe insulation. Due to recent Federal appliance standards geared to cut energy used for water heating with a reduction in consumption, 35% of all homes in 1990 had flow restrictors. Around 17% to 35% had some form of pipe insulation. With government regulations, hot water consumption in the future can be reduced by 40% with the installation of low-flow showerheads, water-efficient washing machines and dishwashers. Nonetheless, today, millions of homes still contain high-flow showerheads and uninsulated water heaters, and the total percentage of energy consumed for water heating has increased from 1978 to 1997. (Figure 1.7)

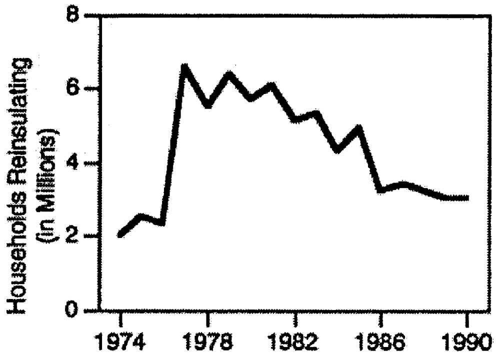

Figure 1.3 Ceiling re-insulation Activity over time

Source: Owens-Corning Marketing Research, September 1991

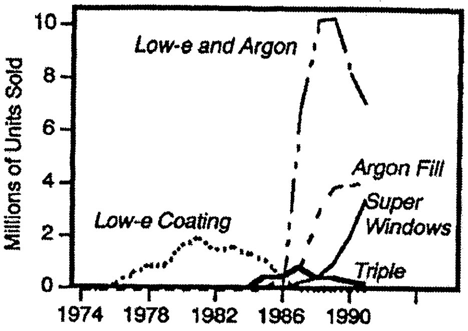

Figure 1.4 Sales of Hi-Performance Windows from 1975 to 1991

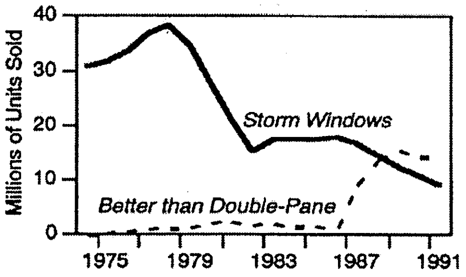

Figure 1.5 Sales of Storm Windows from 1975 to 1991

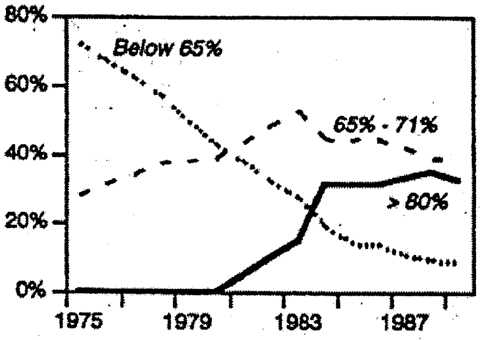

Figure 1.6
Trends in the sale of Furnaces

Source: LBL Report 34172

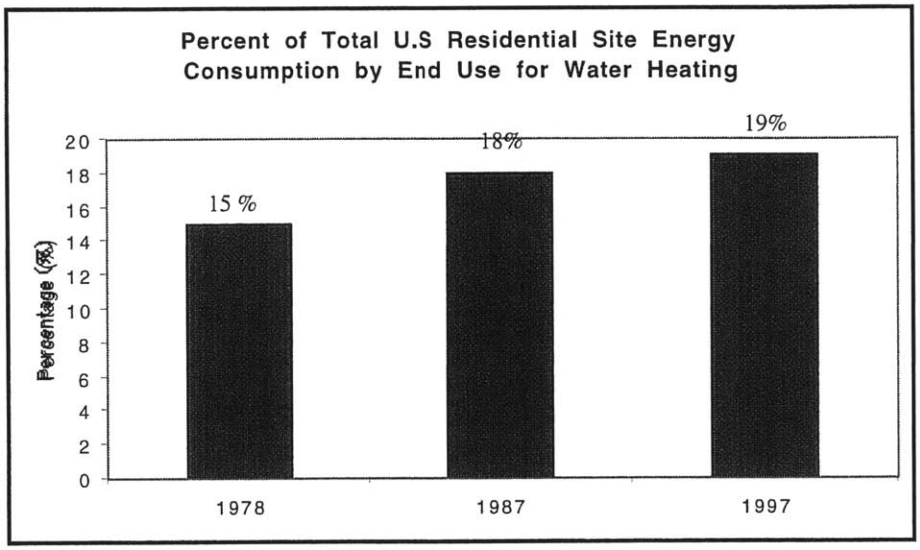

Figure 1.7
1997 Residential Consumption Survey

1.3 Residential Energy Consumption Trends

According to the Residential Energy Consumption survey, the differences between 1980 and 1990 in the use of the specific energy conservation features have been few. There have been a few modest areas of improvement such as the use of roof or ceiling insulation. In the ten-year interval, more households had roof and ceiling insulation. However, fewer households used night set-back.[4] In 1981, 72% of the homes surveyed were likely to have their thermostats at less than 70°F during the night compared with only 52% of households in 1990. A smaller percentage of occupants in 1990 were also likely to have their temperatures less than 70°F during the daytime (or when at home) compared with occupants in 1981.

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[4] Energy Information Administration, Housing Characteristics 1990, U.S Department of Energy, Washington, D.C., May, 1992

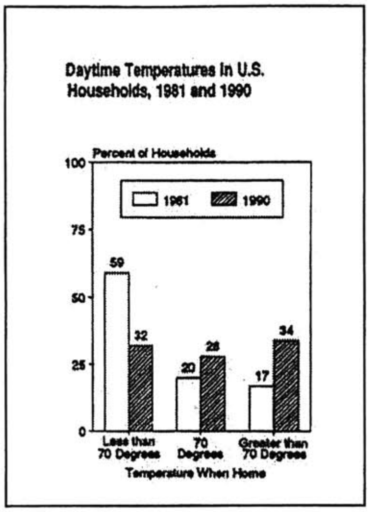


Figure 1.8

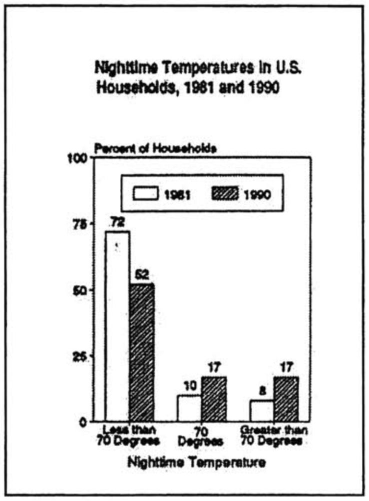


Figure 1.9

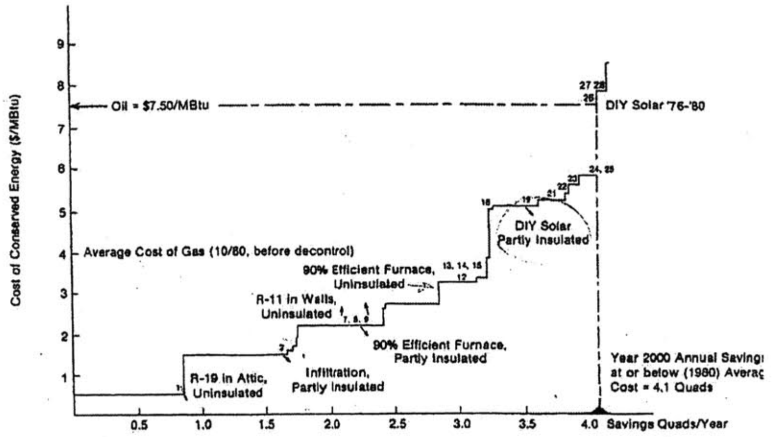
Source: 1990 RECS

From 1978 to 1997, there was an increase in the number of houses constructed in the southern region of the United States. Consequently, the number of air conditioning units installed in these new homes increased, and a greater percentage of households kept their air conditioning units turned on all summer in 1990 rather than in 1981; the percentage increase was from 22% in 1981 to 35% in 1990. This was also due to a greater prevalence of central air conditioning which is more likely to be kept running than room units. In the South, the percentage of housing units with central air-conditioning increased by 33% from 1978 to 1997.

Interestingly, over the decade (1981 to 1990), the total residential heated floor space increased from 122.4 billion square feet to 147.5 billion square feet[2]. This was due to the increase in the size of single-family homes. A greater percentage in the square footage of floor area usually corresponds to greater energy consumption. However, the number of people per household decreased from 2.76 in 1980 to 2.63 in 1990[2]. Fewer people per household indicates that less energy is consumed for daily activities such as cooking, washing, hot water, appliances, etc.

From 1980 to 1987, there was a general trend towards the construction of "shared walls" or attached single and multifamily housing[2]. With fewer exterior walls, there was a reduction in heat losses to the outside air, indicating a savings potential. However, the trend reversed itself from 1987 to 1990, and more detached single family housing was constructed. By 1990, approximately two-thirds of homes were single family units.

Although the numbers of active solar households increased from 1980 to 1990, they still remained a minority. Less than 1% of the 94 million households in 1990 used active solar[2]. Most of these home were located in the western part of the United States. Because of the high cost of these technologies (heat pumps, solar thermal panels, photovoltaic module, etc), they are not cost-effective nor deemed necessary by the average homeowner. Today, solar technology is typically installed in wealthy homes; essentially owners who can afford the loss (a negative net savings over a twenty year span). Figure 1.10 from the SERI solar conservation study shows the cost of conserved energy compared with the annual savings for various conservation measures, applied to retrofitting a home. Based on the incremental increase versus the savings (quads), the application of solar technology is the least affordable when compared with re-insulation activities.

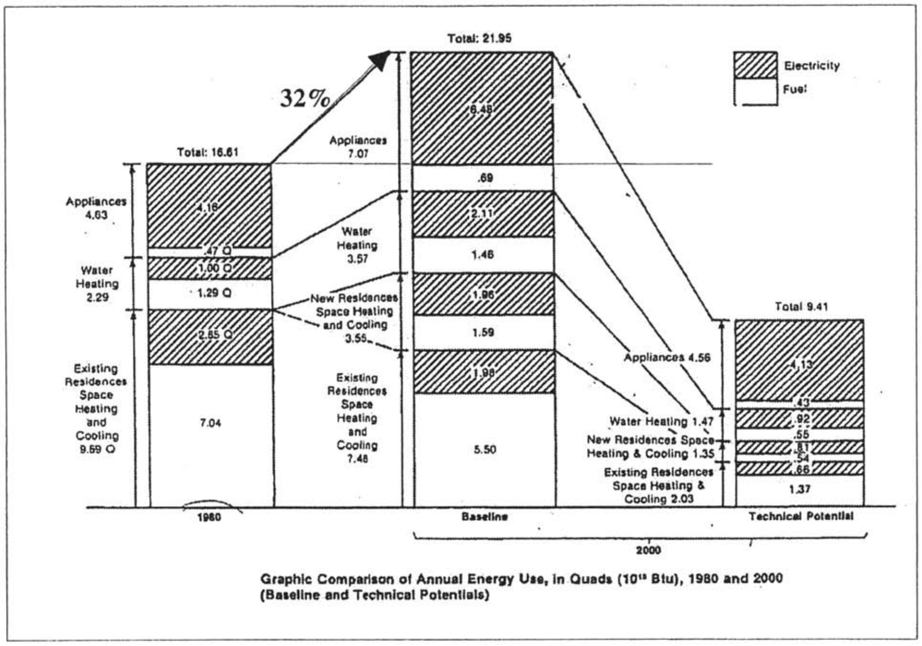


Year 2000 Supply Curve of Conserved Energy (in quads/year) for Space Heat of Fuel Heated Dwellings Built Through 1980.
Year 2000 baseline annual use for this sector is 5.5 Quads, where "baseline" assumes continuation of 1980 average unit energy consumption for existing stock or new additions in that year. Unit cost of conserved energy (in constant 1980 $) assumes that all increased costs are amortized over the useful life of this measure, using a 3% (real-dollar) interest rate. Potential annual savings in 2000, at or below today's cost of oil (7.5 $/MBtu) is 4.1 quads, or 75% of the year 2000 baseline.

Source: 1980 Seri Solar Study

Figure 1.10

The baseline case for the SERI Solar study (figure 1.11) predicted a 32% increase in residential energy consumption from 1980 to the year 2000, under the assumption that energy trends would remain the same. However, based on RECS (Residential Energy Consumption Survey) data, it appears the various steps forward and backward in conservation measure have decreased the rate of increase in residential energy consumption. This indicates that there has been some minimal progress in the reduction of residential energy consumption. For example, in 1980 the annual fuel use of all households was 9.32 quadrillion Btu. In 1997, the fuel consumption increased by 10% percent to 10.22 quadrillion Btu. Figure 1.13 demonstrates that the overall residential site energy consumption decreased from 1978 to 1987, and increased slightly from 1987 to 1997. Over the two decades, the decrease in the amount of energy used for space heating was offset by the increase in the energy used for water heating, electric/AC, and appliances. However, in order to significantly reduce consumption levels, (by 72%) as recommended by the SERI Solar Study, more aggressive measures must be taken by the building industry.



Source: 1980 Seri Solar Study

Figure 1.11

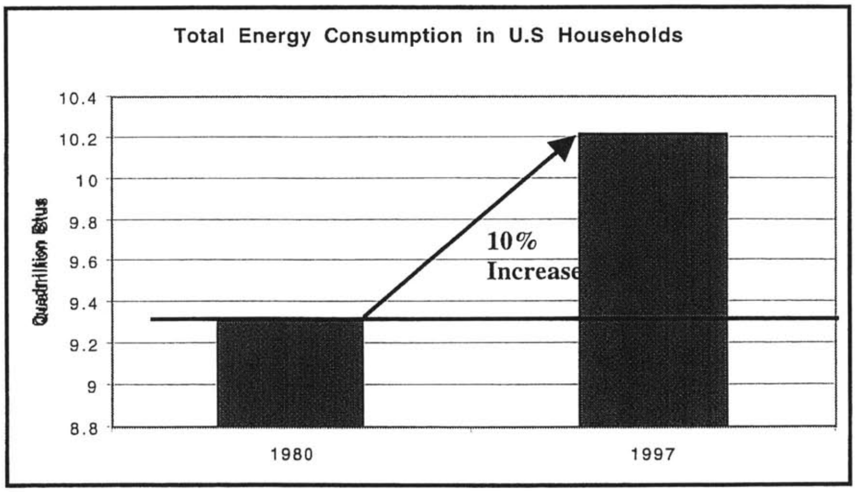


Figure 1.12

1997 Residential Consumption survey

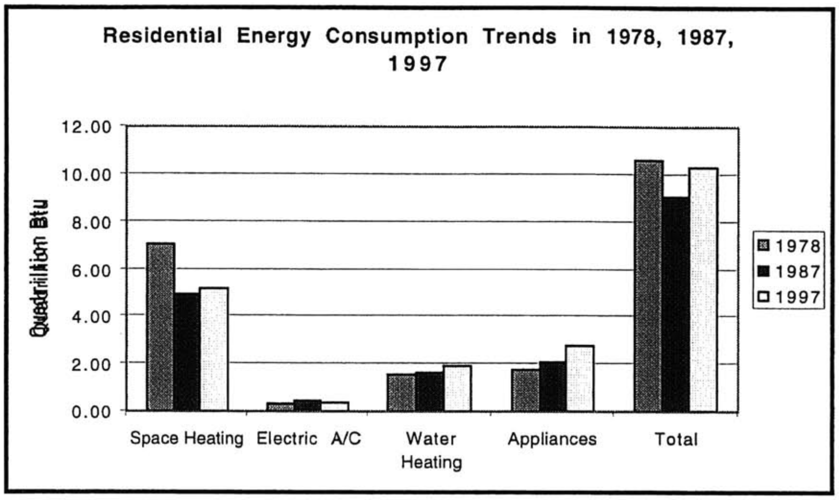


Figure 1.13
1997 Residential Consumption Survey

1.4 Energy Efficient Upgrade Programs

There are several programs across the nation and other countries designed to reduce energy use in homes. In many of the states in the United States, regulatory commissions required utility companies to implement Demand-Side Management (DSM) programs in order to reduce electricity demand. The DSM programs depend on the voluntary participation of homeowners to allow utility sponsored upgrade measures applied to their homes. According to the 1990 RECS report, of 94 million households, 4% were participants in the programs. 89% of the participants were from single-family or mobile home. Studies show that members in the program were more likely to have the following energy efficient measures such as furnace tune-up, water heater insulation, weather-stripping, caulking, storm doors and storm windows. The following chart shows a comparison between participants and nonparticipants in demand-side Management Programs in the year 1990. The participants comprised 4% of the total number households. The non-participants comprised the other 96% of households that did not participate in the program.

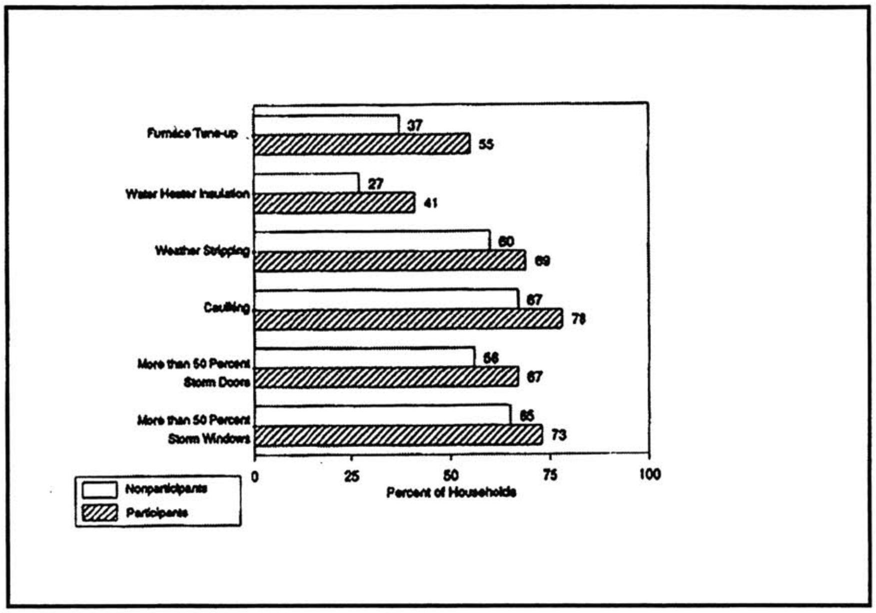


Figure 1.14

1.41 Energy Efficient Programs in Canada: R-2000 and Advanced Houses Program

A study in Canada considered the incremental cost, performance and acceptance of energy efficient upgrades for affordable homes under two initiative programs: The Advanced Houses and R-2000 program. The Natural Resources Canada instituted both programs as leaders in environmentally responsible housing.[3]

Under the R-2000 program, certified builders construct houses that meet very high standards for energy efficiency, ventilation, low emission, resource efficient material selection and water efficiency. R-2000 houses use about one third less energy than houses with conventional construction. In addition, the retrofitted homes are evaluated and inspected for quality assurance.

Under the Advanced Houses Program, ten homes are selected as prototypes across Canada. The houses reflect the building industry's effort to reduce energy consumption to one half of the R-2000 guidelines. Significant measures include the improvement of indoor air quality, and the drastic reduction of the environmental impact of the houses. The program uses two thirds less energy than conventional construction. Ideas from the Advanced Houses initiative have been used to update the R-2000 standard.

From analysis conducted under both programs in Canada, various technologies emerged as the most appropriate and cost-effective for affordable homes:

---

[3] Kevin Lee, "Energy-Efficient Upgrades for affordable homes in Canada", Cadett Energy Efficiency, March, 1998

1. Efficient framing: the optimization of framing, using the least amount of lumber
2. Blown-in Cellulose insulation: cost-effective and improves energy performance
3. Advanced Air Barrier systems: air-sealing techniques
4. Improved Basement insulation: saves energy, reduces heat loss to the ground
5. Energy Efficient windows: installation and replacement of windows with low-e coating, argon fills, insulative spacers
6. Combined space and water heating systems: i.e. ground source heat pumps
7. Heat recovery ventilators: provides effective ventilation by recovering the heat from the exhaust indoor air
8. R-2000 lighting upgrade: installation of energy efficient light bulbs
9. Water efficient fixtures: very little incremental cost saves both energy and water

1.5 Chapter Summary

Based on the statistics, it appears that energy efficiency was not a concern for most homeowners. Over the years, most of the reduction in energy consumption was a result of government-imposed standards on window types, the efficiency of furnaces and efficient water heater technology. Although there was a decrease in the residential site energy consumption from 1978 to 1987, the downward trend reversed itself and increased from 1987 to 1997. The was due in part to the increase in centralized air conditioning units, the construction of single family homes and the increase in energy used for water heating. In addition, there was an increase in electrical consumption because a greater number of homes in 1997 had microwave ovens, dishwashers, clothes washers/dryers and computers.

In 1997, 66% of the residential energy consumption for space heating and electric A/C was used by homes constructed before 1970. To reduce energy consumption, aggressive measures must be taken by the building industry, the government and utility companies.

Chapter 2 Energy Saving Measures for Retrofits

2.0 Overview of Energy Features in the Cambridge House for Sustainability

The Cambridge House for Sustainability incorporates many of the features outlined in the Canadian energy efficient homes programs. These improvements include a building envelope upgrade, the installation of a ground source heat pump, lighting upgrades and water efficient fixtures. The project engineers redesigned the Cambridge House for Sustainability in accordance several ranking systems[1] that take into account embodied energy of materials and societal costs, such as pollution.

The House has the following energy features:

1. Insulated walls, ceiling, slab floor
2. Energy Efficient Windows
3. Ground Source Heat Pump
4. Photovoltaic System
5. Solar Hot Water Heating System
6. Radiant floor/wall/ceiling

All of the above measures reduce energy consumption; however, only a few are more practical and cost-effective for retrofits in New England. The diagram on the following pages outlines possible retrofit measures that a homeowner can apply to his/her house in the northern region.

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[1] Ranking system was based on the Building Science Engineering Energy Sustainability Rating, a ranking system developed by the whole sustainable team. It is based loosely on the Austin Green Builder Program System and the British Colombia BEPAC system for commercial buildings.

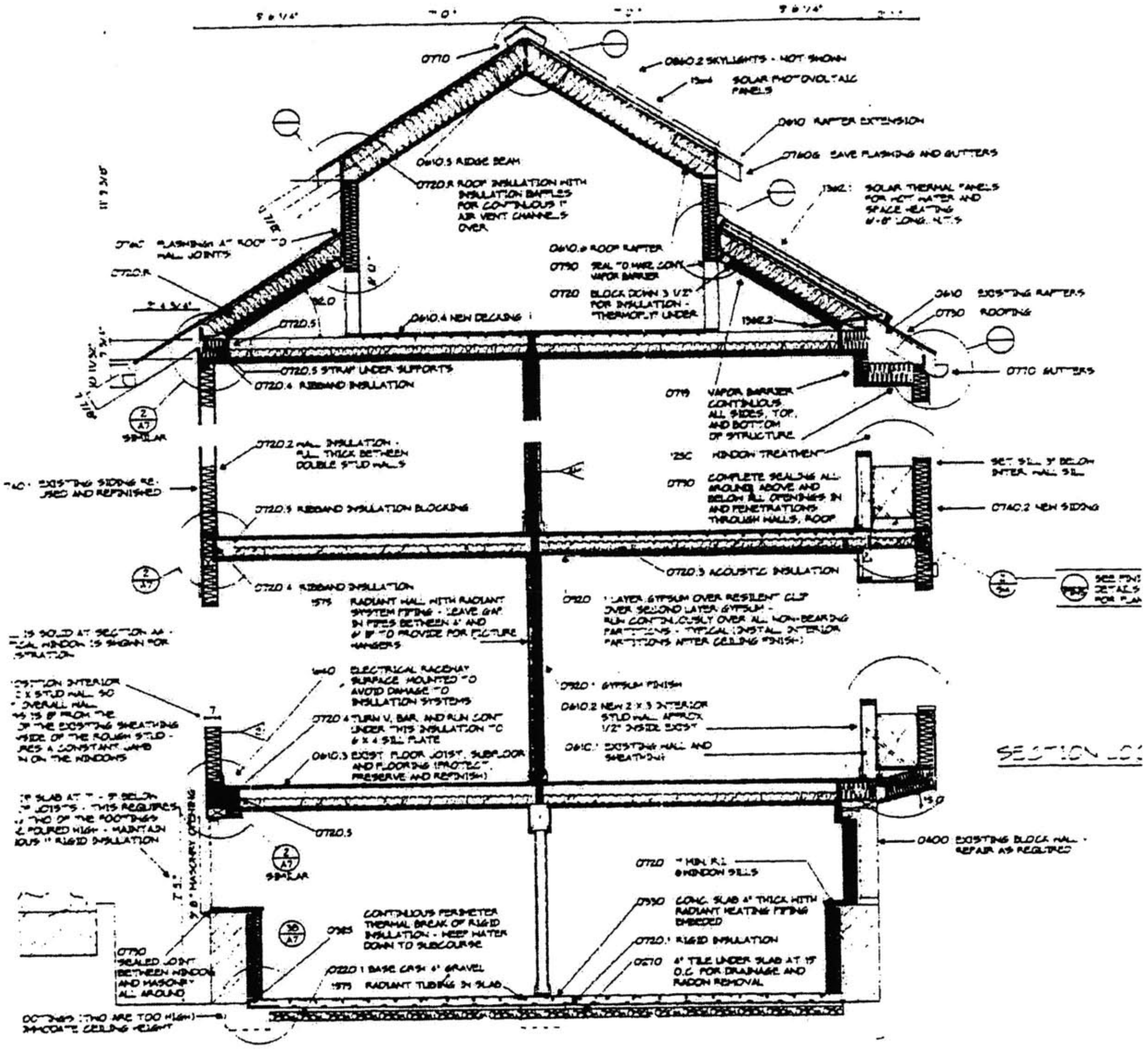
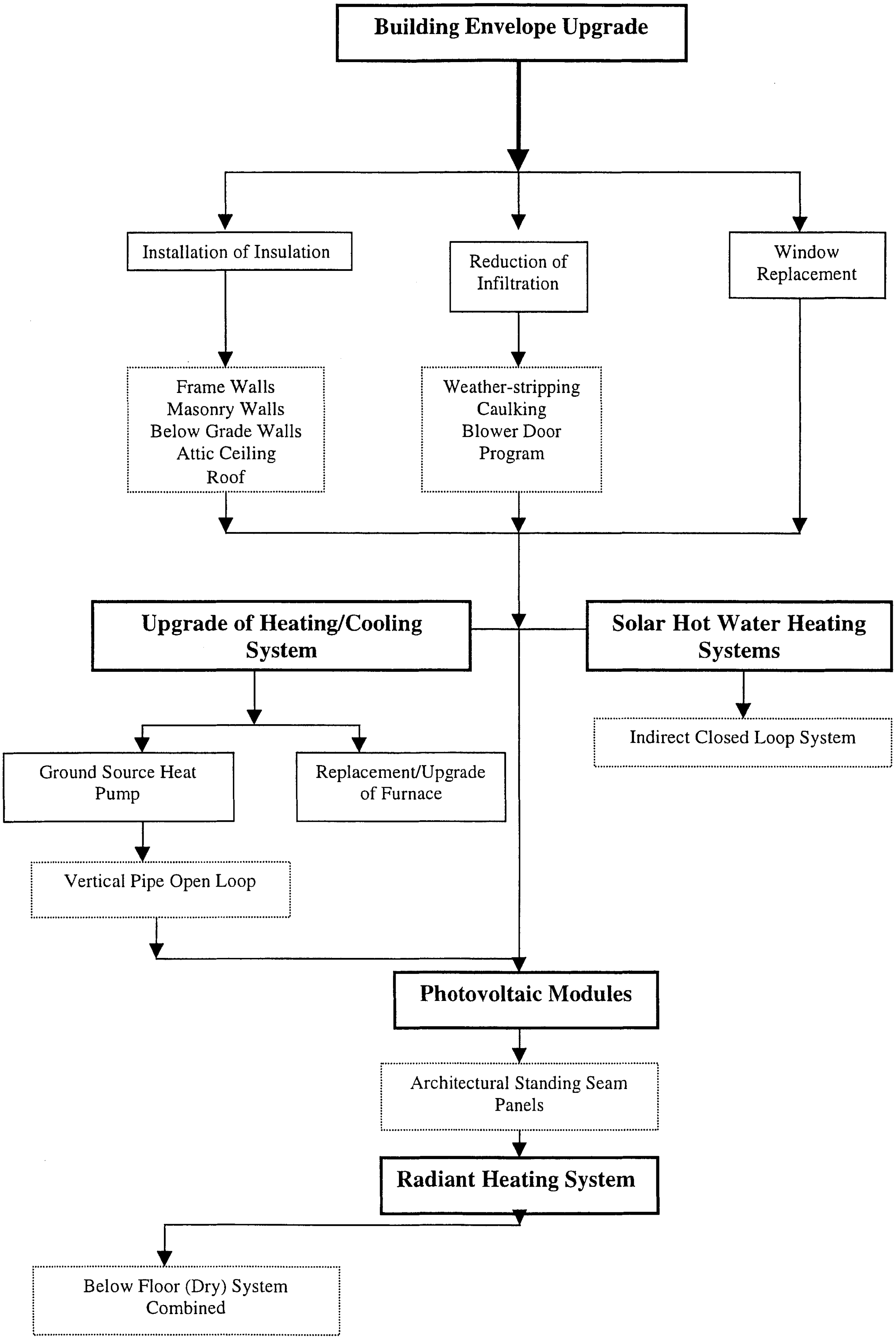


Figure 2.1 Cross Section of Cambridge House


Building Envelope Upgrade
Installation of Insulation
Reduction of Infiltration
Window Replacement
Frame Walls
Masonry Walls
Below Grade Walls
Attic Ceiling
Roof
Weather-stripping
Caulking
Blower Door Program
Upgrade of Heating/Cooling System
Solar Hot Water Heating Systems
Indirect Closed Loop System
Ground Source Heat Pump
Replacement/Upgrade of Furnace
Vertical Pipe Open Loop
Photovoltaic Modules
Architectural Standing Seam Panels
Radiant Heating System
Below Floor (Dry) System Combined

2.1 Building Envelope Upgrade

The Cambridge house was built in the 1920s. Before the renovation, there was little or no insulation in the walls and many leaky areas in the house that allow air infiltration. This house represents a typical home in the New England area that loses most of its heating energy to the outside air. Therefore, a building envelope upgrade should rank as the first retrofit measure performed on a home. Not only are improvements to the building envelope cost-effective, but it decreases the demands on the heating and cooling system by reducing the rate of heat loss to the outside air. There are many methods of improving the envelope such as insulating frame walls, doors, the installation of energy efficient windows and the caulking and weather-stripping of frame walls and windows.

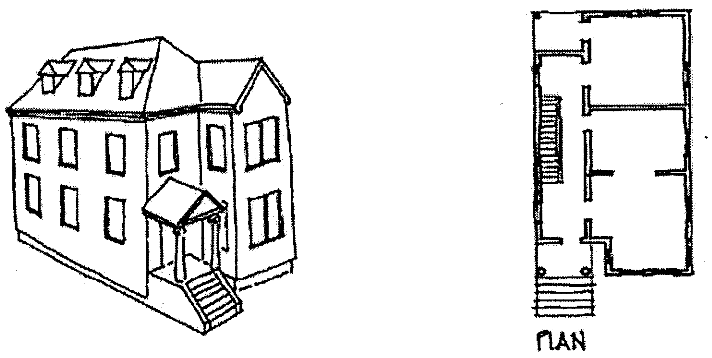


Figure 2.2 Standard Single Family House in New England

2.1.1 Insulation

In the demonstration project, several standard techniques were used to increase the insulation thickness and reduce heat loss. The following basic components of the building envelope were insulated: vaulted ceiling, frame walls, masonry walls, below grade walls, doors and slab floor. The type of insulation was determined by space availability, economic and practical considerations. Plastic board was applied to the doors, walls and the slab floors because of its structural rigidity. Cellulose insulation was placed between the rafters of the vaulted ceiling in the attic. There is usually enough space between the rafters of the attic such that insulation can be added without lowering the overall height of the ceiling.

Each material has certain properties with advantages and disadvantages. It is usually sold in the following forms: batt or blanket (fiberglass), rigid board (sold in sheets), spray/foam and cellulose. Insulating materials differ in cost and effectiveness.

The following table lists the different r-values and prices for cellulose, batt, rigid board and spray foam.

Table 2.1. R-value and Price for Insulation

Type of Insulation	R value (hr ft^2 °F/Btu) per inch	cent per R-foot squared[1]
cellulose (sold in bags)	3.7	1.6
Batt (fiberglass)	3.1	1.4
Rigid Board	5.0	10
Spray foam	5.6	5.2

Fiberglass is cut into different lengths, poured or blown into walls; however it can irritate the respiratory system, and installers must take precautionary measures. The material is flexible, and does not warp as in the case of rigid board insulation. Given its relatively cheap cost, it has a high resistance to heat loss. If fiberglass is wet, it will regain its insulative value once it becomes dry. However, during the period that it is wet, the insulative value is reduced[2].

Polystyrene and Polyurethane are two different types of rigid, plastic board. Plastic boards are attached to frame structures with adhesives, nails and fasteners. Given its brittle properties, it can easily fracture. Polystyrene is good for high moisture areas because it can act as its own vapor barrier. But, the material is flammable and fire resistant protection is needed[2].

Cellulose, recycled paper made from wood or plant fibers, is either blown or poured into frame walls. In high moisture areas, the insulative value of cellulose is reduced. Therefore, it is necessary to install the material with vapor barriers to provide enough ventilation such that moisture particles can evaporate. Because it is sold as a loose fill, small pieces of cellulose can fit in tight spaces. However, the pieces have a tendency to settle which reduces its overall r-value. Cellulose is also flammable and fire resistant treatment is necessary. It becomes ineffective when wet. Consequently, it is not used with masonry, below grade or metal construction[2].

Fiberglass and plastic board are the most common types of insulation used in both new construction and renovations because of their relatively high insulative values and easy installation. A combination of fiberglass and plastic board is a cost-effective measure to increase the overall r-value for the walls. Fiberglass (batt) is cheaper than rigid board insulation; however, it has a lower r-value per inch thickness. A greater amount of fiberglass is needed to obtain a

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[1] Price range based on retail level in 1996. Information on the approximate price range was obtain from Harvey, Henry, *Development of Straw Insulation board: Fabrication Methods, Structure, Thermal Performance*, Thesis, 1996

[2] The Scientific Staff of the Massachusetts Audubon Society, City Lights, a Handbook of Energy Conservation and Renewable Energy for City Homes, Massachusetts Audubon Society, November, 1980

desired level of insulation, which reduces that amount space in the house. Therefore a combination of both batt and rigid board insulation reduces space and cost per unit area of wall. One may also combine rigid board with cellulose to obtain a desired r-value. Cellulose is relatively cheap. Sometimes, it is blown into walls, and used to insulate the attic floor or ceiling spaces.

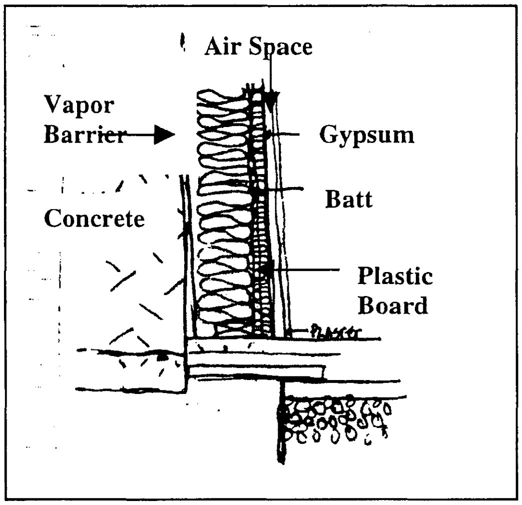


Figure 2.3 Masonry Wall Detail

2.1.2 Installation of Insulation

Installation costs for insulation are estimated at $2.59 per square foot (including labor) in the New England. The initial investment is cost-effective at some insulation levels and can significantly reduce the annual energy bill as much as 45% depending on the type of house.

Given the varying properties of the insulative materials, fiberglass, cellulose and plastic board are most appropriately applied to different areas of a house. The following areas require different types of insulation: the attic floor, the roof, the ceiling, frame walls, the masonry above grade walls, masonry below grade walls, and the basement ceiling.

Attic floor/Roof Insulation/ Ceiling

A homeowner has the option of insulating an attic floor or a roof in order to reduce energy loss. 10% or more of the energy loss can occur through a poorly insulated roof and/or floor.

Loose fibrous and batt or blanket (fiberglass) is usually installed in the spaces of the floor joists of an attic floor. It is either blown in or emptied from large bags. In some houses, it is difficult to insulate the floor so the roof is insulated as an alternative[2]. (Figure 2.4)

Rigid board insulation is usually installed on a roof and covered with sheathing. In a retrofit, an installer must remove the roofing material and attach the insulation to the sheathing. The rigidity of the board is necessary to withstand the weight of people working on the roof. (Figure 2.5)

Interior roof insulation is an alternative to insulating the exterior. On the inside of the roof, batt or blanket (fiberglass) is installed in the spaces between the rafters. A finished surface is then attached to the bottom of the roof rafters. This technique was applied to the Cambridge House and is an easier installation technique compared to the removal of the exterior sheathing.

In cases where it is difficult to insulate an attic or roof, ceiling insulation is necessary. This might involve the construction of a suspended ceiling (lowered 6 inches), where rigid panels are set within a metal or wood frame structure. In other cases, batt or blanket is laid on top of the suspended ceiling or loose, fibrous is blown in. (Figure 2.6)

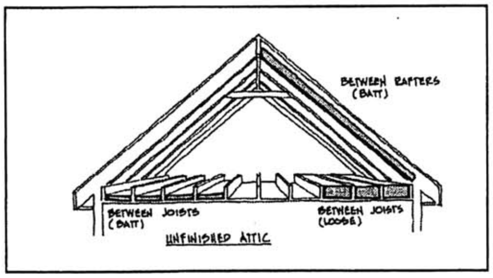
Frame Wall Insulation:

A substantial portion of energy losses can occur through the frame walls; as much as 27% of the energy bill. There are different methods of insulating walls. In some construction, loose-fill-wall insulation is blown into wall cavities through small holes in each stud space. It is either blown in from the inside of the wall through the plasterboard or from the outside exterior face through the sheathing[2]. In other more conventional methods, batt, blanket or plastic board is installed in the stud cavity during the finishing of the interior wall. In retrofits, insulation is either blown into an empty wall cavity or interior plasterboard and finish is removed. Strapping or additional wood is applied to the studs to allow for more insulation (see figure 2.7). A gypsum board finish is then applied to the new extended walls. In the Cambridge demonstration project, strapping was necessary for the frame, masonry and below grade walls to obtain the desired r-values.

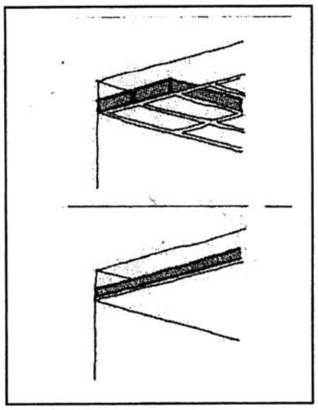
Masonry Wall Above Ground:

In masonry walls (above ground), rigid board insulation is placed inside or outside the face of a masonry wall. If the insulation is on the inside of the house, it is attached with adhesive or nails to a plaster wall and sheetrock is then applied to its surface. If on the outside of the house, the rigid boards are affixed to the exterior wall and covered with siding. In the case where batt or blanket insulation is used instead of plastic, an installer must construct a new stud wall against the inside face of the masonry. The blanket insulation is then placed between the studs and a new finished wall is installed over the stud wall.[2] (Figure 2.8)

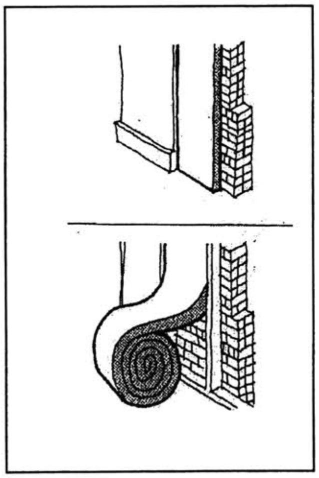
Installation Techniques



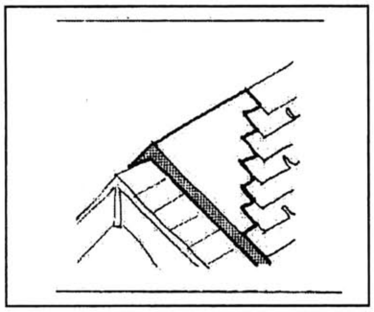
Insulation of attic floor
Figure 2.4



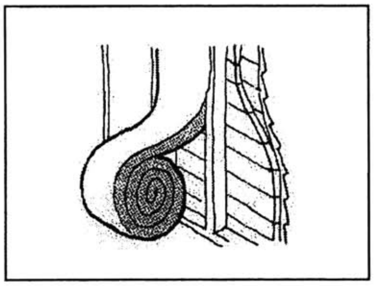
Suspended Ceiling with Insulation
Figure 2.6



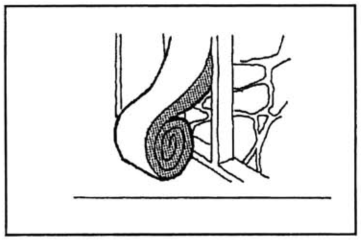
Masonry Wall with Insulation
Figure 2.8



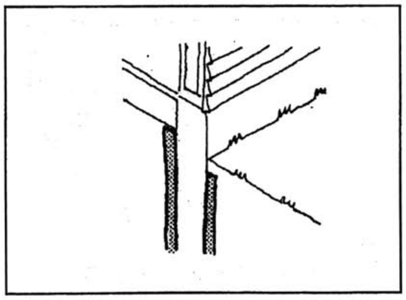
Exterior Insulation of Roof
Figure 2.5



Frame Wall with Strapping
Figure 2.7



Below Grade Wall with Batt Insulation
Figure 2.9



Below Grade Wall with Exterior Insulation
Figure 2.10

Wall Insulation Below Ground:

During installation of the insulation, rigid board is placed on the inside or outside of the below grade wall. There are two basic techniques of applying a finish. On the inside surface, the boards are adhered to an existing plaster wall and a fire resistant material or sheet rock is then applied. On the exterior, installers can affix rigid boards to the below grade wall and cover it with a waterproof finish. With this technique, spaces are necessary for the exterior perimeter drainage. If batt insulation is placed on the inside of the wall, the installer can construct a new stud wall and place fiberglass insulation inside the wall cavity. Foundation walls must be treated with a vapor barrier to prevent incoming moisture. Blanket insulation will draw the moisture into itself (functioning as wick) causing a reduction in its insulative value[2]. (Figure 2.9 and 2.10)

Basement Ceiling Insulation:

Batt or blanket insulation can fit between the floor joists. If the basement is unheated, the vapor barrier should be placed facing towards the upper floors or the warm side.

2.1.3 Vapor Barriers

A well-insulated house can have moisture problems. When the outside air is colder than the dew point temperature of the inside air, the water vapor contained within the warm air will condense and saturate the inside insulation. This reduces the its effective insulative value, causing mold growth, the deterioration of structural material, and the peeling of paint off the walls. There are two methods of solving the problem: proper ventilation and vapor barriers[2].

Vapor barriers are sheets of plastic, paper or foil that retard the transfer of water vapor through insulation. The vapor resistant membranes do not completely bar the transmission of water vapor. These barriers are placed on the warm side of the house. Many types of batt or blanket insulation are sold with a vapor barrier as a backing, plastic boards such as polystyrene and polyurethane as act their own barrier; however, they must be properly sealed at joints and penetrations[2]. A separate barrier is required for loose insulation, such as polyethylene film. In cases where vapor barriers cannot be installed, such as a finished wall, there are alternatives to retarding water transfer. A vapor barrier primer, several coats of oil based paint, or the covering the wall with a ceramic tile or plastic coated panel can serve to slow down the flow of water vapor. These alternatives are not effective in high vapor rooms such as bathrooms and kitchens[2].

Ventilation is another method of controlling the moisture problem in buildings. The circulation of air through structural and insulative materials can remove water vapor. In wood frame buildings, the exterior surface such as sheathing and siding should be constructed of materials that breathe such that the moisture can escape from the building. However, it can accelerate the energy losses from the building.

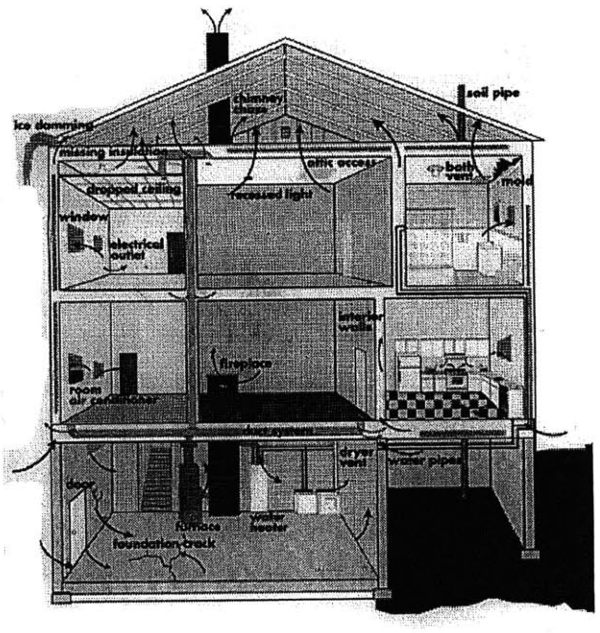


Figure 2.11 Air leakage Areas in a House

2.1.4 Air Leakage

Weather-stripping/Caulking:

One third of the energy losses in a residence can occur through air leakage. A homeowner may consider weather-stripping or caulking as a means of conservation. The caulking of one window may cost around $10.91 dollars per window in the Boston area (1997 Means Residential Cost Data), and serves as a worthwhile investment for a proprietor (if he chooses to do the caulking himself). Heat loss occurs through cracks and seams in the building envelope. The most typical areas are the interstitial spaces between window frames and walls, doorframes and walls, foundation and walls and junctures between porches and exterior walls[3].

Commercially available caulking compounds and weather-stripping materials will vary in price and longevity. A homeowner should purchase the more expensive products for longer lasting results and consequently greater energy savings.

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[3] Steven Winter Associates, Inc <u>HUD Rehabilitation Energy Guidelines for One-To-Four Family Dwellings</u>,U.S Department of Housing and Urban Development, Office of Policy Development ad Research, September, 1996

Air Sealing:

Old houses usually have joints that are hard to locate. Typical areas are joints around electrical and plumbing work. These joints can be sealed with an expanding foam sealant. Air sealing is a critical step in eliminating air leakage "short circuit" that reduces effectiveness of insulation[3]. Quality air sealing requires a professional.

Blower Door Program:

The Blower Door Program was employed by the demonstration project to reduce air leakage. The program is a service available through some utility companies and private organizations where highly trained professional will analyze the energy performance of a home. The cost of professional labor in Boston is estimated at $100 per hour and the approximate time per apartment is 2 to 4 hours. It is one of the most cost-effective means of reducing energy consumption and can provide substantial energy savings.

In order to measure the air leakage of a house, technicians will employ the blower door diagnostic technique. A blower door device is capable of pressurizing or depressurizing the house in order to measure the resultant airflow and pressure. To perform the test, a large fan is mounted on an exterior doorway to cause an exaggeration of air movement through a home. Energy efficient specialists then identify areas of air leakage, and take measures to seal the leaks. The Bernoulli equation relates the pressure difference to the volumetric flow rate. The volumetric flow rate increases with an increase in the pressure difference and effective leakage area.

$$Q = ELA\sqrt{\frac{2\Delta P}{\rho}} \qquad \text{(Eq. 2.1)}$$

Q= volumetric flow rate
ELA = effective leakage area
ρ = Air density
ΔP = pressure difference

The testing also measures the amount of natural ventilation necessary to insure proper indoor air quality. If an inadequate air exchange is detected, the technicians may recommend mechanical ventilation. An alternate test involves the use of infrared photography to provide a visual indication of heat loss through the envelope. The variations in color detected by the infrared scan show the major areas of leakage. Once all the areas are detected, the energy specialist will use a variety of materials to eliminate the air passages. These materials are sealant foams, caulking, weather-stripping, rigid foam board insulation. When less air escapes through the building envelope, unheated attic space and basement, it helps to eliminate moisture problems. The specialist may also determine what areas of the house need insulation upgrades or other areas that may have been overlooked during construction.

The following equipment is used for analysis; duct cleaning equipment, flue gas analyzers, combustion analyzers, back-draft testers and infrared cameras. After the various energy efficient measures have been taken, specialist will perform extensive testing to insure that improvements significantly reduce operating cost.[4]

2.1.5 Windows

In the Cambridge House for Sustainability, all of the old windows were replaced to reduce energy loss. Window replacement is an effective means of energy conservation, particularly in older homes that have poorly fitted frames and single glazing. Over 50% of the energy loss in an older home can occur through the windows. Heat loss is a result of air infiltration as well through, conduction, radiation and convection. The following factors contribute to the overall U value (effective heat transfer coefficient) of a window:

1. Glass thickness
2. Number of panes of glass
3. Size of air spaces between panes of glass
4. Filling of spaces between glass panes with inert gas such as argon, Krypton
5. Coating of glass surface ("low e")
6. Widow frame material and insulating thermal breaks

The new windows of the Cambridge house have double-glazing, low-e glass, and argon gas between the glass panes. Unfortunately the cost of window replacement greatly exceeds the energy savings and such an undertaking is not cost-effective. A homeowner may find that it is better to caulk old windows rather than to replace them. Several types of windows have varying effective resistance and cost. Table 2.2 lists varying window systems and the estimation of the price range in Boston based on information from the 1997 Means Residential Cost Data. Price range depends on the type of each window system, size and construction. Costs vary according to the retailer and the region.

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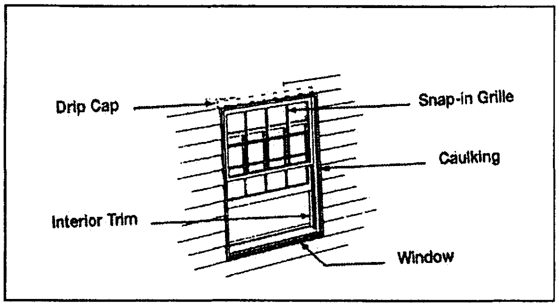
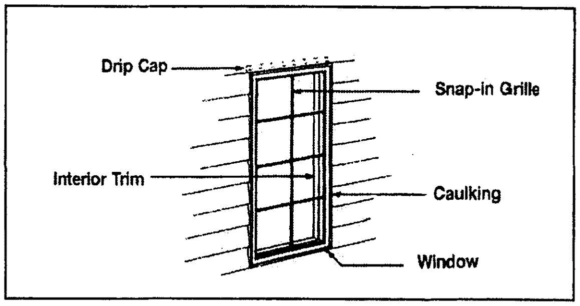
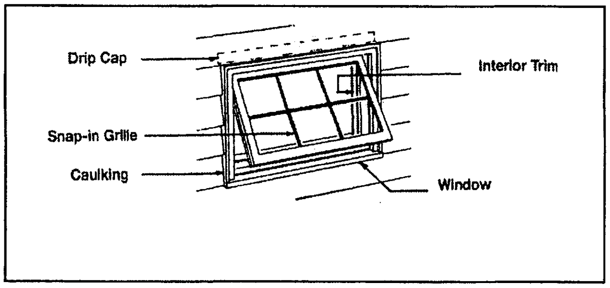
[4] Conservation Services Group, "Comfort Crafted", brochure



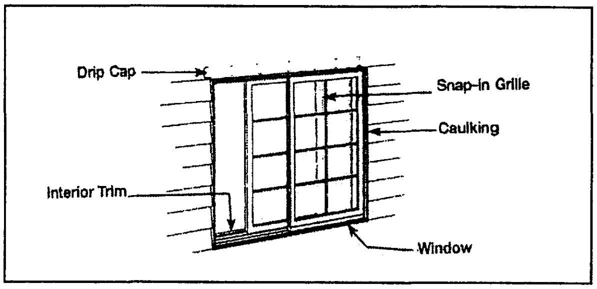
Double Hung Window System



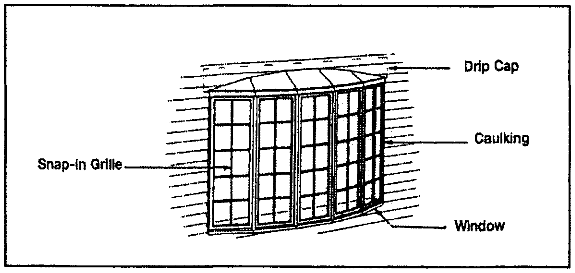
Casement Window System



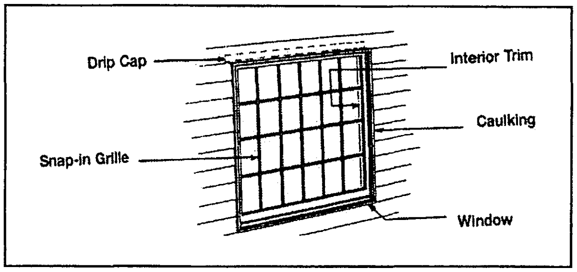
Awning Window System



Sliding Window System



Bay Window System



Fixed Window System

Figure 2.12

Table 2.2 Price Range of Window Systems in Boston

	Cost Range ($)per Window	
Window System	**High**	**Low**
Double Hung	505.91	294.71
Casement	395.44	354.12
Awning	460.80	379.76
Sliding	831.40	352.61
Bay Window	2695.88	1434.87
Fixed Window	964.56	482.52

Source: 1997 Means Residential cost data

Storm Windows

Many storm windows are installed over existing single glazing reducing drafts and improving energy efficiency. The purpose of this design is to create "dead" airspace which acts as an insulative barrier preventing heat loss from inside to outside. In order for them to be effective, the window must be tightly sealed. These windows usually come in wooden or aluminum frames. The aluminum frames have "thermal breaks" which are rubber/plastic parts, which prevent the glass from coming in contact with the metal. The "breaks" also prevent a conductive metal path from inside to outside.

Table 2.3: Effective U and R Values[3]

Window U-factors (Btu/hr •F) and R-Value (hr •F/Btu)		
Window Type	**Approx. U-factor**	**Approx. R-value**
Aluminum/Single	1.10	.91
Aluminum/Double	.61	1.64
Aluminum/Double w/thermal break	.54	1.85
Vinyl/Double	.49	2.04
Vinyl/Double with argon fill	.40	2.5
Vinyl/Double with low-e	.39	2.56
Vinyl/Double with low-e & argon fill	.35	2.86
Wood/Double	.52	1.92
Wood/Double with argon fill	.43	2.33
Wood/Double/with low-e	.42	2.38
Wood/Double with low-e & argon fill	.37	2.7

2.2 Heating and Cooling Systems

2.2.1 Conventional Systems

Once a homeowner has improved the envelope of his/her house, he/she should consider an improvement to the heating and cooling system. An oil boiler with a steam or hot water/ radiator, distribution system, heats a typical 1920s house in Cambridge. A 30 to 50 gallon hot water heater, heated by gas, oil, or electricity[2], services the house. Both the oil boiler and the hot water heater are located (typically) in an unheated basement.

A conventional heating system requires a combustion chamber, a flue to exhaust smoke and a distribution system of ducts or pipes. In the combustion chamber, oil, gas or wood is burned to produce heat at high temperatures. An older furnace may have an efficiency of 65% or lower; therefore, it is reasonable for a homeowner to consider an upgrade or the replacement of an existing system.

2.2.2 Geothermal Heat Pumps

In the demonstration project, the furnace was replaced by a ground source heat pump. Geothermal heat pumps can theoretically reduce the cost of a seasonal heating bill by one third. However, these systems use electricity, which on average costs three times as much as gas. The higher priced energy offsets the sum total of savings obtained on an annual basis. Unfortunately, given the high cost of installation, these systems are not cost-effective for retrofits in the New England region, at present energy rates. Installation costs may run anywhere from $3500 to $6000/ton for inside work. The outside work (drilling, well) may range between $3500 to $10,000 in New England[5].

Although costly, ground source heat pumps (GSHP) can reduce household energy consumption and serve as an alternative to conventional systems. They provide heating and cooling by transferring heat to and from the ground and using the constant temperatures of the earth. In Boston, the average temperature of the earth is around 50°F. Therefore, the earth functions as heat sink and a heat source during the summer and the winter, respectively.

Every geothermal system has three major components: a geothermal unit that moves heat between the building and the fluid in the earth connection, a distribution subsystem for moving heating or cooling to the building and an earth connection for transferring heat between the fluid and the earth. The systems may also have a desuperheater to accommodate or supplement the building's hot water demands. (Figure 2.13)

Heat pumps can extract energy from various heat storage mediums such as rock, earth, ground water, lakes and waterways. The performance of the geothermal systems varies according

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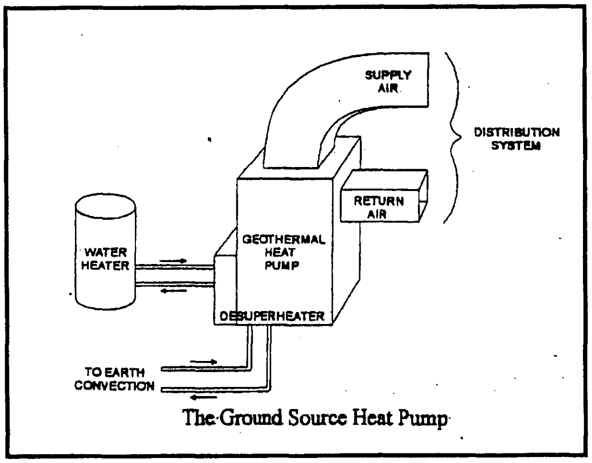
[5] Prices obtained from a thermal consultant, a ClimateMaster Distributor from Water & Energy Systems Corporation



The Ground Source Heat Pump

Figure 2.13 Ground Source Heat Pump Diagram

to geographic location. However, there are some disadvantages. For example, if ground water is used in a system, legal aspects can complicate its use. At the same time earth heating systems can affect ground ecology and stability.

Geothermal heat pumps are classified as either closed or open loop systems. In a closed loop system, there are two methods of designing the earth connection for heat pumps: the horizontal or the vertical pipe system.

Horizontal systems:

Horizontal systems are the most economical, consequently the most common types of earth heating system in areas where there is enough space available. In such a system, a plastic pipe is buried 3.3 to 6.6 feet underground with separations of 2 to 6 feet. A two-pipe system may require 200 to 300 feet of trench per ton of capacity[6]. A typical home with 11/2-ton system would require 450 feet of trench[6]. The length of the trench decreases as the number of pipes in the trench increases or as the overlapping coil increases. In densely populated urban areas, there is little space availability. Horizontal systems are therefore most applicable to rural and suburban areas.

During the heating season, a coolant with a temperature range of 23°F to 50°F circulates in the pipe, consequently cooling the ground. Energy is mostly obtained from the cooling of the ground and the latent heat of freezing from the moisture of the soil.[7] Therefore, the greater the moisture content in the ground, the lesser amount of hose needed for the overall system. After the winter season, the ground returns to its normal level during the spring and the summer from

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[6] Geothermal Heat Pump Consortium ,Inc. "Residential Applications: How Geothermal Heating and Cooling Works", 1995

[7] T.Berntsson, P.Franck, L.Jacobson, B.Modin, P.Wilen, The Use of The Ground as a Heat Source for Heat Pumps in Urban Areas, Swedish Council for Building Research to the earth heat pump group, Chalmers University of Technology, Gothenburg, 1980

insolation, rainfall and ground water flows. The maximum amount of power that can be extracted from the earth ranges from 15 watts to 40 watts per meter of pipe depending on the type of earth, snow coverage, ground water movements, water content and climate[7]

Most companies use rule of thumb methods for dimensioning hose systems of horizontal systems. Computer modeling of the systems is based on single family home, and does not take into account the effects of their installation on a larger scale. Compared with an individual single-family housing system, larger installations have greater impact on the temperature of the ground, which affects the dimensioning of the heating coils and trench length.

Horizontal heat pump systems can be used in conjunction with solar collectors. With the two systems (depending on climate and size), it is possible to obtain an improved coefficient of performance (COP) (the amount of heat delivered for a given amount of electrical input) for the heat pumps or a reduced ground surface requirement[7]. The COP is improved particularly in the spring, summer, and the autumn when more insolation is available. However, high solar collector temperature can dry out the ground reducing the efficiency of the heat pick-up coils. This can potentially lead to their deterioration.

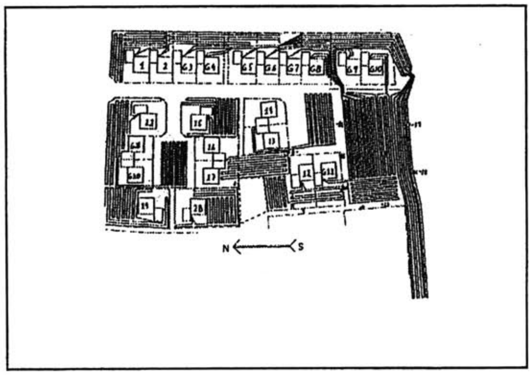


Figure 2.14 Layout of horizontal System in an Urban Area

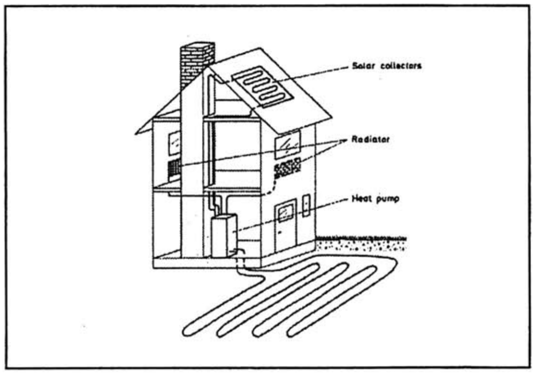


Figure 2.15 Horizontal System Combined with Solar Collector

The efficiency of the ground loop system depends on its connection to the ground. Therefore, careful trenching back fill is required. The backfill must be free of rocks that could potentially damage the pipes. In some cases, the installers use large amounts of water, to break up the soil clumps, assuring optimal contact. This procedure reuses the moved soil of the trench. In other cases, fill is brought to the sight in concrete mixers. The fill contains sand, fly ash and small amounts of cement that provides proper contact.[6]

Vertical pipe systems

The advantage of vertically drilled systems is that they use considerable less area than horizontal systems. Therefore, it is more advantageous in densely populated urban areas, but the installation is costly. Vertical heat store systems are dimensioned to work between 32°F and 59°F around the natural temperature of the ground[7]. Given the varying conditions of the ground, the lengths of loop will vary from 130 to 300 feet per ton of heat exchange. Pipes are generally joined in parallel or series-parallel configurations

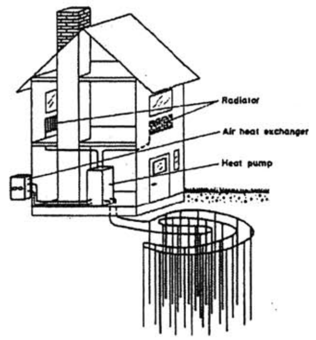


Figure 2.16 Vertical System

In colder climates such as Boston, a percentage of the heat that is extracted from the ground during the winter is replaced by the solar energy in the summer. However, unlike horizontal systems, there is not enough time for the replacement of the heat extracted (during the heating season) by the natural insolation of the ground during the spring and the summer. Therefore, additional energy must be supplied to the system, either by way of the ground water or by other means[7]. Figure 2.17 compares the amount of energy extracted during the heating season to the amount that is replaced in the summer combined with the yearly average horizontal radiation on a horizontal surface (Btu/hr ft^2). Estimates are based on the heating load for Cambridge House of Sustainability.

A thorough investigation of the geological features of the site is necessary in order to ascertain the geo-technical properties of various storage mediums. These mediums may vary according to different operating temperatures. For example, the stability of clay is reduced when exposed to high temperatures. If the stratum of the ground is extremely sensitive, heat extraction from the tubes of the geothermal system could freeze the soil. The resulting frost heave could damage surrounding buildings and reduce ground strength[7].

Open loop systems:

Given that ground water temperatures are nearly constant all year round, they can serve as a heat source for heating and cooling homes. The deeper the extraction point, the higher the ground water temperature and the smaller the temperature variations, which is beneficial to the heat pump operation. Water that is extracted from the ground is pumped through the heat pump and returned to the aquifer. To avoid the cooling effect of the returned water, it is pumped into a second discharge well, located at some distance from the extraction point. It is possible in deep wells, drilled from rock, to return the water to the original extraction point. Another method is to return the water to a waterway or lake, which is in contact with the aquifer[6].

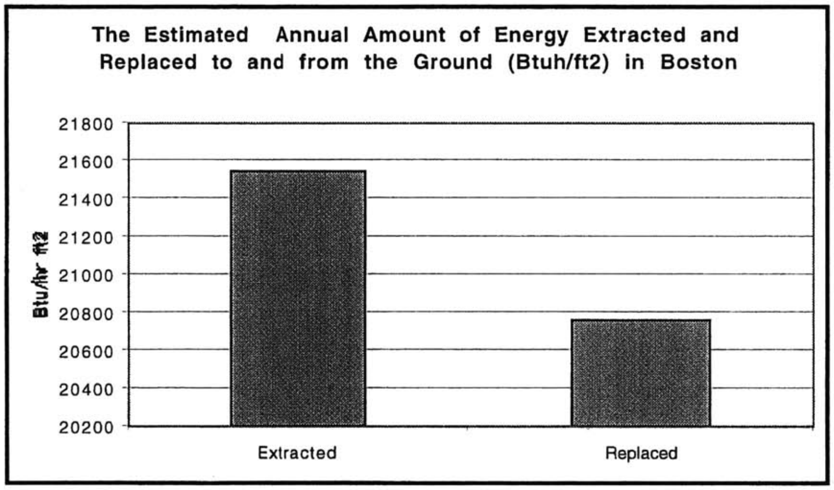


Figure 2.17

It is also possible to increase ground water temperature by means of a solar collector. An additional storage tank can be used during period when heat and cooling is required. Water is pumped to and from the tank in a closed loop system. When the temperature of the storage tank falls out of the operating range, well water can be used instead. This particular system works well during the spring and fall when excessive heating is not required. It is inadequate for uses during the summer and winter. The use of a large domestic hot water storage tank decreases the demand on the pump, and it does not have to run at full load during periods of high demand.

Disadvantages of Open Loop System

In ground water heat pumps, the volume and the well capacity are determined by the maximum power requirements during the coldest periods of the year. The temperature changes of the aquifers are dependent on the following:[7]

1. The total available volume of ground water in the aquifer
2. The total volume needed to be pumped and returned each year
3. Where and how the cool water is returned
4. The properties of the ground water
5. The ground water temperature
6. The magnitude of the temperature drop
7. The size and extent of the thermal flow in the aquifer.

From the available data, very large quantities of ground water are required for heating apartment buildings. This indicates that aquifers may not meet the heating demand on a large urban scale. Although ground water is constantly extracted and returned to the earth, the long-term effects of the temperature drops of the water may gradually decrease the efficiency of the heat pump operation. It is also unclear how the surroundings are affected by the temperature reduction, indicating that further research is necessary. The following graph shows the power requirement for neighborhood of homes in the Cambridge area and the required well capacity for varying changes in temperature.

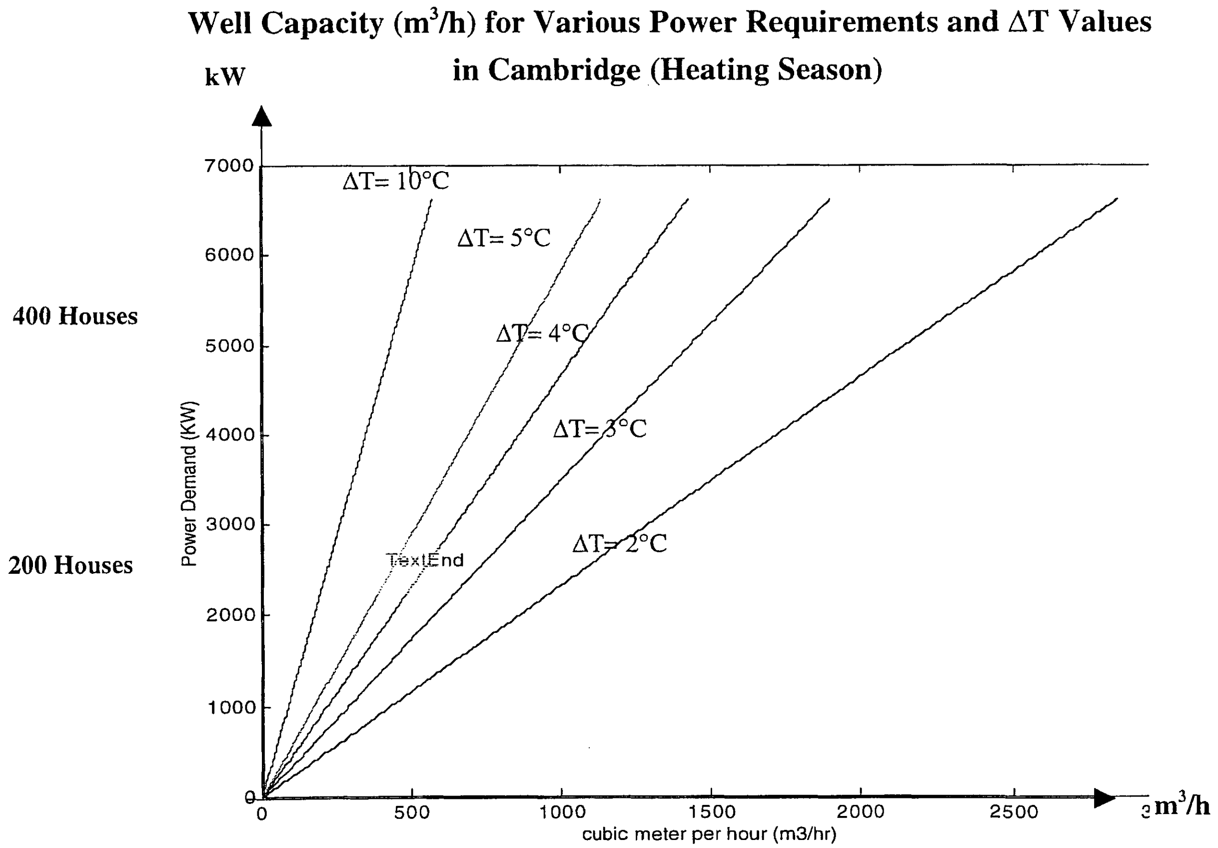


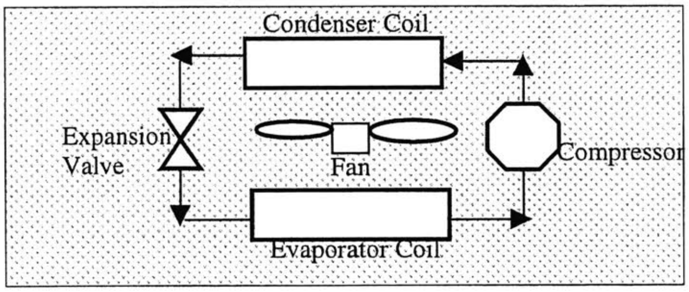
Figure 2.18

2.2.3 Air to Air Heat Pumps

Air to air heat pumps are an alternative to ground source heat pumps. But, in cold climates, they are not a very efficient method of heating a home and have higher operational costs than conventional systems. On the other hand, because the installation is relatively easy, the costs have an estimated range of $2500 to $3575 dollars per ton[8]. During peak periods, the investment of an air to air pump system to temporarily to supplement a furnace that does not meet the entire heating demand can be a more cost-effective measure than furnace replacement.

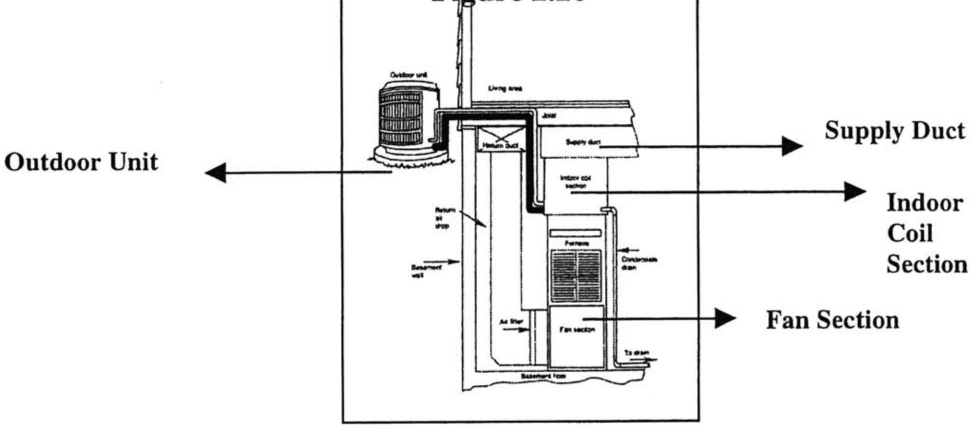
Air to air heat pumps extract energy from the outside air to provide heating or cooling of the indoors. In the summer, heat is taken from the indoor air and expelled to the outside air. In the winter, the opposite occurs, heat from the outside air is used to warm the inside air. A typical system consists of the following components: an evaporator coil, condenser coil, compressor, fans and expansion valves.

Figure 2.19 Heat pump Cycle



In a typical residence, an outdoor heat pump unit rests on a support pad. The outdoor unit will contain the outdoor coil that extracts energy from the air. Lines containing refrigerant are fed through the exterior walls of the house and connected to the furnace. The indoor coil section is installed on the supply side of the furnace.

Figure 2.20



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[8] Prices obtained from two local companies in the Boston Area; Arctic Engineering and B& G Company

Effectiveness of Operation

The performance of an air to air heat pump depends on the geographic location, and the temperature of the outside air. During the wintertime, a decrease in the outside air temperature lowers the heating efficiency of the system. If the outside air is lower than a particular set point, a back-up system is necessary. The set point or cut point is determined when the savings obtained from the heat pump operation are below the operating cost of the system. The suggested cut-off point is around 20°F. During the summertime, high outside temperatures lowers the efficiency of the system as well[9].

Air to air heat pumps are cost-effective when the cost of electricity is low and the winter air temperatures remain in the range of 35° to 55° degrees Fahrenheit. With these conditions, systems will provide savings when compared to fossil fuels. However, if the winter temperatures are out of the specified range, air to air heat pumps are more expensive because of the need for an electric back up. The outside winter weather conditions in the New England region fall out of this range with extreme temperatures of -6° Fahrenheit, indicating the need for back-up. The high cost of electricity makes these systems uneconomical. On the other hand, the back-up systems are less expensive than a regular electric resistance heating system.

Coefficient of Performance

The coefficient of performance (COP), the amount of heat delivered relative to the energy put into the pump, will vary depending on the outside temperature. At 47°F, the COP may range from 3.1 to 2.6 depending on the manufacturer and brand. At lower the temperatures (17°F), the coefficient of performance is lower. Less heat is extracted from the coils at lower temperatures when there is a constant air volume. In order to increase the efficiency, an increase in the surface area of the coils is necessary.

The COP of air to air heat pumps varies greatly when compared to ground source pumps because of the fluctuations in the outside temperature. The ground temperatures, on the other hand, remain fairly stable.

Cooling Mode Efficiencies, EER, SEER, and HSPF

Cooling mode efficiencies are rated in terms of EER, energy efficiency ratio; the higher the EER, the higher the efficiency of the system. The EER is defined as the total output of the air conditioner in BTU/hr divided by the total electric energy input in watts.

The Seasonal Energy Efficiency Ratio (SEER) gives the total cooling seasonal output in BTUs divided by the total electric energy input in watt-hours. The period for the SEER does not

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[9] J.Johnson, W.Hammock, Installing Heat Pumps, Tab Books Inc. Blue Ridge Summit, PA, 1983

exceed 12 months. The Heating Seasonal Performance Factor (HSPF) is the total seasonal heating output divided by the total electric energy input during the same period. In both cases, a particular unit is more efficient with higher values for SEER and HSPF[9]. A typical heat pump will have SEER equal to 11 and a HSPF between 6 and 8.

The following graph compares the cost of heating a home in Cambridge in dollars per kilowatt-hour when there is a change in the outside temperature. The cost for the ground source heat pump remains constant because it is relatively unaffected by the temperature outside. The graph shows that GSHP is lower than the air to air pump.

Cost of the Air to Air Heat Pump

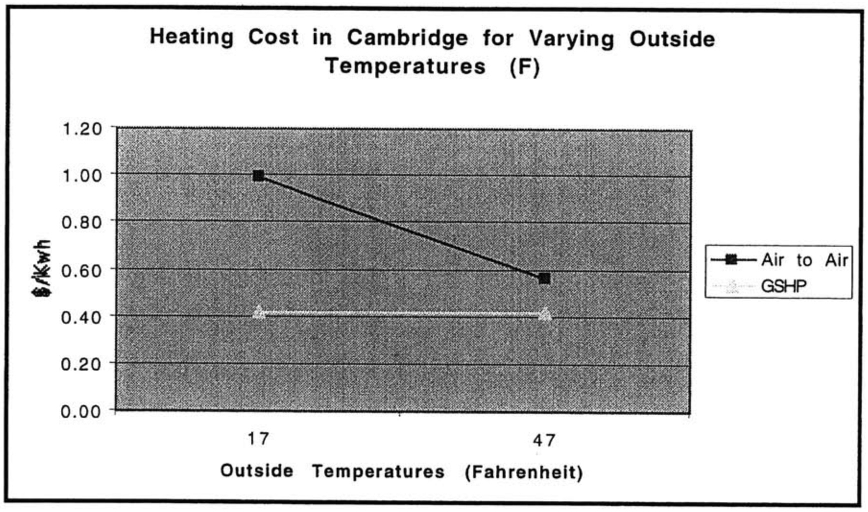

Figure 2.21

2.3 Renewable Energy Systems

2.3.1 Solar Thermal Systems

A solar hot water and space heating system was also installed in the Cambridge Demonstration project. In New England, these systems are very cost-effective, and have a large payback if all of the solar energy collected is used for both hot water and space heating. If the system is used for only domestic hot water, it may result in a net loss over a twenty year span. The reason for the loss is that the majority of the solar energy collected in the summer exceeds the hot water energy demand, and consequently it is wasted. Important factors affect performance such as the tilt angles, orientation, and temperatures within the collector, as well as varying weather conditions. A system may cost around \$857 dollar[10] per collector or \$27/ ft^2 or

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[10] cost obtained from local designer of solar thermal system, henry Vandemark

more in the northern region, and may supply all of the hot water demands of a multi-family dwelling.

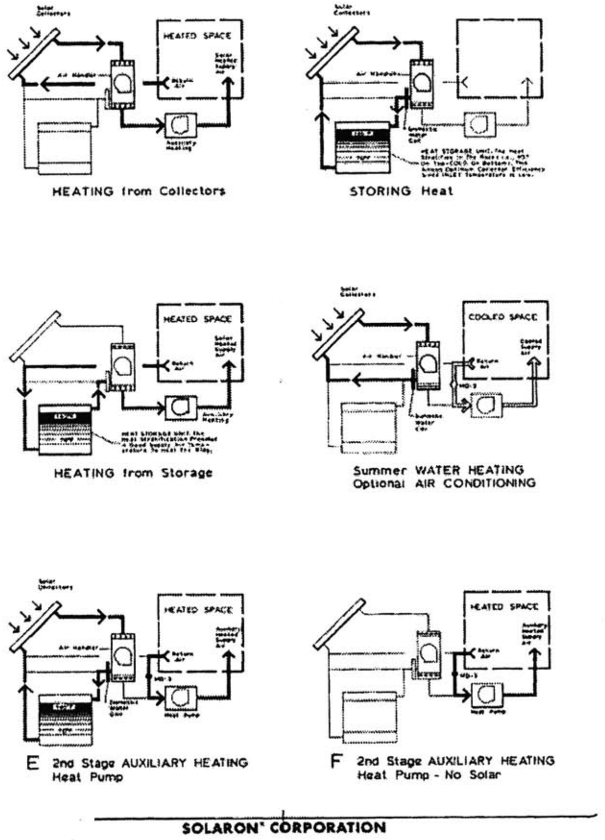

Figure 2.22 Solar Thermal Diagrams

Most systems have the following components: a collector, a storage medium, controller, air handling unit, and auxiliary heater. Water or air enters the collector at a low temperature and leaves at a higher temperature. In some system designs, the water or air leaving the system is used to directly heat the space with the addition of an auxiliary heater. When space temperature requirements are satisfied, the heated fluid from the collector is circulated to a storage tank. In the storage tank, there is temperature stratification with higher temperatures at the top and lower temperatures at the bottom. During cloudy days, the energy in the storage medium is used to heat the space instead of the collector.

In an all air system, the return air from the space is circulated to the bottom of the storage medium (usually rocks) and is gradually heated as it moves to the tank's surface. The heated air is then supplied directly to the space with an additional auxiliary system, if necessary. In some water systems, hot water from the surface of a storage tank is circulated to a fan coil unit and supplied to the building. In other system designs (all water), cold water from the bottom of the tank is circulated to the collector's surface, heated and the supplied to the top of the tank. For direct systems, water is circulated directly to the collector; however, in an indirect system, antifreeze passes through the collector and heat energy is transferred to the storage tank via a heat exchanger.

Types of Collectors

Solar gains depend on radiation intensity, optical properties, transmitting, absorbing surfaces and thermal losses. There are several types of collectors characterized as either a flat plate or a concentrator.

Concentrators obtain high temperatures by utilizing direct radiation and focusing it on a small absorber. Given the small surface area of the absorber, thermal losses are minimized. Usually concentrators are situated on a mechanical device that rotates to optimize the angle of the sun. The efficiencies of the collectors are usually around 65%[11].

Unlike concentrators, flat plate collectors use both direct and diffuse radiation. Their overall efficiencies are around 50%. Flat plates use 70% of direct radiation and around 85% to 30% of diffuse radiation[11]. On an annual basis, these collectors have higher efficiencies than concentrators. Because of their geometry, flat plates are easier to install on rooftops (than concentrators) and are more common in retrofits and new construction.

Flat Plate Collector

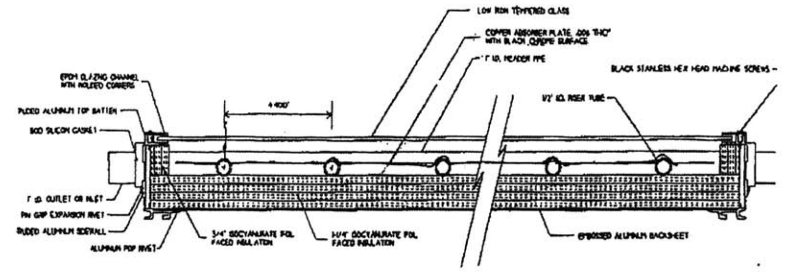

Figure 2.23

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[11] SOLARON Corporation Saving Energy, application engineering manual, SOLARON Corporation, edition number 4, Englewood,, Co , May 1980

Types of Concentrators

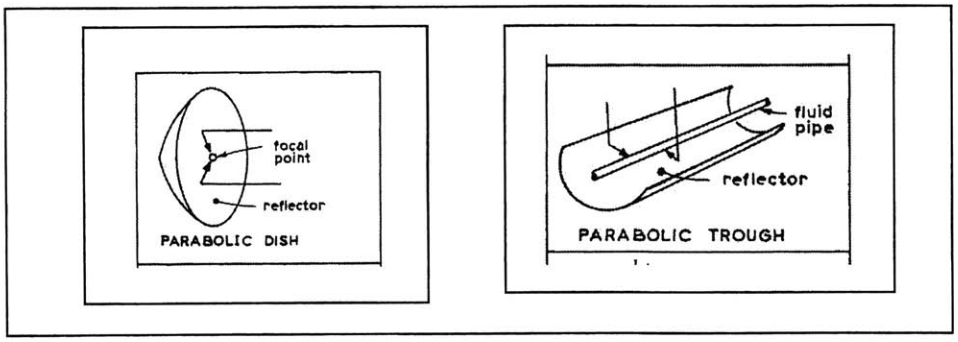


Figure 2.24

Storage Mediums

In the Demonstration project, a hot water tank was used to store solar energy obtained from the collector. There are two basic types of storage medium: rock and water.

In rock storage systems, hot air from the collector is blown down into the tank and air circulates at a rate of 20 to 30 feet per minute (fpm). The top layer of rock in the tank extracts energy from the air because it is at a lower temperature. As the cycle is repeated (with the air returning to and from the collector), the upper layers reach the air temperature and the heat energy moves to the lower layers of rock, hot air from the collector travels through the cracks and crevices to the cooler rock layers. The temperature stratification from top to bottom may range from 140° to 70° Fahrenheit. The lower temperature, 70°F, becomes the inlet temperature to the collector[11]. A fan blower creates a pressure difference from top to bottom to insure the circulation of air.

In water storage systems, water or antifreeze circulates through the collector, absorbs solar energy, and is then circulated to the bottom of the tank. As in a rock storage system, there is temperature stratification, but not as great. The range in temperature from the top to the bottom of the tank may vary from 110°F to 120°F with only a 10°F difference, compared to a 70°F difference in a rock storage system[11]. As a result, water storage systems are not as efficient as rock storage systems because inlet temperatures to the collector are greater.

The advantage of a water storage system is the space savings and a lower fan power consumption. A comparison of the heat capacity and the density of water demonstrates that the volume of rock needed to satisfy a space heating demand is about 2.7 times greater than the volume of water[11].

Phase change materials are also used as a storage medium. However, there is very little stratification because temperatures remain constant during a phase change. The materials have an unstable life and a high cost.

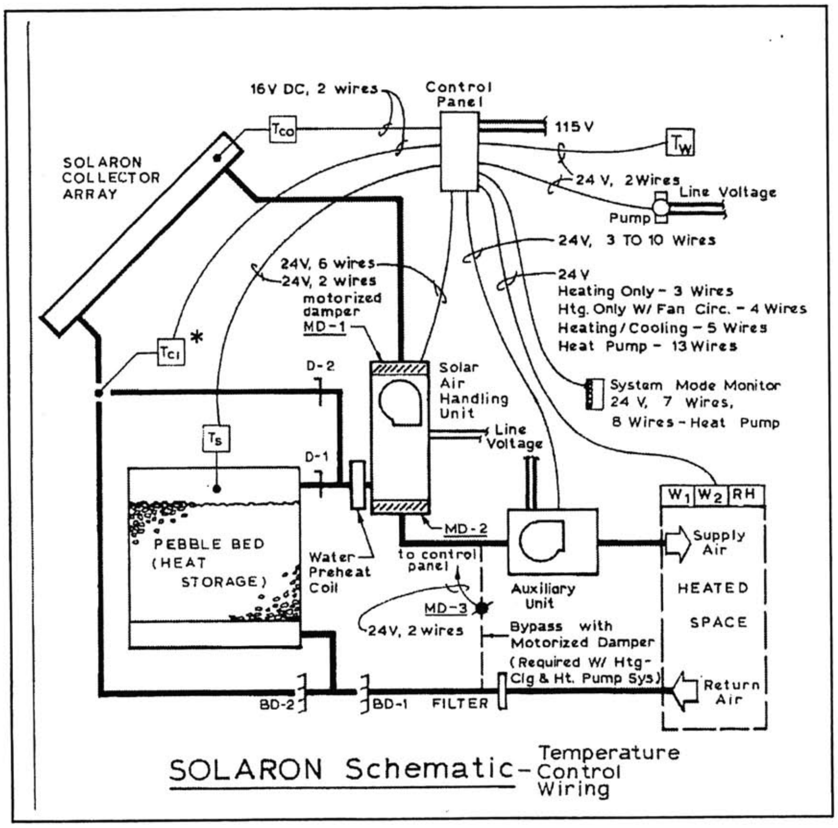


Figure 2.25

Types of Solar Water Heating Systems

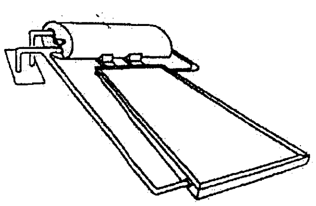
There are several system designs for different climatic regions. The ones that are applicable to colder climates are indirect closed loop systems, indirect PV systems and drain back systems. All of these designs provide some form of freeze protection for water circulating in the pipes. The Indirect PV system was installed in the demonstration project.

Indirect closed loop systems are used in colder regions where freezing temperatures occur more frequently. The system consists of a collector, connecting piping, pump, an expansion tank and a heat exchanger. Antifreeze is circulated through the collectors instead of water. Heat energy is transferred to potable water in the storage tanks by way of a heat exchanger. The heat exchanger is wrapped around the perimeter of the bottom of the tank where the temperatures are coldest. This, in effect, maximizes heat transfer[12].

Indirect PV Systems have a similar design to the indirect closed loop system; however, a photovoltaic panel powers the DC pump. When there is sufficient solar energy available to insure heating of the water in the tank, the pump circulates the antifreeze through the collector. As in the indirect closed loop system, a heat exchanger transfers heat energy to the stored potable water in the tank. The rate at which the antifreeze is pumped through the collector is proportional to rate at which solar energy is collected by the photovoltaic and solar thermal panel. The pump shuts off when there is insufficient solar radiation[12].

Drain Back Systems insure that there is no freezing of water in the collectors or the piping. The collectors are mounted at an angle so that when the system is not producing heat, water from the collectors and the piping is drained back into an insulated reservoir tank. A differential control senses when solar energy does not meet system requirements, and the pump is shut off causing the drain back of fluid. It is a closed loop system, and the distilled water or antifreeze does not come in contact with the potable water in the storage tank. A Heat exchanger transfers energy from the collectors.

A thermosiphon system is a simple "free flow" design that does not require a controller or a pump. Unlike the other systems, the collectors are positioned at lower angle than the tanks. As the water in the collector is heated for solar radiation, it becomes buoyant and rises to the tank. The cooler more dense water from the tank flows down into the collector to replace the water at higher temperatures. This cycle results in a tank of hot water at the end of the day. Thermosiphon systems do not provide freeze protection and are therefore not used in cold climates. In addition, they are difficult to mount on rooftops with the additional weight of the water tank.



Thermosiphon System

Figure 2.26 Good for Warm Climates

2.3.2 Photovoltaic Modules

Fourteen photovoltatic panels were installed on the south-facing roof of the Cambridge House for Sustainability. The panels are 12ft^2 each and supply approximately 117 kWh of electricity per panel per year. The entire system supplies approximately 13% of the household energy demand. Although an energy savings is attainable, it is minimal compared to the initial investment. The cost range for a system in estimated at $683 to $953 per panel or $60 to $79

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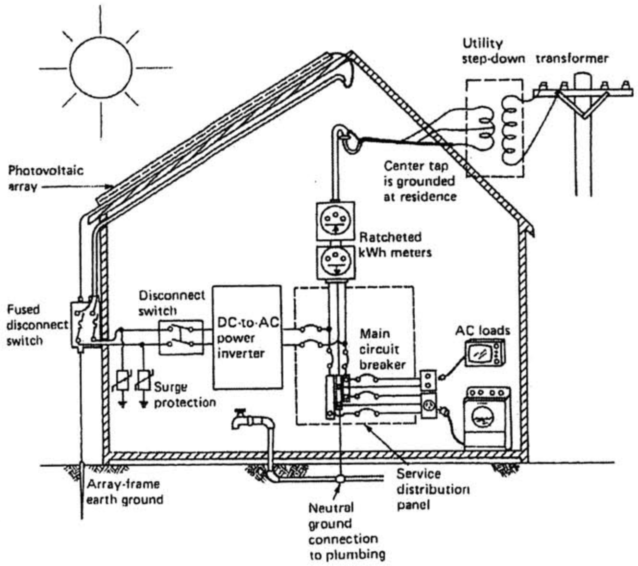
[12] American Energy Technologies (AET), solar thermal catalog, January, 1993

dollars/ft^2.[13] Unfortunately, the overall system is not very cost-effective at present energy rates and results in a large negative net savings over a twenty year span.

If the initial cost is reduced, these systems are potentially a viable option for retrofits because they reduce household energy consumption and provide energy cost savings. Photovoltaic panels convert sunlight directly into the most expensive form of energy: electricity. The panels are made of polycrystalline or amorphous silicon. Polycrystalline structures are better for colder climates and can have an efficiency of 15%. Amorphous, thin film, structures are best in warm climates because the high temperatures increase the efficiency during the summer months.

A typical system consists of a PV cell, batteries, power controller and an inverter. The inverter/controller controls the flow of electricity and converts 12 volts of direct current to 120 volts of alternating current. The electrical output of the system depends on the number of modules, size, electrical connection and environmental conditions.



Block diagram of a utility-interactive photovoltaic system. (M.I.T. Lincoln Laboratory.)

Figure 2.27

PV Power

A typical silicon solar cell of one square foot generates ten watts of power or under noonday sun^2. The current generated for a given cell area is directly proportional to the solar irradiance. Large surface areas are necessary to meet power requirements.

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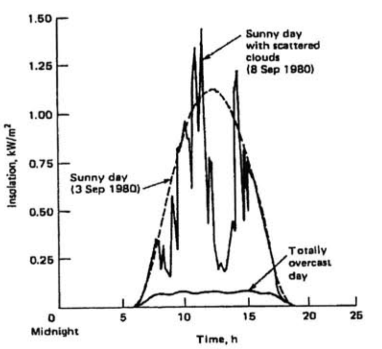
[13] Cost obtained from a lecture sponsored by the Northeast Energy Association

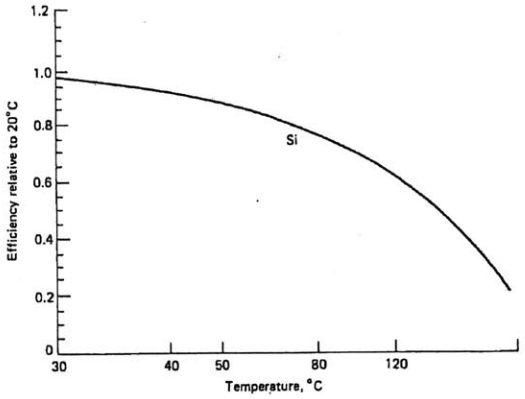
The temperature in the cell and the light intensity greatly affect the performance of photovoltaics. If the temperature of the cell increases, the performance decreases and has a lower voltage output. Under circumstances where there is an increase in the brightness of the sun, it is necessary to keep the cell as cool as possible by allowing space for air movement. Cloudy conditions can significantly decrease cell output.

64 PHOTOVOLTAIC ENERGY SYSTEMS



Solar power on a latitude-tilted south-facing surface versus time of day for partly cloudy weather with natural sunlight concentration resulting from light being reflected off clouds. (M.I.T. Lincoln Laboratory, Natural Bridges National Monument, Utah, weather station.)

Figure 2.28
Sunny vs. Cloudy Sky Output



Silicon solar-cell efficiency versus temperature. (From: Woodall and Hovel, *Journal of Vacuum Science & Technology*, 12, American Institute of Physics, N.Y., 1975, p. 1000.)

Figure 2.29
Efficiency vs. Cell Temperature

Solar Cell Characteristics and Efficiency

The solar cells within a module can produce electricity because the cells have the properties of a semiconductor material. A cell consists of two specially treated layers of silicon. When the sun hits the silicon, negatively charged ions are dislodged from their orbits around atoms and sent into a free flowing stream through material. This stream of negatively charged electrons is the electric current.

The efficiency of photovoltaics is not very high, ranging from 3% to 15%. There are several reasons for the low efficiencies of modules. One reason is that cells do not absorb different wavelengths of light equally and cannot use all of the solar radiation. Another reason is that only a certain amount of energy is required to knock an electron from orbit. When the solar energy received by the cell exceeds the energy required to dislodge an electron, the additional solar energy is converted into heat[2]. The heat produced increases the cell temperature and decreases the efficiency. Unfortunately, not all of the energy is used to produce electricity. Some of it is absorbed through the material and reflected. Shading is another factor that could significantly reduce the performance of the PV cell. Even a small shaded portion of cell could greatly reduce output because it produces heat, which could cause failure to the system. Higher efficiencies are possible with the use of concentrators.

Although photovoltaics vary in size and shape, the most common and commercially available is the flat sandwich type. It contains 36 PV cells in series and can charge a 12-volt battery. Other types of photovoltaics are concentrator modules, which have a higher operating efficiency than flat plat collectors. But, concentrators require a sophisticated tracking system to optimize performance and are therefore higher in cost. Usually, such systems are used in applications that require ten kilowatts of power or greater.

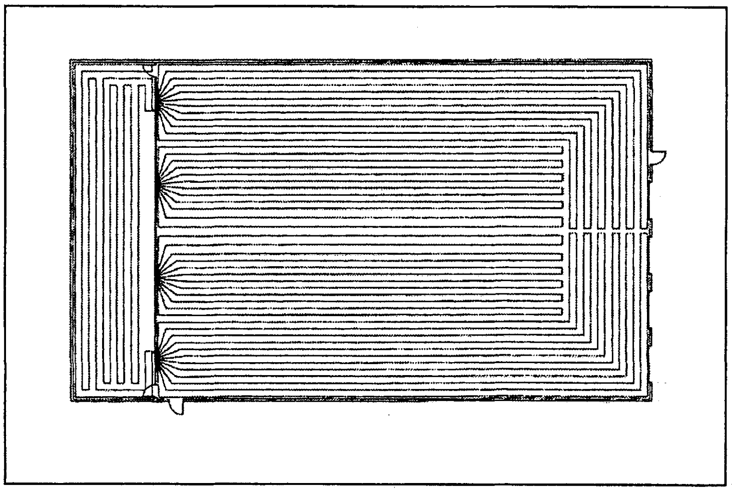


Figure 2.30
Diagram of Radiant Floor with tubing

2.4 Distribution Systems: Radiant Heating

A radiant floor, wall and ceiling were installed in the house as a means of distributing heating energy to the house in addition to fan coil units. Radiant floor systems are an alternative to baseboard heaters in distributing heat to homes. Most systems consist of the following components: a central heating source, hot water tubes and pipes carrying hot water over the entire surface area of the floor. They are constructed from materials with high specific heat and mass and can provide space savings, thermal comfort and some energy savings when compared with a conventional oil/gas fired system[14].

The installation of radiant system may cost around $3.25 per square foot. In general, it is not a very cost-effective investment because the energy saving is minimal is comparison to the capital investment.

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[14] R.Dodge Woodson, Radiant Floor Heating, McGraw-Hill, New York, 1999

Advantages of Radiant Floor Heating Systems:

Radiant floor systems have many benefits when compared to conventional systems for the following reasons: an increased thermal comfort, lower operating cost, minimal noise, less dust and space savings. These systems have a nearly ideal temperature distribution with higher temperatures near the floor and lower ones near the ceiling. This helps to reduce heat loss through the roof and increases thermal comfort. The even distribution of tubing is very effective in warming an entire room uniformly whereas baseboard heaters warm the perimeter. Water temperatures in the tubing of radiant systems are also lower than baseboard heaters, leading to lower operating cost and energy savings[14]. The tubes of the radiant systems are installed inside the floor, thus increasing space availability. Air systems, on the other hand, require space for ductwork, and baseboard heaters disturb the interior space. Diffusers, baseboards and radiators also collect dust and can create considerable noise. Whereas radiant systems collect minimal dust and are virtually noiseless if designed properly.

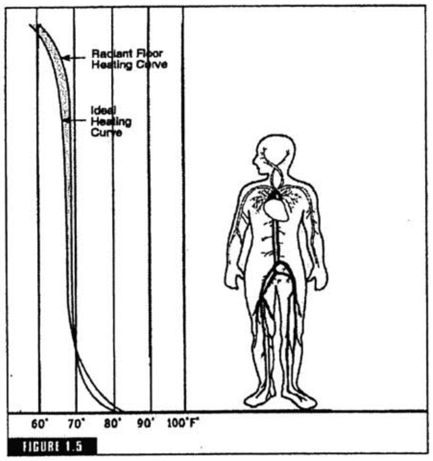

FIGURE 1.5

Radiant floor heating curve. (*Courtesy of Wirsbo.*)

Figure 2.31
Temperature Distribution Curve

Disadvantages of Radiant Floor Systems:

Unfortunately, the installation of radiant floor systems is not considered standard practice by industry, and on-site contractors may require training. In addition, a house with only a radiant system can have poor indoor air quality (a problem in general for all water systems). Some system designs would require a separate mechanical ventilation system to provide fresh air rates. This can lead to an increased installation cost, reducing the economic feasibility of such measures for an average homeowner.

In retrofits, the installation of a radiant system involves a considerable amount of demolition the to the existing fabric of the building and an added complexity of merging it with the existing heating, cooling system. With minimal energy savings, it could lead to a considerable economic loss.

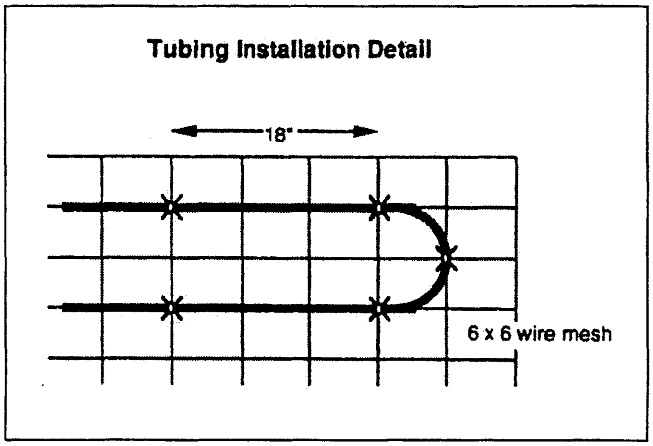

Figure 2.32

Installation of Radiant Floor Systems

During installation, it is necessary to protect the tubing that carries the hot water through the concrete slab. Quite often, tubing is tied to a wire mesh and looped across the floor area. The spacing between the loops varies and distances are calculated based on the heating load. In most systems, loop distances are one foot apart. The depth of radiant tubing affects system performance and is usually placed in the middle of the slab. Lower depths decrease efficiency causing an increase in water temperatures to meet heating space requirements. The costs of the floor, PEX (plastic tubing) cross-linked polyethylene are an important part of installation.

There are three basic types of radiant floor systems: slab-on-grade systems, thin-slab systems and dry systems.

Slab-on-grade installations

Slab-on-grade consist of a concrete slab, wire tie, slab insulation, wire mesh and base material. Rigid foam insulation is placed underneath the tubing to prevent radiant heat loss to the earth. This maximizes the overall efficiency. Older homes with uninsulated below grade floors have radiant systems with a lower output. Slab-on-grade systems require site preparation in order to eliminate rocks and clumps that damage tubing and insulation.

Thin Slab installations

Thin-slab installation is a possible technique for retrofits. In this application, plastic tubing is fastened to an existing wooden subfloor and a thin slab of concrete is poured over the tubing. The thickness of the concrete does not exceed 1 1/2 inches. It is necessary to have some batt insulation between the floor joists of the wooden floor to prevent heat losses. The weight of the concrete is a design consideration, and additional support may be needed.

Gypsum-based underlayment is an alternative to concrete in thin-slab systems. Contrary to intuition, the gypsum compound has more weight than lightweight concrete, indicating a possible need for structural reinforcement. In a gypsum application, a sealant and bonding agent is sprayed on top of the wood subflooring for strengthening purposes. Once all of the tubing and mesh structure is layered on top of the floor, the gypsum underlayment is poured over the mesh.

Gypsum based materials have advantages when compared to concrete. The material doesn't crack, and has a relatively easy application. On the other hand, a chronic water leakage can damage the compound, which eventually causes deterioration. It also has a lower thermal conductivity than concrete, which decreases the efficiency of the radiant floor system.

Lightweight concrete is not affected as much by moisture. However, it has a tendency to crack. Careful attention must be given to floor covering to insure effectiveness of the system. For example, a carpet covering is not as ideal as tile.

Dry Systems

In dry systems, radiant heating tubes are installed beneath the floor. It is called a dry system because material (concrete or gypsum) is not poured over the tubing. Such an application is better for retrofits without the additional weight as in thin slab installations. Dry systems do not have concrete or gypsum to increase conductivity. Therefore, plastic tubing is connected to aluminum heat transfer plates for lateral heat conduction.

Above-floor (Dry) systems:

In above-floor systems, the tubing is placed in between the finished floor and the subflooring. To add space and prevent damage, a sleeper system is installed. It consists of a series of wooden strips with cavities for tubing. An installer can nail the strips to subflooring. Once the strips are affixed, aluminum heat transfer plates are attached to the wooden strips. The tubing is placed inside the plates, located in between the sleeper members. A second subflooring is required. The overall layers of construction raise the floor height by one inch. This can reduce the size of an interior space.

Below-floor (Dry) systems:

Below -floor systems are easier to install, and are more efficient in time, labor and material. Unlike above-floor systems, there is no need for the sleeper system or a second subflooring system. Aluminum plates are nailed directly to the bottom subflooring. The tubing is placed inside of the plates. In order to maintain the structural rigidity, tubing is also located in the middle of the sub-floor joists. The below-floor systems were used in the Cambridge house because of the easy installation.

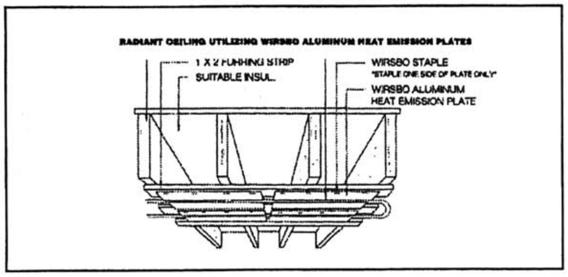

Figure 2.33
Radiant Ceiling

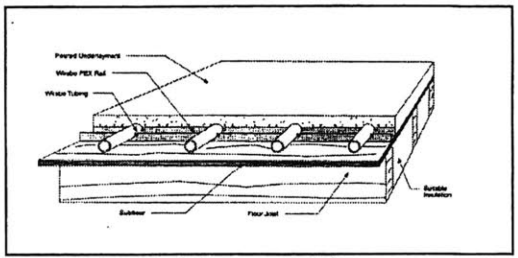

Figure 2.34
Thin Slab System with Poured Underlayment

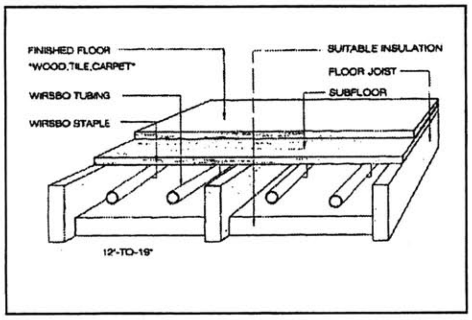

Figure 2.35
Below Floor Dry Systems

Combined in-floor and baseboard Radiant Floor Systems

Combined in-floor and baseboard systems are not common in new construction but are more likely in retrofits. In cases where an existing system has a low efficiency and does not meet heating demands, a radiant floor can compensate for the remainder to the heating load. One problem in a combined system with a single source heater is the difference in the water inlet temperatures for a radiant floor versus a forced air or baseboard heater. Conventional water, or air-water, requires high inlet water temperatures to warm interior spaces. Baseboard heaters have copper tubing with fin heating elements that increase heat transfer rates. Radiant floor systems use plastic tubing, which requires a lower temperature. Plastic will melt under very high temperatures. Several factors affect water supply temperatures for radiant systems: spacing of the tubes, type of installation, nature of the finished floor materials, and heat load requirements.

Types of Radiant Floor System

There are several types of radiant floor systems. Some are combined with baseboard heaters; others use only radiant heating. In systems with only radiant heating, there is no need for temperature control. A condensing boiler or a water tank is used as a heating source. Condensing boilers are designed to operate at low temperatures. The low temperature of the return water causes the flue gas in the boiler to condense, and the heat gained from condensation warms the water. Condensing boilers do not heat the water to sufficiently high enough temperature for baseboard heaters. Therefore, they are not used in combined systems.

In combined systems, a non-condensing boiler heats the supply water to the required temperature for baseboards and radiators. In these boilers, the return water must reach a set temperature. If it is too low, the highly acidic flue gases within the boiler will condense causing potential damage. To prevent this from happening, an additional control valve or tempering valve is needed to protect the boiler from low temperatures, yet at the same time, supply the proper temperature to the radiant floor.

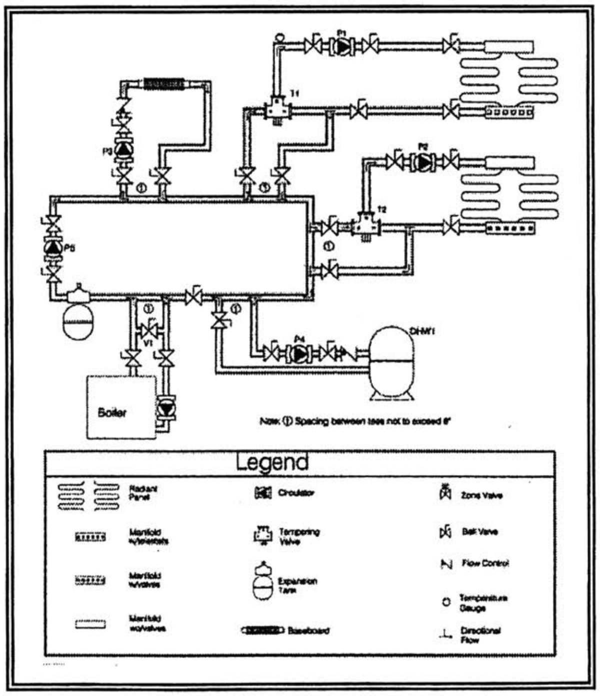

Figure 2.36
Diagram of Combined System with Radiant Floor

2.5 Heat Recovery Systems

2.5.1 Graywater Heat Reclaimers

Heat recovery systems are another method of reducing the household energy consumption. Graywater heat reclaimers (GHR) are used to recover heat from wastewater, generated from washing machines, showers, baths, dishwashers and sinks. With a simple heat recovery, GHRs can potentially reduce the domestic hot water energy bill by 30%[15] or more.

GHRs have two modes of operation. In one mode, continuous flowing hot water enters the tanks and heats cold water flowing in at the same rate. In the second mode, a batch of hot water from a bathtub, for example, enters the tank and a large cold water draw extracts most of the energy. When the plug of the bath is pulled, the water in the tank is flushed out, and a new batch of hot water enters. Tank temperatures range from 80°F to 85°F[15] and will decrease only slightly during the night because the tanks are well insulated. System operation is self-regulating with a digital temperature sensor to monitor tank temperatures.

Graywater Reclaimers are most applicable to new construction as opposed to older building because, such system require separate drain lines which may be difficult to install in multi story buildings. In addition, installers must avoid connecting the drain lines to kitchen disposals with solid waste and cold water drain lines.

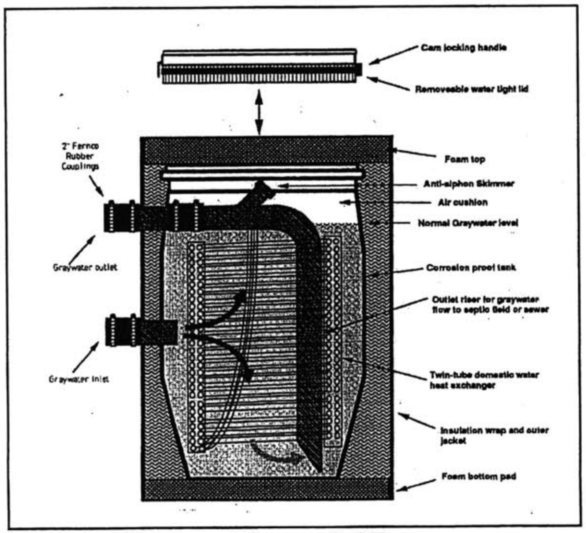

Figure 2.37
Diagram of Greywater Heat Reclaimer

2.5.2 Heat Recovery Ventilators

The installation of a heat recovery ventilator is another energy saving measure for homeowners. These systems help provide the required fresh air rates to a building by recovering energy from exhaust air. During the summer, the exhaust air extracts energy from the outdoor air, and during the winter it loses energy to the outdoor air. In addition to heat recovery, there is also partial pressure driven moisture between the hot and cold streams of fluid. A filter located in

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[15] Earthstar Energy Systems brochure

the device will block any contaminants from the outgoing stream. Air to Air ventilators will usually have an efficiency of around 80% or more. They are most applicable to homes that have an air/water or all air system, and provide greater energy savings by reducing the total amount of energy needed to pre heat or cool the outside air before entering a heating/cooling device.

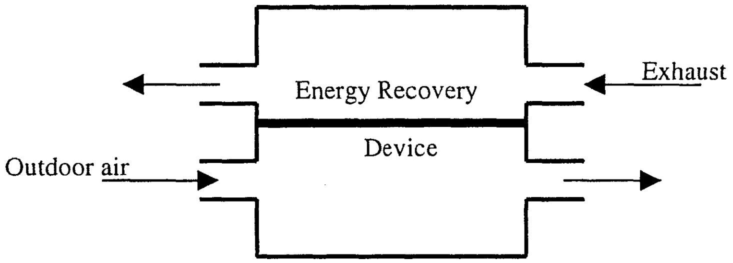


Figure 2.38

2.6 Conclusions

In older homes, it is important to upgrade the envelope by installing insulation, applying vapor barriers and air sealing cracks and crevices. Fiberglass and plastic board is used to insulate masonry, below grade, frame walls and attic ceiling and floor spaces. It is necessary to protect batt insulation and cellulose from water vapor so that their insulative value is not reduced. Although window replacement reduces energy losses, it is not cost effective. Therefore, a homeowner may consider caulking or weather-stripping windows as an alternative.

To improve the efficiency of a heating/cooling system, a homeowner has the option of upgrading the existing furnace, replacing it with a ground source heat pump or an air to air heat pump. Given the high cost of electricity, heat pumps are not very cost-effective in the New England area. Geothermal pumps provide some minimal savings; however have high initial cost. Air to Air pumps have a lower installation cost compared to ground source pumps, but a much higher operational cost than a conventional system with little or no energy savings. Therefore, it is more practical to upgrade or replace a furnace.

Solar thermal panels are only cost-effective when all of the energy collected in used for either space heating and domestic water. Unfortunately, a great percentage of the energy collected is wasted during the summer months. Although radiant floor systems and photovoltaic modules, provide some savings, it is relatively minimal compared to the initial cost of installation. In radiant floors, thin slab installation and dry floors are most applicable to retrofits. These systems are most likely used in conjunction with baseboard heaters.

In chapters 4, all of above energy savings measures are analyzed according to performance and cost.

Chapter 3 Case Study: Cambridge House for Sustainability

3.0 House Description

Before the renovation, the house was a two family dwelling constructed in the 1920s. In 1957, it was converted into a four family dwelling. Although there are no original documents of the house available at the building department, one can conclude that it was most likely a shingled or clapboard wood-framed building with a pitched roof, two floors, an attic and a basement. There was an entrance from the front/back or side, and a single stairway connecting all floors.

After the renovations, the four apartments were redesigned to accommodate eight residents. The house was completed gutted from the inside with the entire heating system replaced; floors and walls were torn out and re-constructed. Only the basic structural elements were left intact and reinforced. The wood frame house sits on a concrete and masonry foundation. A portion of the masonry on the basement level is above ground to allow light into the interior spaces.

Cambridge House for Sustainability

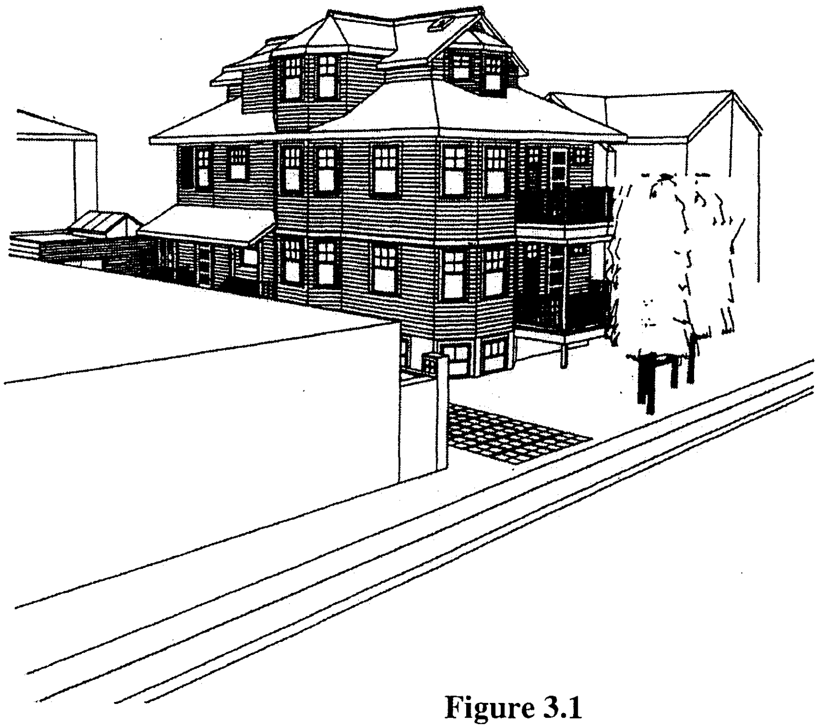


Figure 3.1

3.1 Site Location

The house is located in a quiet residential neighborhood on 136 Appleton Street in Cambridge, Massachusetts. The longitudinal axis of the house faces south such that there is a large south-facing surface area available for solar radiation throughout the year. The residential building on the south side of the house is at a far enough distance to prevent any shading of the solar systems.

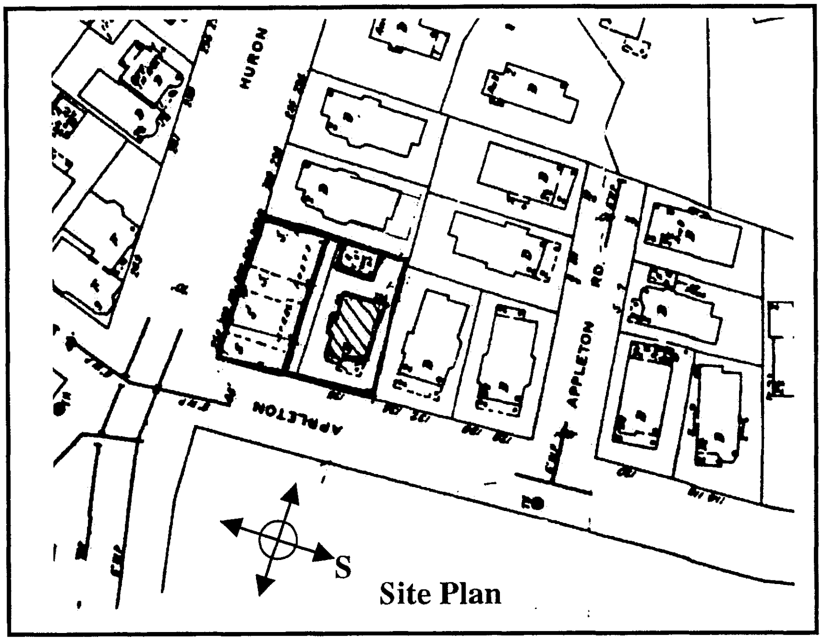


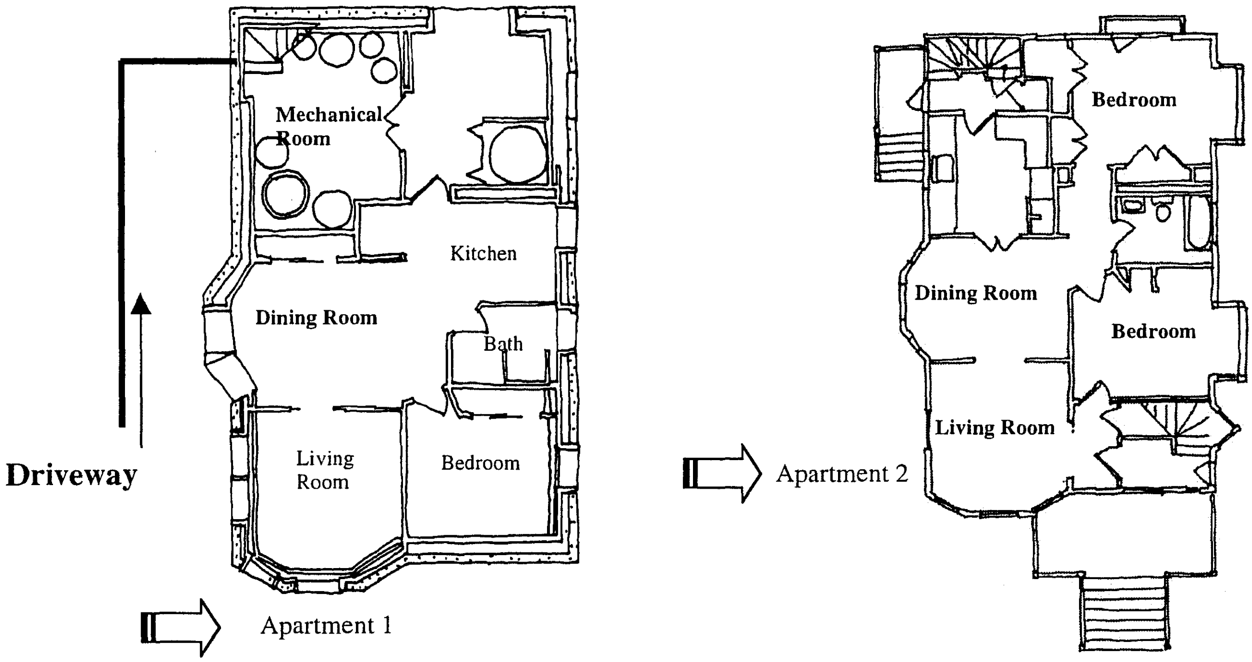
Figure 3.2

3.2 Plans/Elevations

With an open plan, the designers were free to redesign the spatial interior. The basement was converted into one apartment with a large percentage of the floor space given over to the mechanical room. The apartment in the basement is accessed from the driveway area alongside the house. Two staircases located in the front and the back of the house function as circulation spaces for the apartments on the upper floors.

The first floor apartment has two entrances, one in the front of the house, the other from the driveway. It has a living room space, which leads into a kitchen area, one bathroom and two adequately sized bedrooms. The second floor is divided into two dwelling spaces with an interesting arrangement. The apartment situated on the south side of the building (viewing the plans with the front entrance facing west) is designed for a single person with a one living room, one bedroom, bath, and a small kitchenette. The arrangement is similar to a 'shotgun' house with a straight-line circulation space connecting the rooms. The other apartment, on the same floor, is split in two levels. The first level has a living/dining room area which leads into the kitchen. A central staircase leads to the second level, which contains two bedrooms and a bath.

Basement **First Floor**



Second Floor **Third Floor**

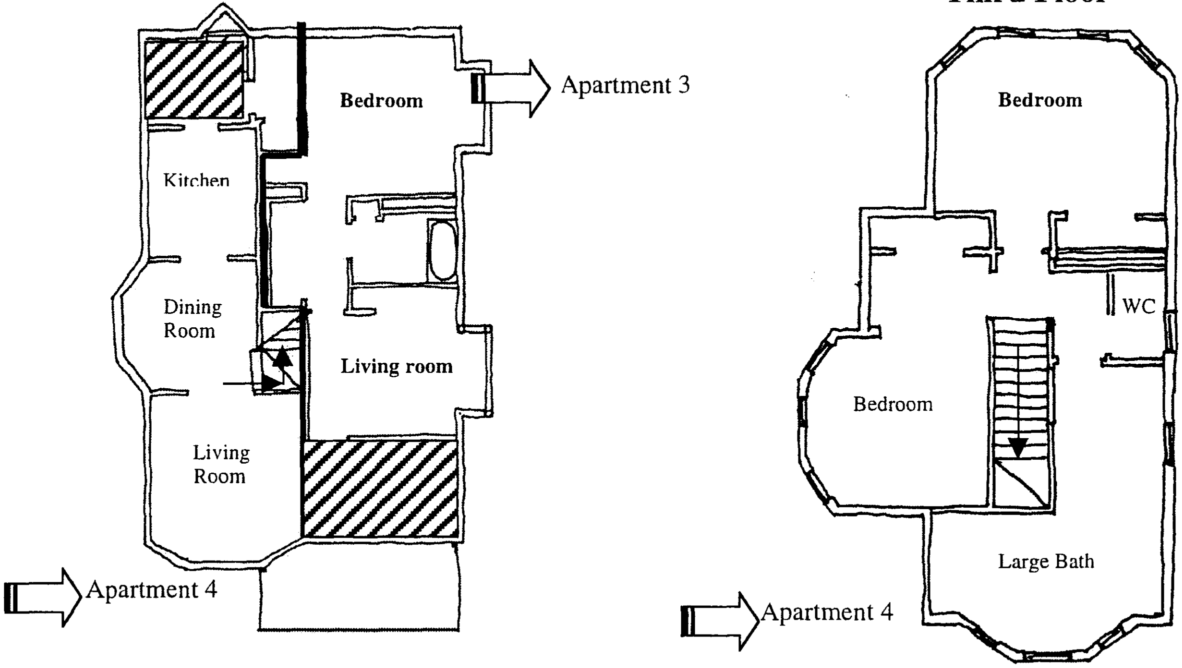


Figure 3.3

Elevations

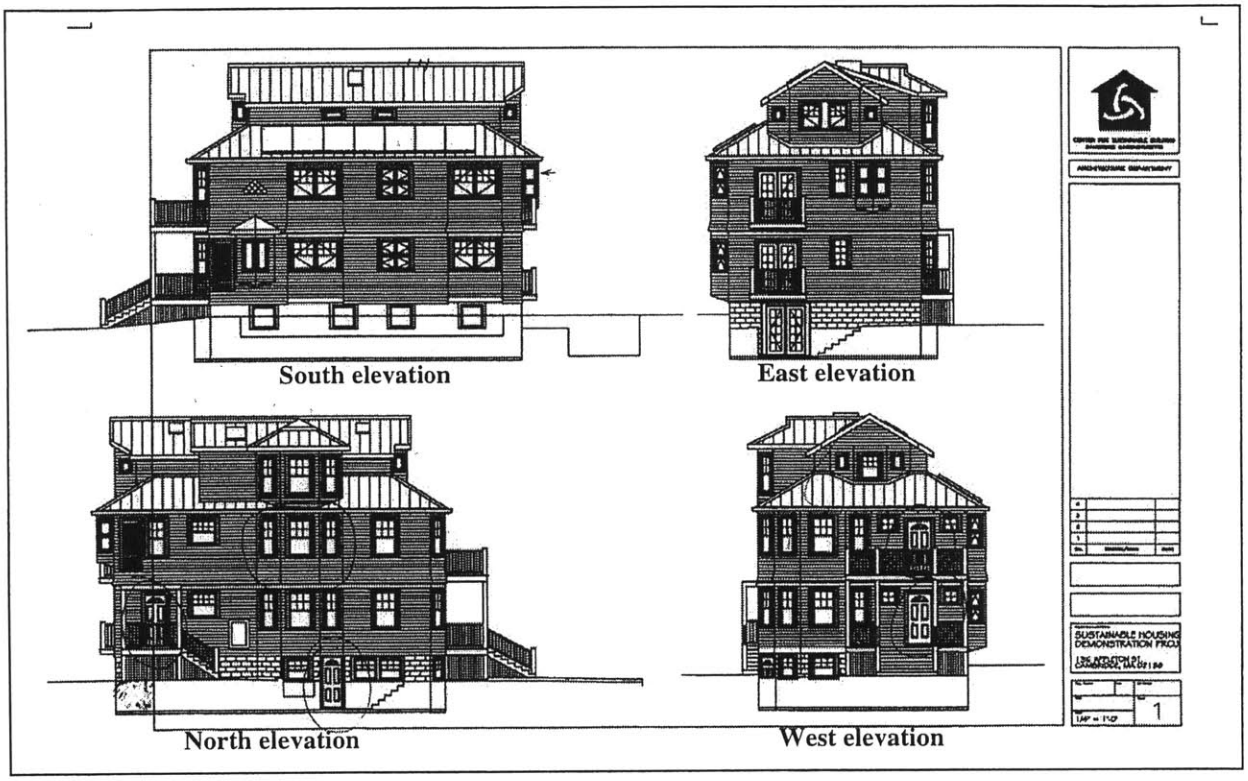


Figure 3.4

3.3 Energy Features of the Cambridge House for Sustainability

The following energy features were added to the Cambridge House for Sustainability.

1. Building Envelope Upgrade
2. Photovoltaic Panels
3. Ground Source Heat Pump
4. Solar Thermal Panels
5. Radiant floor/wall heating system

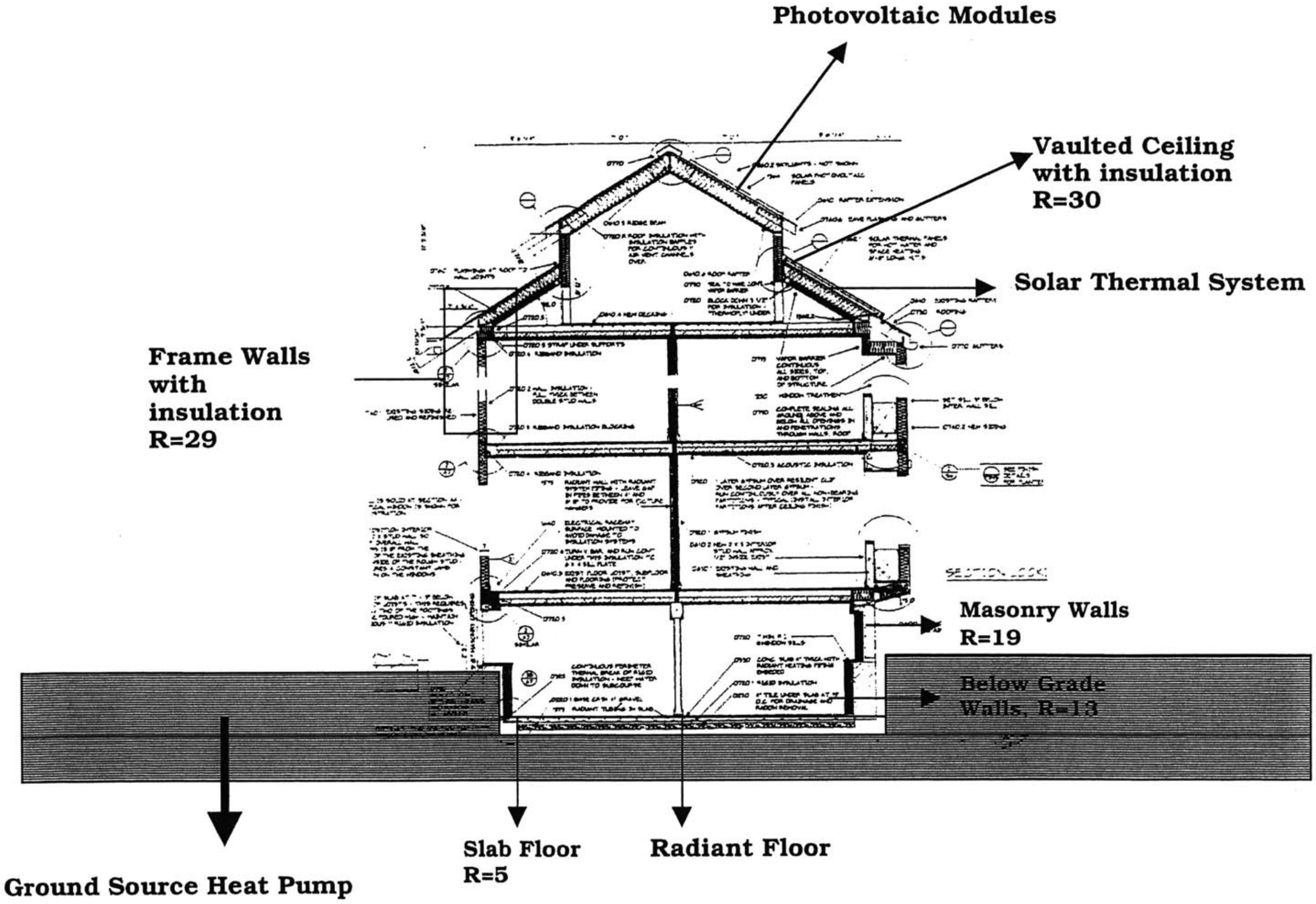


Figure 3.5

1. Building Envelope

Several areas of the building envelope were upgraded to reduce the energy loss. Approximately, 6" of insulation were placed in between the rafters of the vaulted ceiling. The overall r-value of the vaulted ceiling is 30 hr ft^2°F/Btu.

The frame walls were insulated to an r-value of 29 hr ft^2°F/Btu. In order to achieve this level, it was necessary to strap the walls. A wooden framing system was constructed and a combination of cellulose and rigid board was placed in between the studs. This consequently resulted in the reduction of floor space. The wall system was then covered with gypsum and plaster. Careful attention was given to the placement of air spaces and vapor barriers. Strapping was also necessary for the masonry and below grade walls. Rigid board was used to insulate the doors to an r-value of 5 hr ft^2°F/Btu.

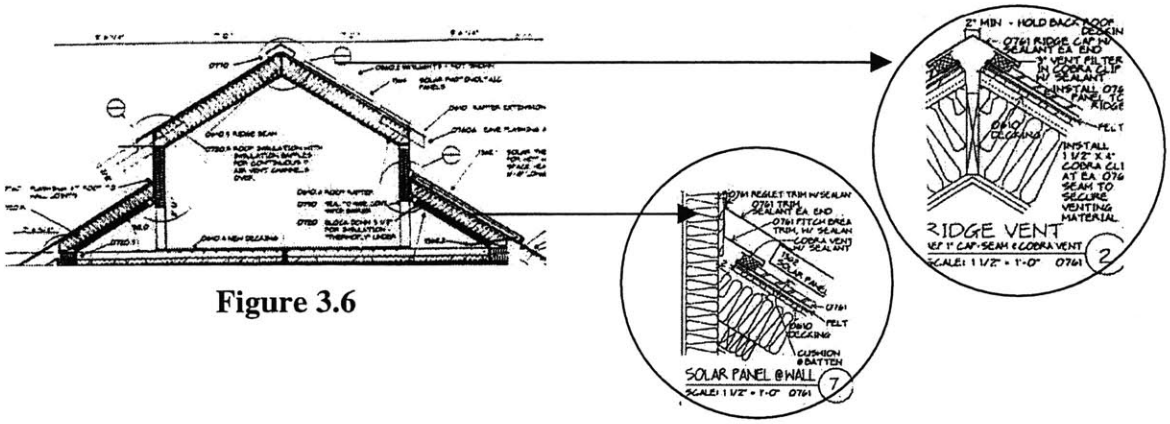


Figure 3.6

All of the old windows were replaced by double-hung windows with an extruded aluminum frame. The new windows have low-e glass with invisible oxide coating, double-glazing and argon gas for insulation. Window replacement helped reduce infiltration. In addition, the Blower Door Program (Comfort Home Program) was employed to caulk the leaky areas of the building envelope. The house has an estimated .2 air changes per hour.

Upgrade Measures

Vaulted ceiling	R-30
Frame Walls	R-29
Masonry Walls	R-19
Below Grade Walls	R-13
Doors	R-5
Windows	R-3
Slab Floors	R-5
Infiltration	.2 ACH

2. Photovoltaic Modules

Fourteen architectural standing seam panels, 64 watts each, are located on the south side of the house on the third floor. The panels are connected to an inverter, which converts DC current to AC current. One of the fourteen panels is used to power the pump for the solar thermal panels, located on the second tier of the roof. The electricity generated is channeled back into the power grid, which turns the on-site meter backwards. The electric company credits the house with the energy gains from the panels.

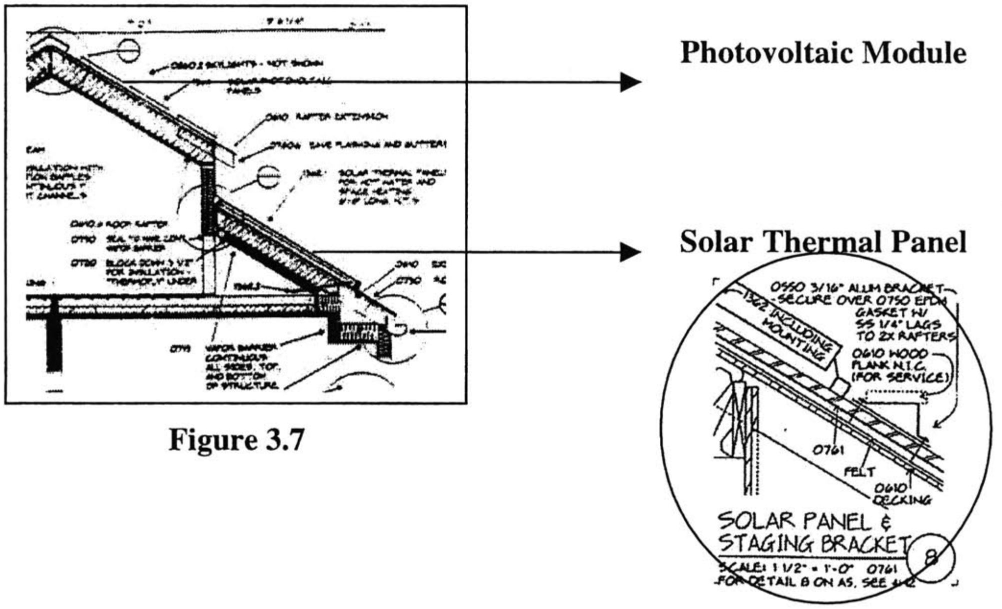


Figure 3.7

3. Ground Source Heat pump

A ground source heat pump was installed to meet the heating and cooling loads of the house. A well, 650 ft feet deep, is located beside the house. Water is pumped at 30 gallons per minute from the bottom of the well at a temperature of 50°F and channeled into a heat exchanger where it interacts with a refrigerant at approximately 25°F. The water loses 10°F to the refrigerant and is then discharged to the top of the well. The refrigerant is compressed until it reaches a high temperature. It is then circulated into an accumulator (storage tank) where it heats the water. The hot water is pumped from the accumulator and used to heat the house during the wintertime. During the summer, the cycle is reversed; cool water provides cooling for the house. The system is sized to provide 120,000 BTUs for heating and 130,000 BTUs for cooling.

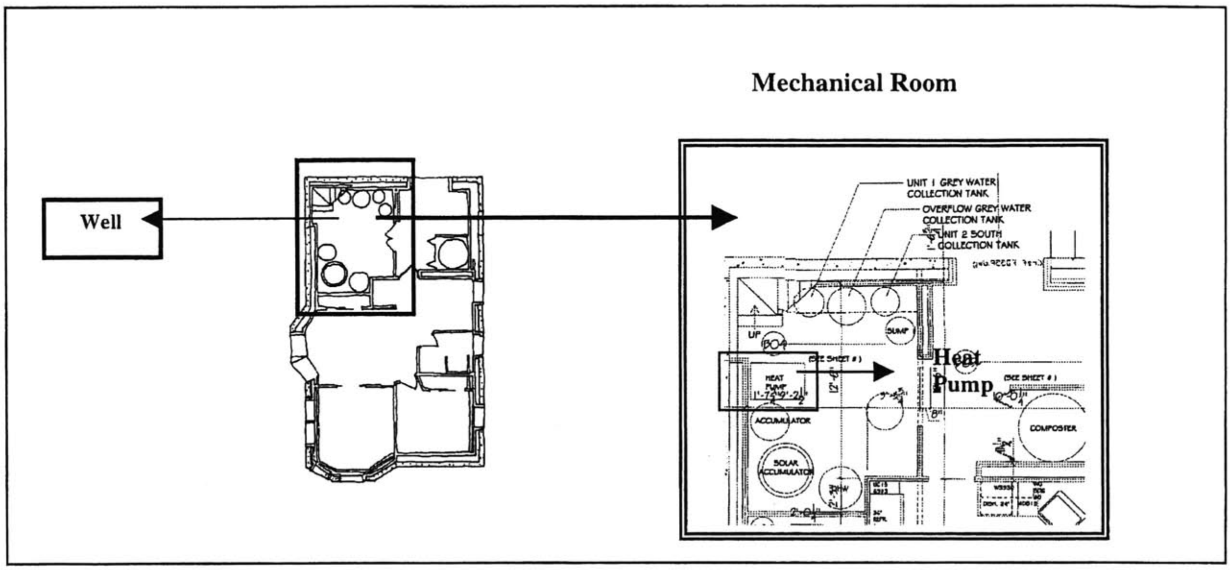


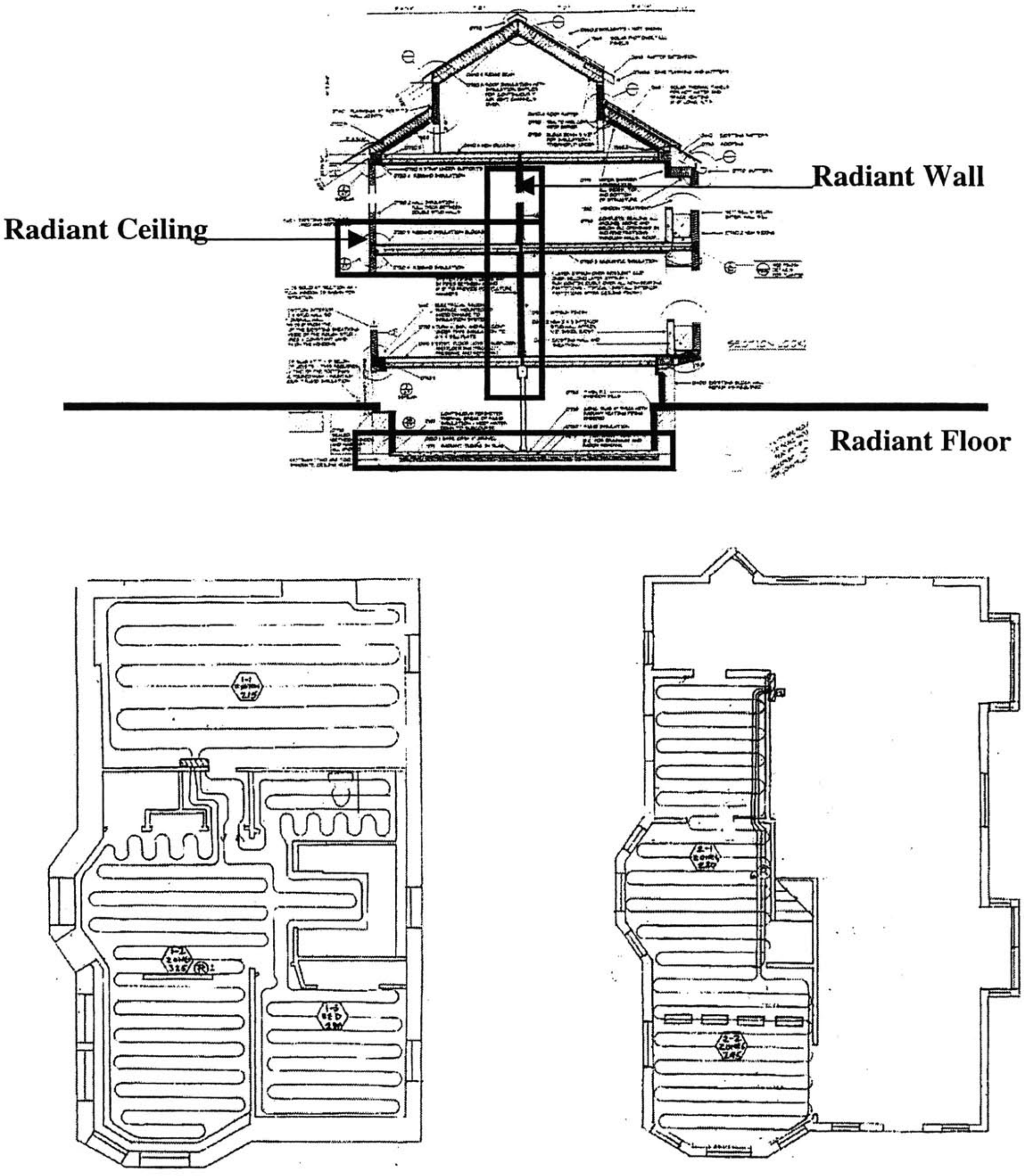
Figure 3.8

4. Solar Thermal Panels

Seven solar thermal panels, located on the south side of the house, help provide the heating of hot water. The system is an "indirect (Closed loop) IPV" and it accommodates climates where freezing weather is more frequent. Antifreeze flows through the collector where it is warmed from the temperature differences between the outside air and the inside temperature of the collectors. It then flows from the roof into a heat exchanger located inside of a storage tank. The exchanger is at the bottom of the tank, thus, maximizing the heat transfer from the antifreeze to the coldest water in the storage tank. The system is indirect because the antifreeze never comes in contact with potable water. The energy that is required to power the pump is provided by one of the photovoltaic panels, which converts sunlight into DC current. The DC pump and the PV are suitably matched to ensure optimal performance. The pump starts when there is sufficient solar radiation available to heat thermal collector. The pumping speed increases with the increase in the amount of sunlight. This provides a flow rate matched to the level of heat transfer required. The system shuts off when the available solar energy diminishes.

5. Radiant Floor/Distribution System

The house has a radiant floor, ceiling and wall. The radiant floor is located in the basement. The radiant ceiling is a below-floor dry system located underneath the floor joists of the second level. Plastic hot water tubes are placed within aluminum plates to maximize radiation. The radiant wall extends from the first to the second levels of the house. Some of the energy from the solar thermal panels is used to heat the mass walls as well as meet the domestic hot water load.



Radiant Floor

Radiant Ceiling

Figure 3.9

3.4 Mechanical Design

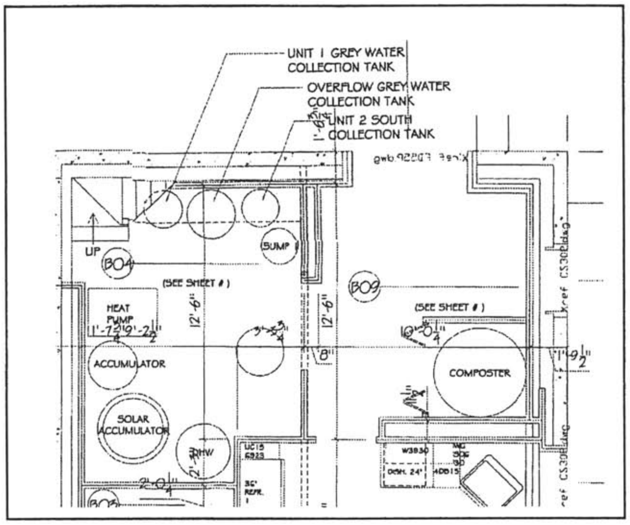


Figure 3.10

The mechanical design relates the ground source heat pump, the solar thermal panels, the accumulator and the domestic hot water storage tank. From the design, the ground source heat pump has a dual function of providing energy to the accumulator and servicing the solar tank, thus contributing the domestic hot water load. The solar energy from panels is used for the dual function of supplying domestic hot water and providing energy to the radiant system, specifically the mass walls. The overall design is complex and involves a considerable number of controls to regulate and moderate temperatures. In addition, the system is not very cost-effective.

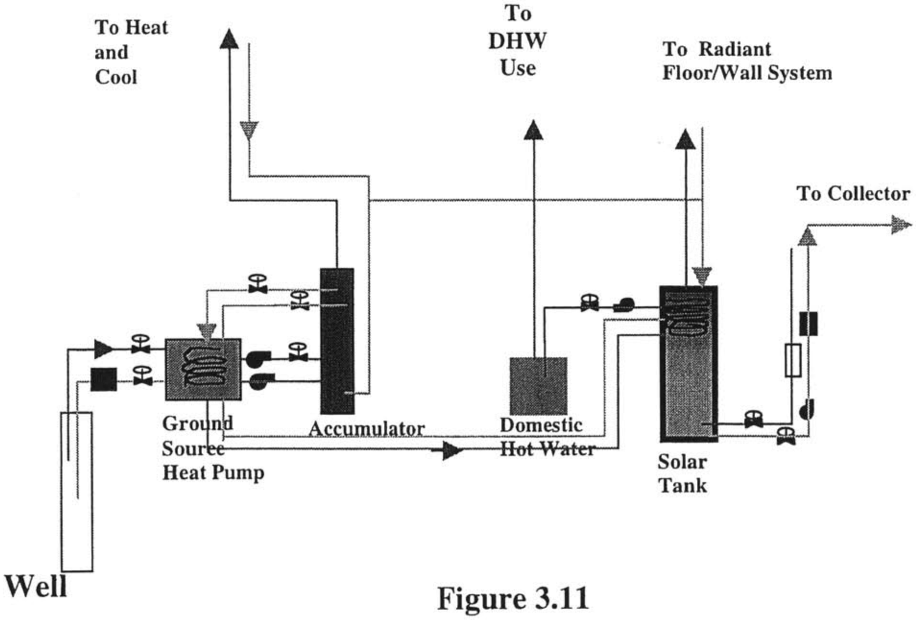


Figure 3.11

Chapter 4 Performance and Analysis

4.0 Performance and Analysis

The following chapter is an analysis of the likely performance of the energy saving features of the Cambridge House for Sustainability. Given that the actual performance data for the house has not been collected, the analysis in this chapter is based on theoretical approximations.

The intent of this exploration is to determine the most cost-effective measures at present energy rates. The relative energy savings is assessed according to two base case models: one model built according to a Cambridge code standard and the other according to an estimated 1920s standard.

4.1 Building Envelope Upgrade

Table 4.1 is a comparison between the energy improvements made by the Cambridge Sustainable house, a Cambridge code standard and a typical uninsulated 1920s House.

Table 4.1: Comparison of Standards

	Cambridge Code	Cambridge Sustainable House	1920s Cambridge House
Vaulted Ceiling	R-30	R-30	R-4
Frame Walls	R-11	R-29	R-3
Masonry Walls	R-11	R-19	R-3
Below Grade Walls	R-11	R-13	R-0
Doors	R-3	R-5	R-3
Windows	R-2	R-3	R-1
Slab Floors	R-0	R-5	R-0
Infiltration (ACH)	.5 estimated	.2 estimated	.8 and 2 estimated

4.1.1 Calculating Heating/Cooling load and Annual Energy Costs for the Sustainable House

Calculations for the heating and cooling load of the house were based on equations from the ASHRAE Handbook. The degree-day method was used to estimate the loads of the vaulted ceiling, frame walls, masonry walls, doors, windows and infiltration. In Boston the number of heating degree-days is 5620 and the number of cooling degree-days is 661.

$$Q = UA\,(DD) \qquad \text{(Eq 4.1)}$$

Where

Q = Heat loss, Btus
U = Effective resistance, Btus/hr•ft^{2}F
A = Area, ft^2
DD = Degree days, cooling/heating

Calculations for the heat loss through the below grade walls were based on methods from 1981 ASHRAE handbook. Table 3 (25.7) in the handbook gives an estimate on the heat loss through a below grade wall at various depths and insulation levels.

Table 4.2: Heat Loss from Below Grade Walls

	Heat Loss, Btu/h • ft² • F			
Depth (ft)	**Uninsulated**	**R = 4.17**	**R = 8.34**	**R = 12.51**
(0-1)	0.410	0.152	0.093	0.067
(1-2)	0.222	0.116	0.079	0.059
(2-3)	0.155	0.094	0.068	0.053
(3-4)	0.119	0.079	0.060	0.048
(4-5)	0.096	0.069	0.053	0.044
(5-6)	0.079	0.060	0.048	0.040
(6-7)	0.069	0.054	0.044	0.037

At each depth, the heat loss in Btu/h ft² °F is multiplied by the square footage of below grade wall area to obtain the heat loss in Btu/h °F. The sum of the heat loss rate at each depth is added together to obtain the total heat loss across the wall. To calculate the total heat loss in Btu/h, the sum total is multiplied by the difference between the internal temperature, t_i , and the external design temperature across the wall. The external design temperature is the difference between the Amplitude (A) and the mean annual temperature of the soil. The line of constant amplitudes are given from the 1981 ASHRAE hand book, 25.7. fig.4.

$$\textit{External Design Temperature} = (T_a - \mathrm{A}) \qquad \text{(Eq. 4.2)}$$

Based on fig. 4, the amplitude for Boston area is 18°F and the value ,$T_{a,}$ is 50°F. To obtain the annual heat loss through the below grade wall, the heat loss in Btu/h is multiplied by 24 hours. Extrapolations on the above data were used to estimate the relative heat loss through the wall at varying r-values of insulation.

The following equation was used to calculate the heat loss through the slab floor.

$$\mathrm{Q} = \mathrm{f}_2\,\mathrm{P}\,(t_1 - t_2) \qquad \text{(Eq. 4.3)}$$

Q = heat loss through perimeter of floor slab, Btu/h
f_2 = heat loss coefficient, (Btu/h°F per foot of perimeter)
P = perimeter of exposed edge of floor, ft
t_I = indoor temperature, °F
t_o = *outdoor* temperature,°F

Values for the heat loss coefficient, f_2, for a slab floor were taken from the table 5, 25.9 of the 1981 ASHRAE handbook, based on the cross section of the slab floor and wall construction and the number of degree days. Extrapolations on the data were used to estimate the effect of insulation on heat loss. The assumed temperature difference for the summer and winter ($t_i - t_o$) was 58°F and 38°F, respectively.

Table 4.3: Heat Loss Coefficient for Slab Floor

Heat Loss Coefficient of Slab Floor Construction, f_2		
Construction		**Degree days(65FBase)5350**
4-in block wall, brick facing	**Uninsulated**	**0.84**
	R = 5.4 from edge	**0.49**

4.1.2. Annual Costs ($) of Heating and Cooling

Based on citations from Boston Edison and the Boston Gas Company, the cost for heating is estimated at $1.10 per therm of gas and the cost for cooling is $0.12 cents per kilowatt/hour.

The estimated annual heating cost for the house, according to Cambridge code, is $1641.55 and $313.62 for the annual cooling cost. Given that a large percentage of infiltration occurs through the windows, the calculations below combine the total energy loss due to infiltration with the total energy loss due to conduction through the windows. In later sections of this chapter, calculations determine the percentage of losses due to the windows versus the frame walls. The major form of energy loss occurs in the following hierarchical order:

Table 4.4: Percentage of Annual Energy Bill (Cambridge Code)

	% of Energy Bill Cambridge Code	**Annual Cost $ Cambridge Code**
Windows, R-2	**28**	**544.40**
Infiltration, .5 ACH	**26**	**516.61**
Total(combined)	**54**	**1061.01**
Frame Walls, R-11	**17**	**323.107**
Slab Floors, R-0	**14**	**279.02**
Doors, R-3	**6**	**109.55**
Masonry Walls, R-11	**4**	**79.51**
Vaulted Ceiling, R-30	**3**	**56.40**
Below Grade Walls, R-11	**2**	**46.59**

On the other hand, the house built according to 1920s standard would lose energy in the following hierarchical order and have a substantially higher annual heating and cooling cost.

Table 4.5: Percentage of Annual Energy Bill (1920s House)

	% of Energy Bill 1920s House	Annual Cost $ 1920s House
Windows, R-1	**25**	**1078.55**
Infiltration, .8 ACH	**19**	**820.10**
Total (combined)	**44**	**1898.65**
Frame Walls, R-3	**27**	**1174.43**
Vaulted Ceiling, R-4	**10**	**419.65**
Masonry Walls, R-3	**7**	**289.26**
Slab Floors, R-0	**6**	**275.75**
Below Grade Walls, R-0	**4**	**157.43**
Doors	**3**	**108.69**

A homeowner, interested in retrofitting his/her home, would have different priorities depending on whether the house was built according to Cambridge Code or in the 1920s. If the home were built according to Cambridge code, he/she would consider upgrading windows, reducing infiltration and insulating frame walls and the slab floor. With limited funds, these retrofit activities would significantly reduce energy lose. If the home was built according to the 1920s standard, appropriate measures would include the reduction of infiltration, a window upgrade, insulating frame walls and the vaulted ceiling. Clearly, in both cases, a window upgrade, infiltration reduction and the insulation of frame walls rank as the top three areas for energy conservation.

The various improvements made by the Cambridge house for Sustainability reduce the annual energy bill by 45% when compared to Cambridge code house. The annual cost for heating is $890.68, and the cost for cooling is $165.92. The total annual saving is $898.56.

Annual Energy Cost	Camacode	Cambridge (Sus)	Diff
Heating	$1641.55	$890.68	$750.86
Cooling	$313.62	$165.92	$147.70
Total	$1955.17	$1056.61	$898.56
Average Monthly	$162.93	$88.05	$74.88

Each energy saving feature in the Cambridge house for Sustainability (Sus) provided a 2% to 25% reduction in the annual energy cost of a house built according to Cambridge Code. 35% of the total 45% savings was achieved with the retrofit activities listed below:

- **Reduction in infiltration from .5 ACH to .2 ACH,**
- **A window upgrade from R-2 to R-3**
- **An increase in the insulation of the frame walls from R-11 to R-29.**

The following table shows the hierarchical savings of each energy saving measure, and the percentage reduction of the annual energy cost of a Cambridge Code house (Camacode).

Table 4.6: Percentage Reduction of Annual Energy Cost (Cambridge Code)

	Cambridge (Sus) $ Savings	%reduction of annual energy cost (Camacode)
Infiltration, .2 ACH	**311.58**	**16**
Windows, R-3	**184.68**	**9**
Total (combined)	**496.26**	**25**
Frame Walls, R-29	201.51	10
Slab Floors, R-5	118.17	6
Doors, R-5	44.33	2
Masonry Walls, R-19	33.84	2
Below Grade Walls, R-13	4.01	0
Total	898.56	**45**

An even greater reduction in cost is obtained when the improvements made by the Cambridge house for Sustainability are compared to a 1920s house. The overall percentage saving is 76%.

Annual Energy Cost	1920s Cambridge	Cambridge (Sus)	Diff
Heating	$3709.41	$890.68	$2818.73
Cooling	$615.43	$165.92	$449.51
Total	$4324.85	$1056.61	$3268.24
Average Monthly	$360.40	$88.05	$272.35

The percentage saving of each measure is in the range 3% to as high as 31%. A homeowner of a 1920s house can reduce his energy bill by a 63% by performing the following retrofits:

- **An investment in reducing infiltration from .8 ACH to .2 ACH,**
- **Replacing single glazed window, R-1, with low-e window, R-3**
- **Insulating frame walls from R-3 to R29**
- **Insulating the vaulted ceiling from R-4 to R-30**

The following table shows that the hierarchical savings obtained from the retrofitting a 1920s home. Clearly, the window upgrade and the reduction of infiltration comprise a major percentage of the savings. The insulation of the frame walls reduces the energy bill by 24%. In the Cambridge code house, the insulation of the frame walls reduced the energy bill by 17%. In addition, the insulation of the vaulted ceiling reduces energy cost by 8%.

Table 4.7: Percentage Reduction of Energy Cost (1920s House)

	Cambridge (Sus) $ Savings	**%reduction of annual energy cost (1920s House)**
Windows, R-3	718.83	17
Infiltration, .2 ACH	615.07	14
Total (combined)	1333.90	31
Frame Walls, R-29	1053.83	24
Vaulted Ceiling, R-30	363.70	8
Masonry Walls, R-19	243.58	6
Slab Floors, R-5	114.90	3
Below Grade Walls, R-13	114.85	3
Doors, R-5	43.47	**1**
Total	3268.24	**76**

The following graph compares the relative percentage saving of an upgraded Cambridge code house versus a 1920s house. In both cases, A homeowner obtains the largest reduction in energy cost by reducing infiltration and upgrading the windows. If both proprietors have a restricted budget, they may opt to insulate the frame walls. However, the 1920s proprietor would have a larger percentage reduction of his/her energy bill compared to the Cambridge code proprietor. Clearly, the retrofit of older homes yields a higher energy savings.

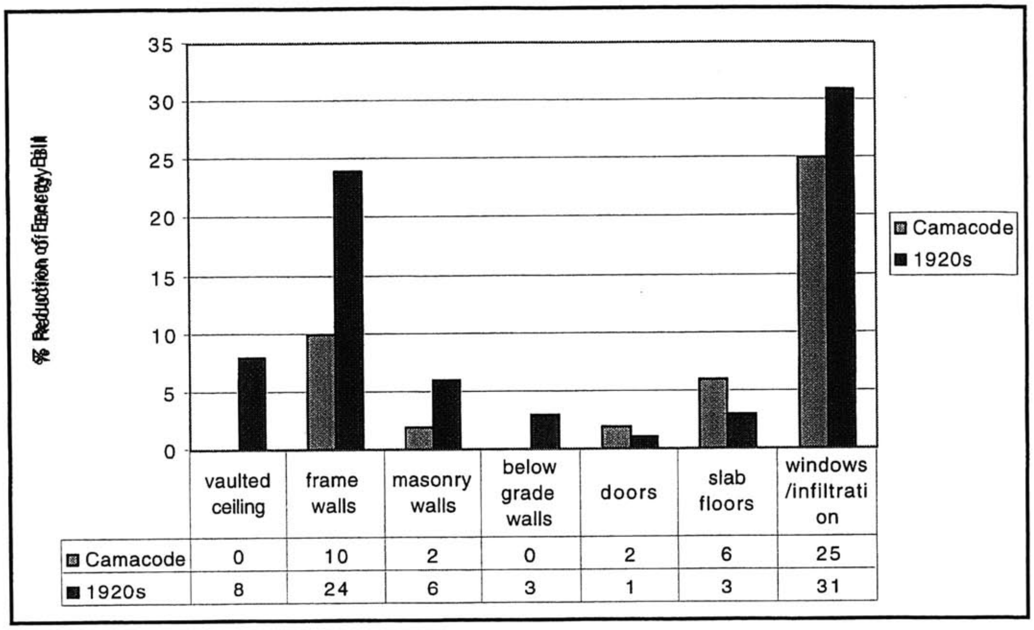


Figure 4.1

One might conclude that a homeowner with limited means might opt to invest in the envelope components that provide the most annual savings. However, clearly the initial investment in each feature may or may not exceed the net present value of the annual savings over a period of twenty years. Whether the owner stands to gain or lose in the long term determines if each investment is a viable and economically sound option.

4.1.3 Costs of Windows and Insulation of Walls

1.Cost for frame walls, masonry walls and slab, floor, doors

Estimates on the cost per square foot of partition framing and insulation are based on the Means Residential Cost data book. The partition framing system with insulation has the following components:

Framing system	Cost $ (per square foot, p.s.f)
2" by 4", studs 24" O.C	.63
Plates, double top	.30
Cross bracing	.12
Gypsum with plaster	.87
Insulation labor	.50
Total	2.42
Region factor (1.07)	
Total (p.s.f)	**2.59**

Each additional 1/2" of wood required to increase the insulation thickness is estimated at $.09 per square foot. The above-stated cost was used to calculate the necessary capital for the frame walls, masonry walls and below grade walls. The cost to insulate the framing system is estimated at $.50 cents per square foot.

For the slab floor, it is assumed that the insulation is placed on top of the concrete slab because was no insulation under the slab before the renovation. A 1/2" of sheathing is placed on top of the insulation. The cost is estimated to be the following:

Slab Floor	Cost $ /per square foot (p.s.f)
EPS	0.25
Sheathing(1/2")	0.91
Total (p.s.f)	1.16

2. Cost for reduction of infiltration

To reduce infiltration, Blower Door Program is estimated to cost $100 per hour of professional labor. The approximate time per unit (apartment) is 2 to 4 hours. Thus, four units would require 8 hours as a lower estimate. An upper estimate is 16 hours. The calculations are based on the assumption that the actual amount is between the lower and upper estimates of approximately 10 hours for the entire house.

3. Cost for windows

The new double hung windows of the house have the following features: low-e glass (invisible oxide coating), double glazing, an extruded aluminum frame on the outside, argon gas for maximum insulating potential. Based on the Means Residential Cost data, the cost for a metal clad double hung window system is $294.70 per window or approximately $27.50 per square foot of glass.

Metal Clad Wood Window *2'by 3', Double hung*	Cost $ (per window)
Window, metal clad, deluxe, 3'by 5' (insulating glass)	164.00
Trim, interior casing	20.13
Paint, interior, primer & 2 coats	49.78
Caulking	**10.20**
Snap-in grille	29.70
Drip cap, metal	1.62
Regional factor (1.07)	
Total	294.70

4.1.4 Cambridge Code Base Case Scenario

Net Present Value Analysis

The analysis in this section calculates the net savings over a twenty-year span using a discount factor (DF) at three different interest rates, 4%, 8% and 10%. Calculations are based on a gas price of \$1.1/Therm and an electricity rate of \$.12/kWh. The capital costs for investments are based on section 4.1.3. For example, the cost of insulating a frame wall is estimated at \$2.59/ft^2. An additional 1/2" of wood required to increase the insulation thickness would add an additional \$.09/ft^2 and increase the total cost to \$2.68/ft^2. The extra cost is the difference between the base cost of (\$2.59/ft^2) and each additional 1/2" of insulation added to the frame wall system.

(1). Annual Energy Savings (\$) = Energy Savings (Btu) × Energy Price (\$)
(2.) Net Present Value of Savings (\$) = Annual Energy Savings × (DF)
(3). Net Savings (\$) = Net Present Value of Savings - Extra Cost

Based on the estimates of the initial cost of each component of the envelope, one can assess the optimal return on each investment. The optimal return is defined as the maximum net present value of the annual savings (at three different interest rates (4%, 8%, 10%) over a span of twenty years, minus the extra cost. The following table shows the optimal return for an investment in insulation based on a house built according to Cambridge code. These values are compared to the improvements made by the Cambridge House for Sustainability (Camsus).

Table 4.8: Optimal Return based on Cambridge Code House (Camacode)

	Optimal 4%	Optimal 8%	Optimal 10%	Camsus
Frame Walls	6.5"(R-20)	5.5"(R-17)	5"(R-16)	9.0"(R-29)
Masonry Walls	6.5"(R-20)	5.5"(R-17)	5"(R-16)	6.0"(R-19)
Below Grade Walls	0.0"	0.0"	0.0"	4.0"(R-13)
Doors	4"(R-13)	3.5"(R-11)	3"(R-9)	1.5"(R-5)
Slab Floors	4.5"(R-14)	4.5"(R-14)	4.5"(R-14)	1.5"(R-5)

From the above table, it is clear that the insulation level for the Cambridge House for Sustainability (Camsus) exceeds the optimal return value for the frame walls and below grade walls. This indicates that the homeowner does not receive the most return for his initial investment. In the case of the below grade wall, any increase beyond the Cambridge code specification of R-11 results in a net loss over a span of twenty years. However, for the doors and the slab floors, Camsus is below the optimal values. This may be due to practical issues, such as whether it is feasible to have insulation thickness greater than 3.5" on doors or 4" on slab floors.

Increases in insulation thickness decrease the overall space in a house. In addition, considering that the doors only account for 6% of the total energy bill, it is reasonable to invest more in insulating the frame walls , which account for 17%. The slab floor, on the other hand accounts for 14% of the energy bill, indicating that it is better to invest in insulating the floor rather than both the below grade walls and the masonry walls which, combined, account for 6% of the energy bill. With regard to slab floors, the increase in insulation beyond 4.5" results in negligible heat losses to the ground. Thus any further investments would not improve overall energy efficiency of the floor. However, if the insulation investment for the slab floor is below 1.5", the overall saving is minimal resulting in a net loss over the twenty year span. Therefore, the range in investment in insulation for the slab floor is in the range of 1.5" to 4.5".

Graph 4.3 shows the sum of the optimal insulation investments (for frame walls, below grade walls, masonry walls, and slab floor) in comparison to the Camsus improvements at different interest rates (4%, 8%, 10%). The optimal investments are in the range of \$8.00/ft^2 (per square foot of wall area) to \$3.00/ft^2. Whereas, the sum total of the Camsus improvements are in the range of \$4.00/ft^2 to \$1.00/ft^2. If the house was designed according to a optimal case scenario at 4%, 8% and 10% percent, the homeowner would obtain an annual energy savings of 43%, 41% and 40% (of energy bill for space heating and cooling) respectively. All of this analysis is based on present energy rates.

Figures 4.4 and 4.5 show the net savings/ft^2 and the energy savings/ft^2 versus the increase in insulation thickness.

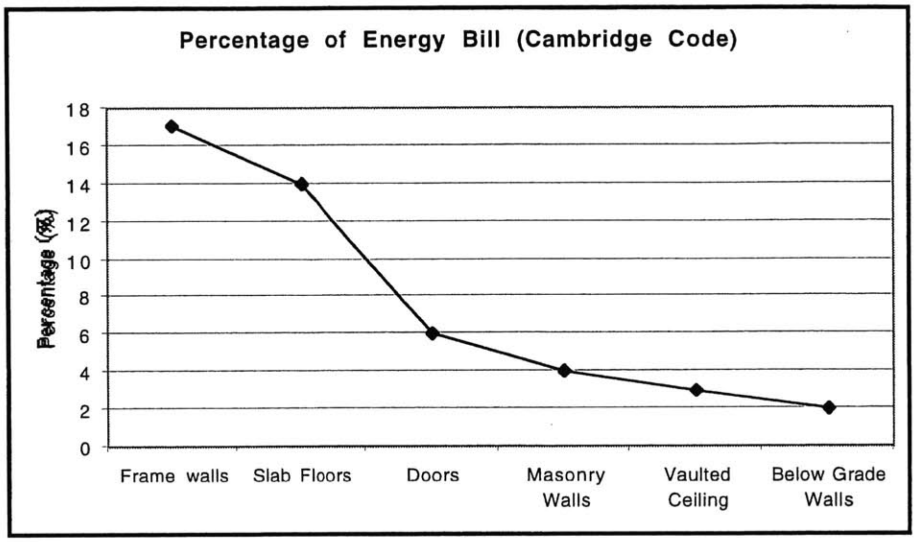


Figure 4.2 Percentage of Energy Bill (Camacode)

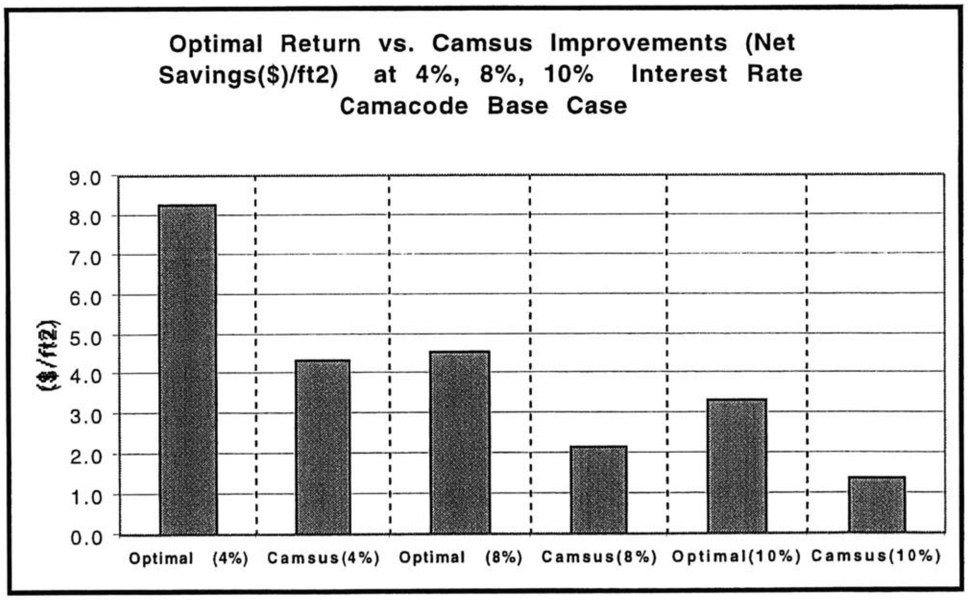


Figure 4.3 Optimal vs. Camsus

Optimal Return on Investment for Cambridge Code House
Net Savings per Square Foot ($/ft^2) Vs. Insulation Thickness (inches)

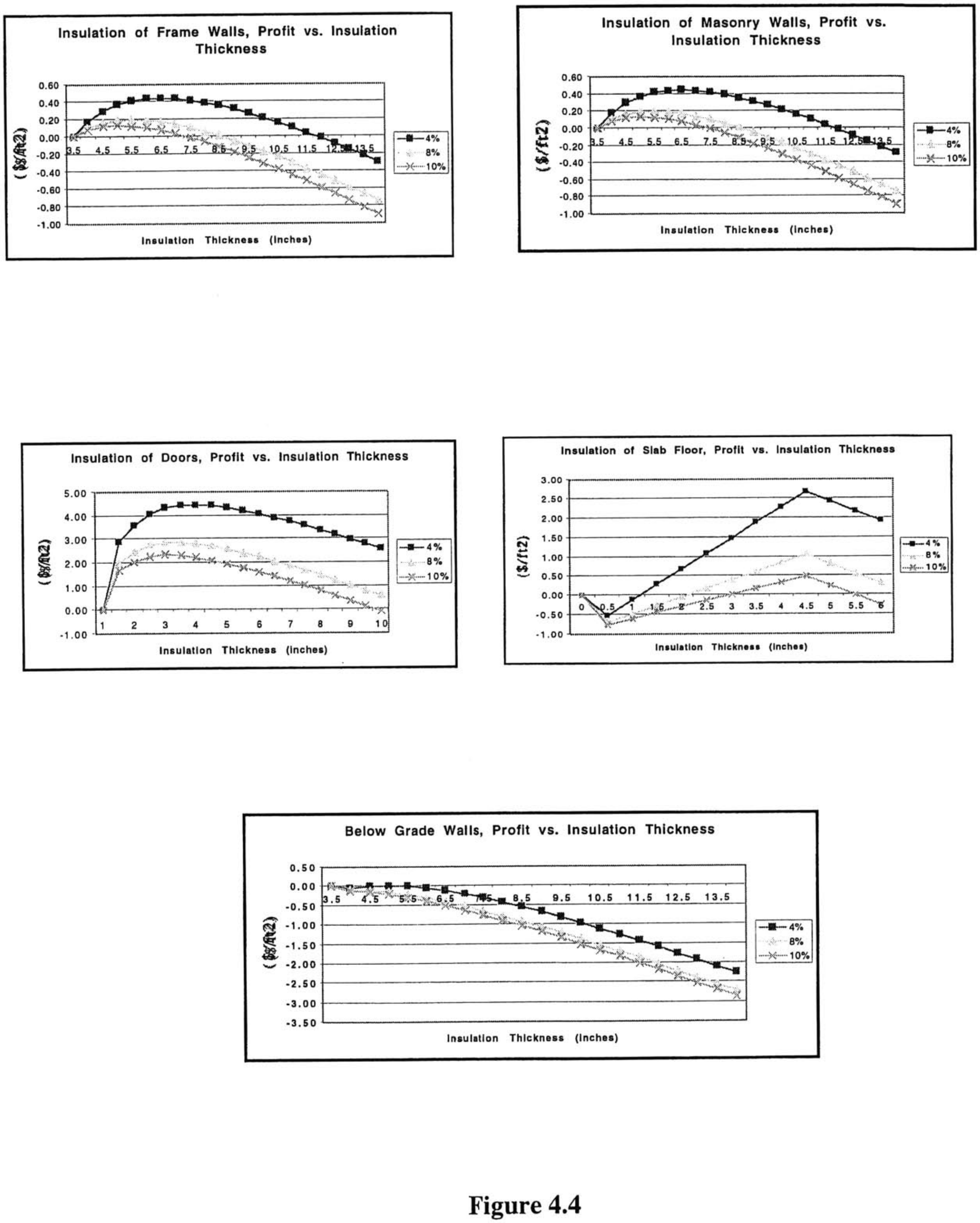
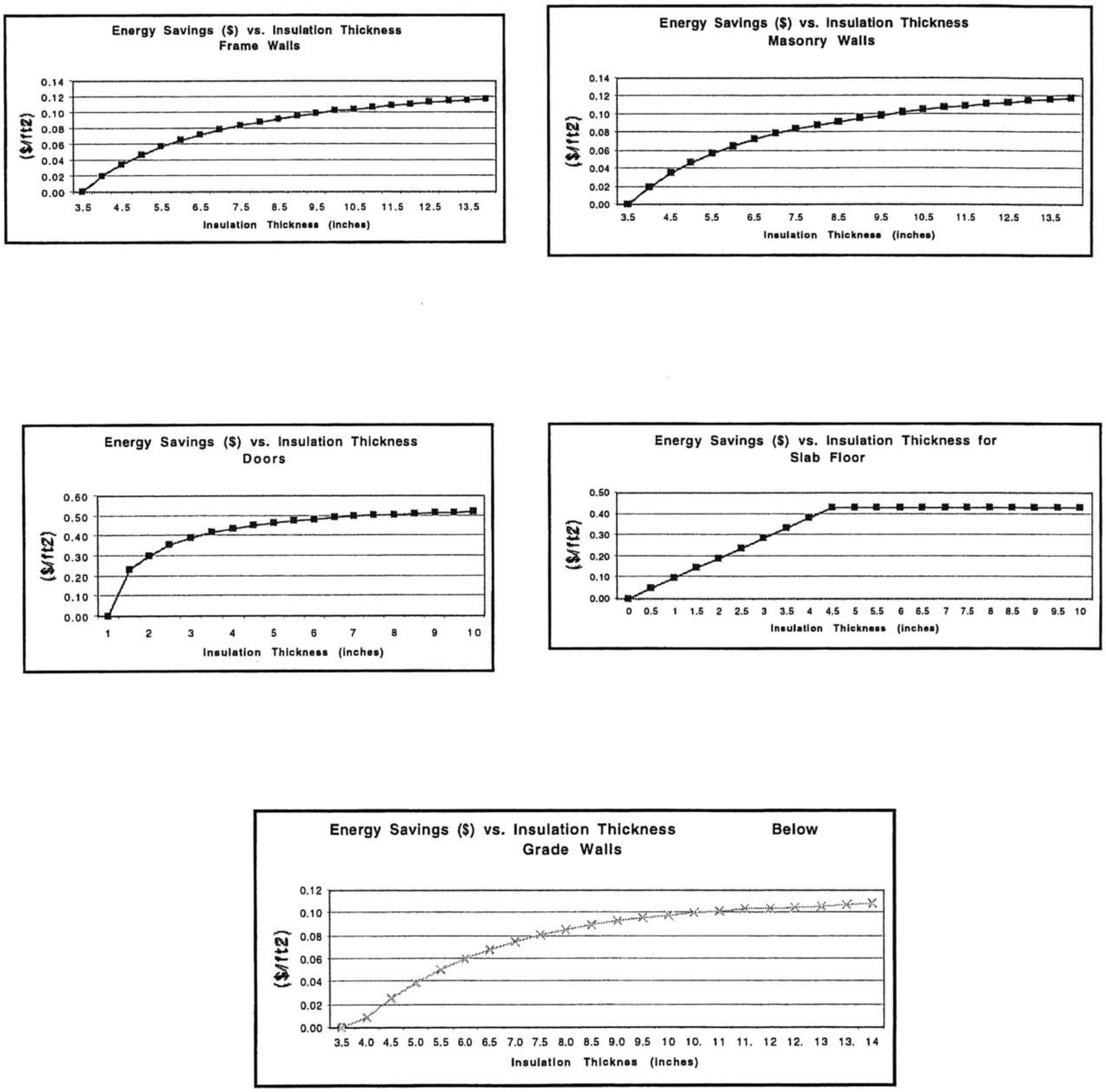


Figure 4.4

Annual Energy Savings ($\$/ft^2$) Vs. Insulation Thickness (Inches)
Cambridge Code House


Energy Savings ($) vs. Insulation Thickness
Frame Walls

Energy Savings ($) vs. Insulation Thickness
Masonry Walls

Energy Savings ($) vs. Insulation Thickness
Doors

Energy Savings ($) vs. Insulation Thickness for
Slab Floor

Energy Savings ($) vs. Insulation Thickness Below
Grade Walls

Figure 4.5

4.1.5 1920s Home Base Case Scenario

Table 4.9: Optimal Return for 1920s House

	Optimal 4%	Optimal 8%	Optimal 10%	Camsus
Vaulted Ceiling	6.5”(R-20)	5.5”(R-17)	5.0”(R-16)	9.5”(R-30)
Frame Walls	6.5”(R-20)	5.5”(R-17)	5.0”(R-16)	9.0”(R-29)
Masonry Walls	6.5”(R-20)	5.5”(R-17)	5”(R-16)	6.0”(R-19)
Below Grade Walls	4”(R-13)	3.5”(R-11)	1.5”(R-5)	4.0”(R-13)
Doors	4”(R-13)	3.5”(R-11)	3”(R-9)	1.5”(R-5)
Slab Floors	4.5”(R-14)	4.5”(R-14)	4.5”(R-14)	1.5”(R-5)

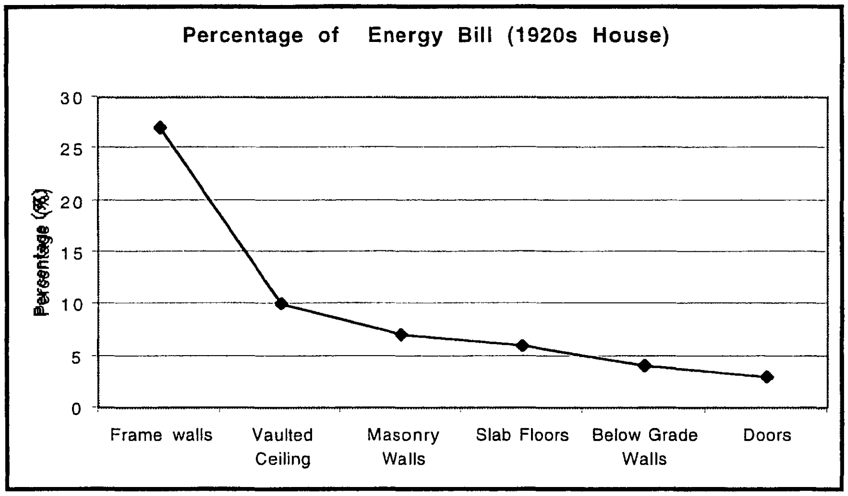


Figure 4.6 Percentage of Energy Bill (1920s Home)

In comparison to the 1920s base case house, the improvements made by the Cambridge House for Sustainability exceed the optimal insulation investments for the vaulted ceiling and frame walls. However, given that the frame walls comprise a large percentage of the energy loss, it is possible to exceed the optimal value and achieve a significant profit after a twenty years. For example, the optimal profit at 10% interest (net present value of savings minus the capital cost) is $6179.59 or $3.02 per square foot of frame wall area. The Cambridge House for Sustainability yielded a profit of $2.68 per square foot of wall area. Interestingly, an increase in insulation thickness from R-3 to R-16 yields a 22% reduction in the energy bill for a 1920s house. An increase in insulation thickness from R-3 to R-29 yields a 24% reduction in the energy bill with only a 2% variation from the optimal case. On the other hand, there is significant percentage increase in capital cost from 28% to 57% when the two upgrade measures are compared with one another. Therefore, one can conclude that any increases beyond the R-16 insulation level does not provide a significant energy savings, but can potentially double the percentage increase in capital cost.

Energy losses through the attic spaces or the vaulted ceiling can account for more than 10% of the annual energy bill in older homes. The Cambridge house for Sustainability has an insulation level of R-30, which provides an 8% reduction in the overall energy bill. At a 4% interest rate, the optimal insulation level (R-20) also provides an 8% reduction in the energy bill. Thus, the increase in insulation from R-20 to R-30 has a negligible effect on the bill. If the homeowner opts to invest at the optimal level, he/she will obtain a net saving in the range of $3.72/ft^2 to $2.01/ft^2 (per square foot of wall area).

The masonry walls account for 7% of the energy bill of a 1920s home. Apparently, the Cambridge House only slightly exceeds the optimal levels of insulation investments at 8% and 10%. It is slightly smaller than the optimal insulation investment at 4%. Therefore, one can conclude that 6" of insulation at R-19 approximately equal to the average of the optimal values at the three different interest rates. An upgrade from R-3 to R-19 of a 1920s home leading to 6% reduction in the annual energy bill and a net energy savings in the range of $5.32/ft^2 to $3.03/ft^2 (per square foot of wall area).

The below grade walls contribute to 4% of the energy bill of an older home. The Cambridge House exceeds the optimal levels of insulation at 8% and 10% interest rate. At a 4% interest rate, the improvement made by the Cambridge house is equal to the optimal level of insulation. The upgrade from zero insulation R-0 to R-13 yields a 3% reduction in the annual energy bill. The net saving per square foot of wall area is $2.46.

The following graph shows the sum of the optimal insulation investments (vaulted ceiling, frame walls, below grade walls, masonry walls and slab floor) in comparison to the Camsus improvements at different interest rates (4%, 8%, 10%) for a 1920s home.

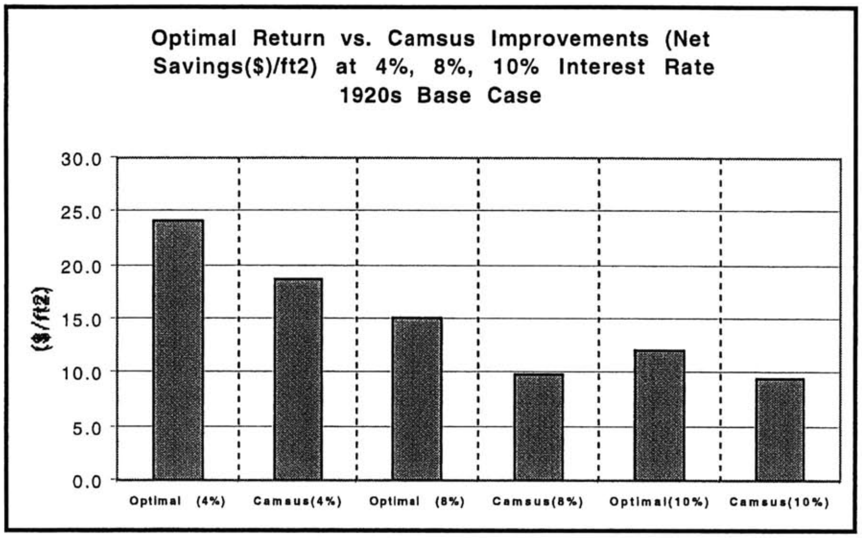


Figure 4.7

Clearly, the sum total of the optimal insulation investments exceeds that of the Cambridge House for Sustainability. At a 4% interest, a homeowner can obtain a net saving of \$24.20/ft^2. Whereas, if he/she invests at the various insulation levels in the Cambridge House, he/she obtains a net savings \$18.62/ft^2. Thus, he/she has a potential gain at \$5.60/ft^2 by optimizing his/her investment. On the other hand, an investment in the optimal insulation levels slightly decreases the annual percentage energy savings. For example, the Cambridge house improvements provide a 76% percent reduction in the annual energy cost of a 1920s house. The optimal improvements provide a 59% to 61% reduction (at the different interest rates) of the annual energy bill. It should be noted that the net savings per square foot of wall area is an order of magnitude greater when upgrading a 1920s home when compared to the upgrade of a home built according to Cambridge Code.

Optimal Return on Investment for the 1920s House
Net Saving per Square Foot ($/ft^2) Vs. Insulation Thickness (inches)

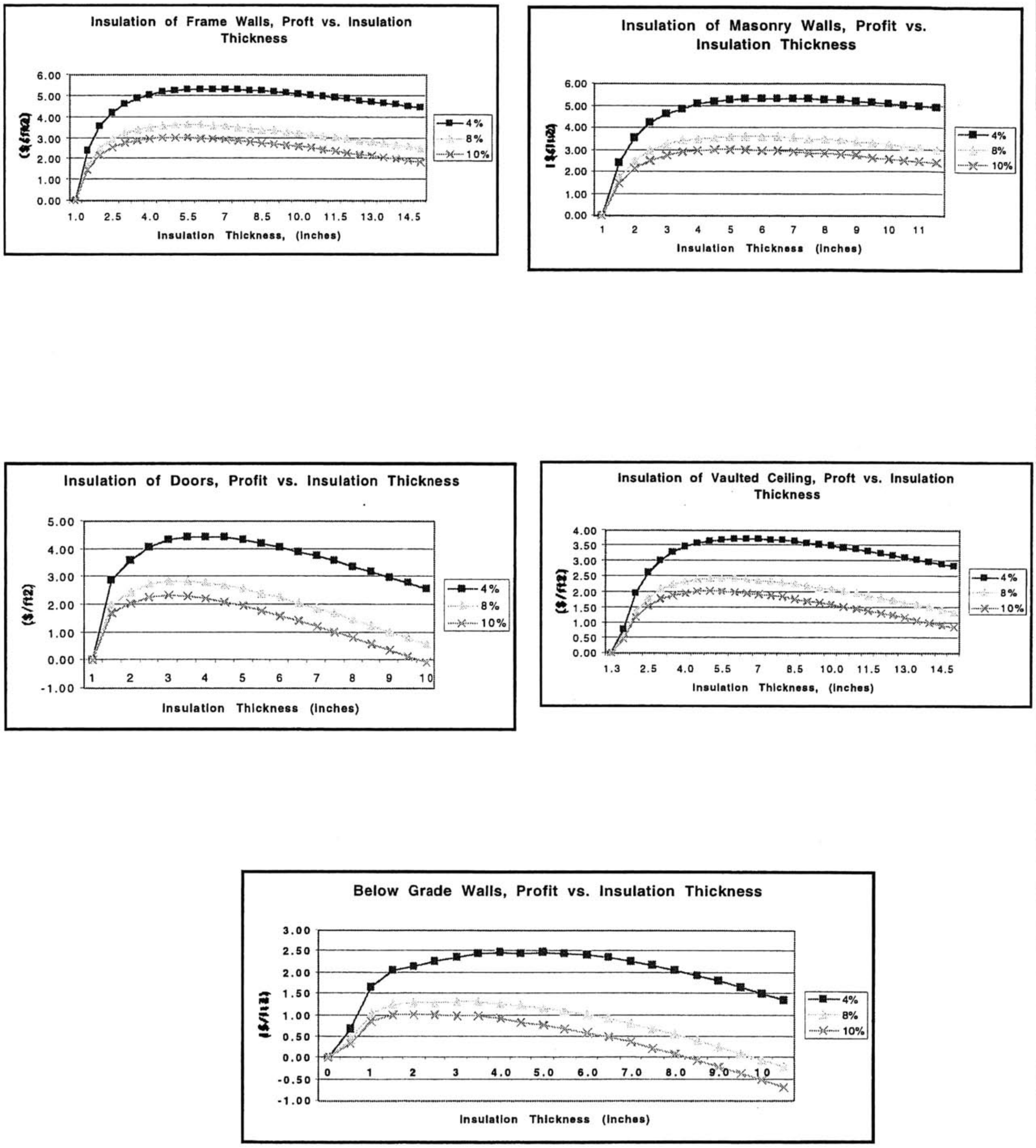


Figure 4.8

Savings ($/ft^2) versus Insulation Thickness (inches)
1920s House

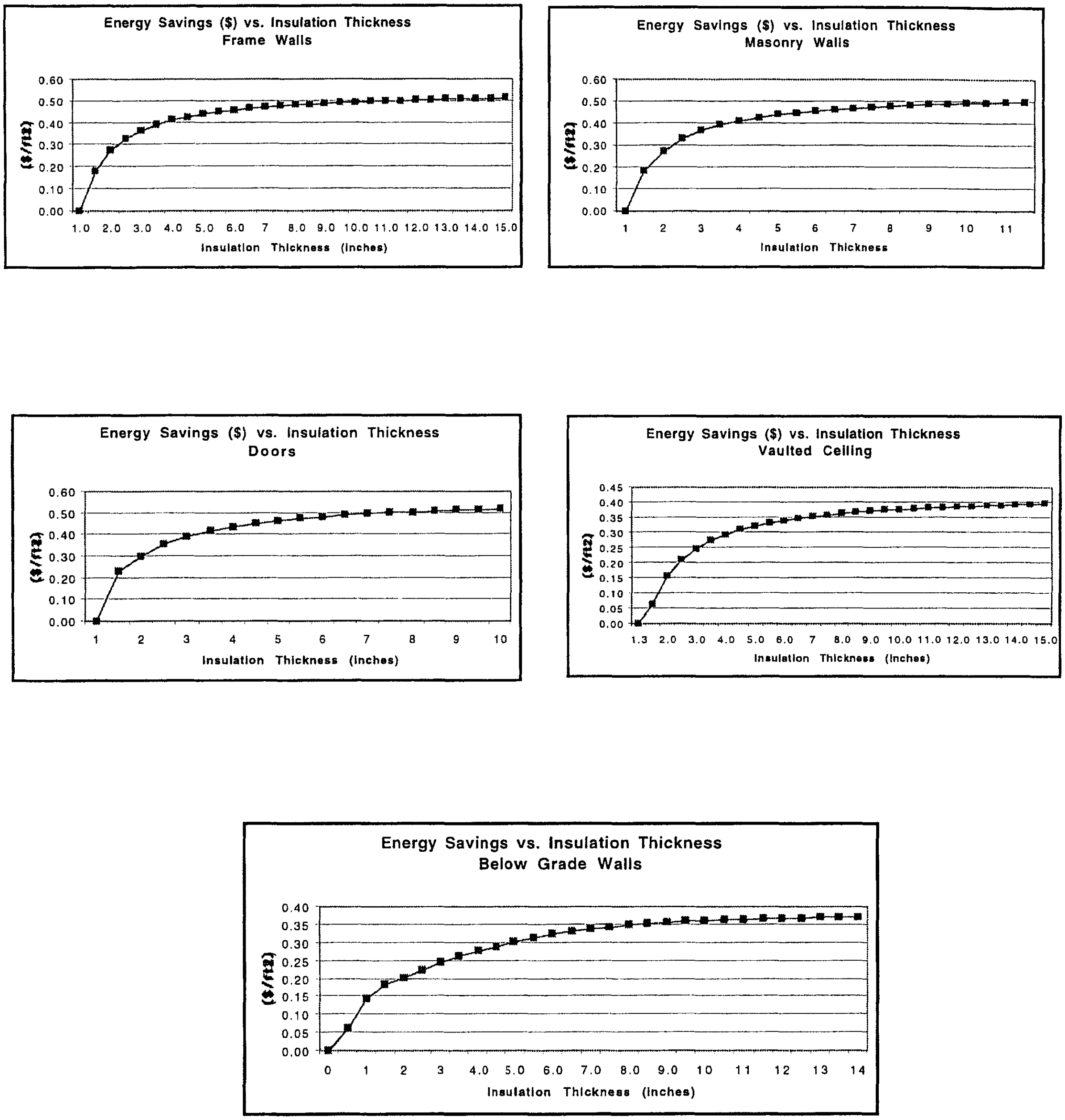


Figure 4.9

4.1.6 Windows Analysis

Insulation investments in the vaulted ceiling, walls, and slab floors provide significant energy savings; however, the majority of energy losses occur through infiltration and conduction through windows. In both the Cambridge Code house and the 1920s house, windows and infiltration account for 54% and 44% of the energy bill, respectively. Therefore, an owner stands to gain the most savings by addressing these major areas of energy loss. Possible conservation measures include: caulking, weather-stripping, use of the Blower Door Program and window replacement.

Infiltration and Pressure Difference

Infiltration is a result of the nonlinear interaction between the stack effect and the wind pressures on the exterior of the building envelope. The stack effect is caused by the density differences between the indoor and outdoor air. The wind pressure on a building surface is the result of wind acting on the windward and leeward faces of the building. Pressure differences across building surface are caused by the internal pressure of the building that will balance the total inflow and outflow of air over leakage areas; i.e. (cracks/crevices) in the envelope.

From the ASHRAE Fundamentals Handbook, there are two methods used to calculate the pressure differences, P_s, due to the stack effect. One equation is a result of the density difference, and the other is a result of the temperature difference across the envelope. Temperature differences between the inside and outside air cause changes in air density.

$$P_s = (\rho_o - \rho_i)gh \tag{Eq.4.4}$$

where

P_s = the pressure differences due to the stack effect, Pa
ρ = air density, kg/m^3
g = the gravitational constant, 9.8 m/s^2
h = distance to neutral level, (m),(positive if above neutral level and negative below
T = absolute temperature Kelvin

subscripts

i = inside
o= outside

The following assumptions were made when calculating the value of P_s, during the heating season, for the Cambridge House for Sustainability.

T_i = 294 K (70°F)
T_o = 272 K (32°F), average outside winter temperature
ρ_i =1.1614 kg/m^3, density of air at 300K
ρ_o = 1.3947 kg/m^3, density of air at 250K
h = 4.57 m, height above neutral level, is assumed to 1/2 the height of the building

Based on the above equation and assumptions, the resulting difference in pressure due to the stack effect between the inside and outside of the Cambridge House is approximately **4.25** Pascal. The ASHRAE equation for the pressure differences between the windward and leeward faces of the building is:

$$P_w - P_i = \frac{(P_w - P_l)}{\left(1 + \frac{A_w}{A_l}\right)^{\frac{1}{n}}}$$

P = wind pressure
A = leakage Area
n = flow exponent, between .5 and 1, usually .65 for leakage openings

(Eq. 4.5)

subscripts
w = windward
i = inside
l = leeward

The ratio of the exposed windward area to leeward area (A_w/A_l) can change depending on the direction of the wind. The resulting pressure (P_w ,P_l) on the both sides of the building is dependent on the wind speed.

$$P = 1/2\rho v^2 C_w$$

where

(Eq. 4.6)

υ = wind velocity m/s
C_ω = factor approximated as ≈ .7 - .8 windward side
≈ -.4 -.5 leeward side

Wind Velocity

The wind velocity varies according to the terrain coefficient (α), height of building (Z), gradient height of boundary layer thickness (Z_g) and free stream velocity (υ_g).

$$V = V_g\left(\frac{Z}{Z_g}\right)^{\alpha}$$

(Eq. 4.7)

The following table relates the terrain coefficient to the gradient height of the boundary layer thickness for different landscapes.

Table 4.10: Terrain Coefficient & Boundary Layer Thickness

	α	Z_g (m)
Open Country	.16	275
Suburban Areas	.28	400
City Centers	.40	500

In Boston, the average free stream velocity is around 5 m/s, and peak gusts are in the range from 20 to 27 m/s. Wind speeds are usually larger during the winter months and come from predominately the southwest direction during seven months out of the year.

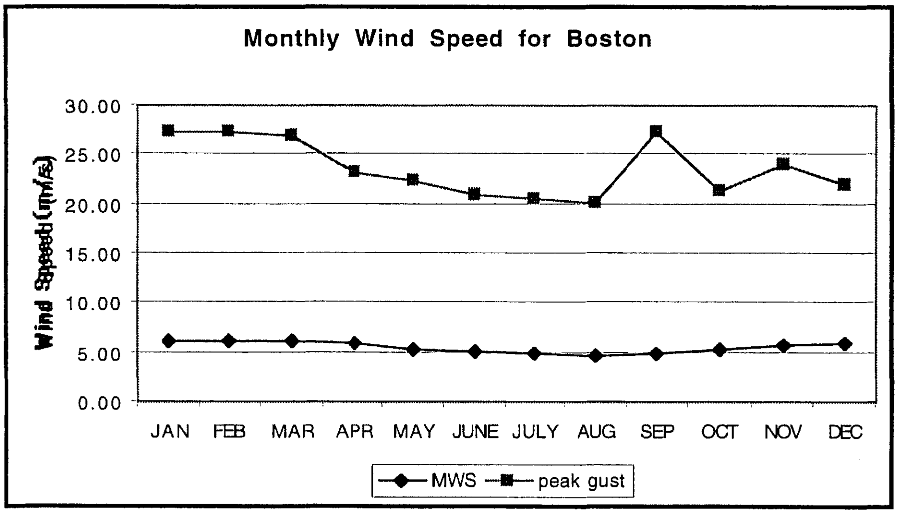


Figure 4.10 Mean Wind Speed
The Weather Almanac

In order to estimate the wind speed around the Cambridge House for Sustainability, one can assume that its somewhere in the mid range between suburban area and a city center. One can also assume that the free stream velocity, V_g , is in the range of 5 m/s to 20m/s. The two values for the free stream velocity are an upper bound and lower bound for the velocity profile acting on the surface the building envelope. The following graph shows the given pressure difference acting on a wall surface with V_g equal to 5 m/s.

The range of pressure difference at height of 4.57 meters (1/2 the height of the Cambridge house) is .49 Pa for a Suburb to .14 Pa for a City with the free stream velocity equal to 5 m/s. The average between the two is .31 Pa. The pressure difference across the wall surface varies greatly with the change in free stream velocity. With a free stream velocity equal to 20 m/s, the range in pressure difference at 4.57 meters is 7.78 Pa for a suburb and 2.22 Pa for a city. The average between the city and suburb is 5 Pa.

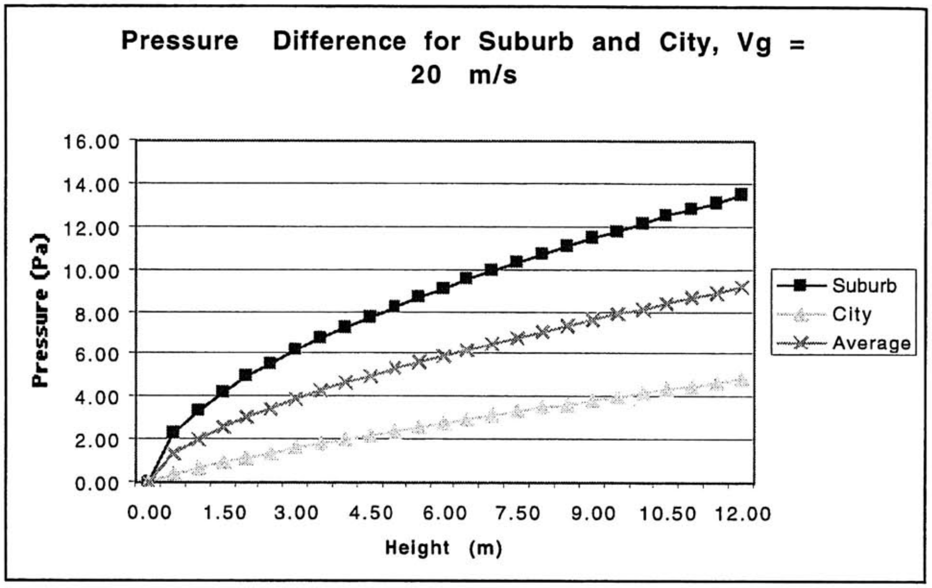


Figure 4.11 Pressure Difference

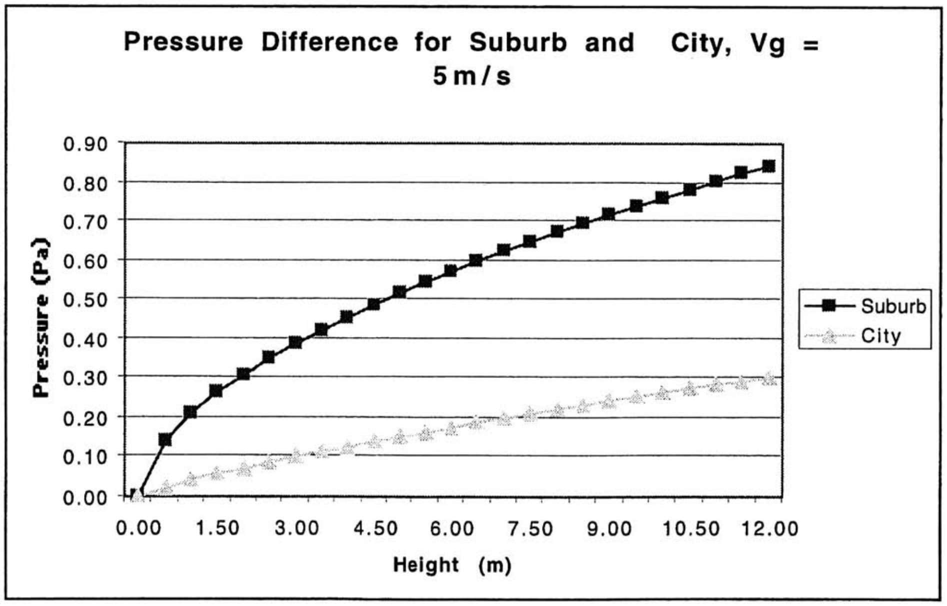


Figure 4.12 Pressure Difference

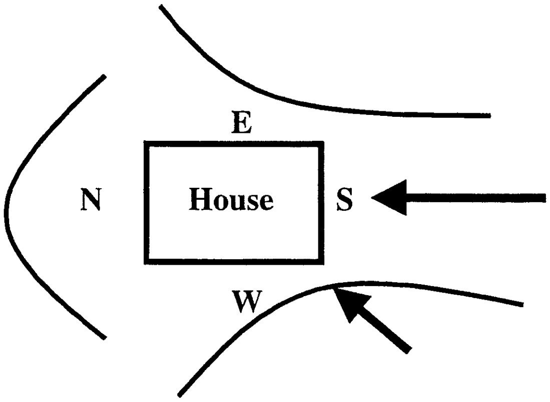


Figure 4.13 Prevailing Wind Direction

Stack Effect and Wind Pressure

Although the total pressure is the result of the non-linear interaction between the stack effect and the wind pressure, the two terms can be added together to obtain an estimate of the pressure difference across a wall surface.

$$P_{tot} = P_s + P_w \tag{Eq. 4.8}$$

Subscript
tot = total pressure difference
s = stack effect
w = wind pressure

Given the above analysis, one can conclude that the total pressure difference for a residential home located in Cambridge is in the range of 4 Pa to 9 Pa. At average wind speeds, the stack effect has the dominant contribution to the overall pressure. However, at peak gusts, the wind pressure is twice as large as the stack effect, contributing to a total pressure as large as 15 Pa.

Calculation of Energy loss from Windows

The amount of airflow through the cracks and crevices of windows is dependent on the pressure difference and the geometry of the opening. The Bernoulli equation describes the relationship of volumetric airflow through openings and relates the pressure difference to the effective leakage areas, and the discharge coefficient. The discharge coefficient, C_D, is a number dependent on the geometry of the crevice and the Reynolds number of the airflow. In a laminar flow, C_D, is dependent on the square root of the pressure difference. However, in turbulent flows, C_D, remains constant at a fixed Reynolds number.

$$Q = C_D A\sqrt{2\Delta P/\rho}$$

Where

Q = airflow rate, m^3/s

(Eq 4.9)

C_D= discharge coefficient, dimensionless
A = cross-sectional area of opening, m^2
ρ = air density, kg/m^3
ΔP = pressure difference across opening, Pa

The cross sectional areas of openings, A, or the effective leakage areas for low-rise residential applications are given in the 1997 ASHRAE fundamentals handbooks. These values are based on a pressure difference of 4 Pa and a discharge coefficient, C_D, equal to one. The following table lists various window types and estimates on the effective leakage area, cm^2 per linear meter of crack, lmc. For a given type of window, there are cracks and crevices due to the nature of the fitting between the window and the frame. The table estimates the effective area for the airflow. Once the effective area is determined, the total volumetric flow, Q, through a window can be calculated.

Table 4.11: Effective Leakage Areas

Window Type	Best estimate cm^2/lmc	Minimum estimate cm^2/lmc	Maximum estimate cm^2/lmc
Casement, weather-stripped	0.24	0.1	3
Casement, not weather-stripped	0.28	▨	▨
Double Horizontal slider, not weather-stripped	1.1	0.019	3.4
Double Horizontal slider, wood, weather-stripped	0.55	0.15	1.72
Double Horizontal slider, alum, weather-stripped	0.72	0.58	0.8
Double-hung, not weather-stripped	2.5	0.86	6.1
Double-hung, weather-stripped	0.65	0.2	1.9
Double-hung with storm, not weather-stripped	0.97	0.48	1.7
Double-hung with storm, weather-stripped	0.79	0.44	1
Double-hung with pressurized track, weather-stripped	0.48	0.39	0.56

Based on the estimates on the volumetric airflow through the various window types, the total annual energy loss, MMbtu/yr, is determined using the following equation:

$$q = Mcp\Delta\mathbf{T} \tag{Eq.4.10}$$

Where:
Q = annual energy loss, MMbtu/yr
M = mass of air, kg
Cp = specific heat of air, Btu/lbm°F
ΔT = heating / cooling degree days for Boston

From the best estimates of airflow and the above energy equation, one can rank the efficiency of each window type from the most efficient to the least efficient. Calculations are based on the linear meter of crack length, lmc, obtained from the Cambridge House for Sustainability.

Based on the following list, it is clear that casement, weather-stripped windows are the most energy efficient. On the other hand, double-hung, not weather-stripped windows are the least energy efficient. Interestingly, double-hung, weather-stripped windows use around 1/4 of the energy of double-hung, non weather-stripped windows. In all of the above cases, the weather-stripped window systems reduce energy consumption in the range of 14% to 75%. Clearly, the replacement of a window system can contribute significantly to the annual energy savings. However, the weather-stripping of an existing window system can provide savings at a significantly smaller investment.

	Annual Energy Loss MMbtus/yr for entire House
1. Casement, weather-stripped	7.01
2. Casement, not weather-stripped	8.18
3. Double-hung with pressurized track, weather-stripped	14.02
4. Double horizontal slider, wood, weather-stripped	16.07
5. Double-hung, weather-stripped	18.99
6. Double horizontal slider, aluminum, weather-stripped	21.04
7. Double-hung with storm, weather-stripped	23.08
8. Double-hung with storm, not weather-stripped	28.34
9. Double horizontal slider, not weather-stripped	32.14
10. Double-hung, not weather-stripped	73.04

Double-hung window systems are common in residential homes. In the Cambridge house for Sustainability, the old single-glazed 1920s windows were replaced by double-hung, low-e window system with an extruded aluminum frame on the outside. The following graph compares the ACH, air changes per hour, of double-hung, weather-stripped and non weather-stripped windows based on the maximum, minimum and best estimates of volumetric air flow rates. Double-hung, non weather-stripped windows have an estimated range of .27 to 1.95 ACH. Double-hung, weather-stripped windows are in the range of .06 to .61 ACH.

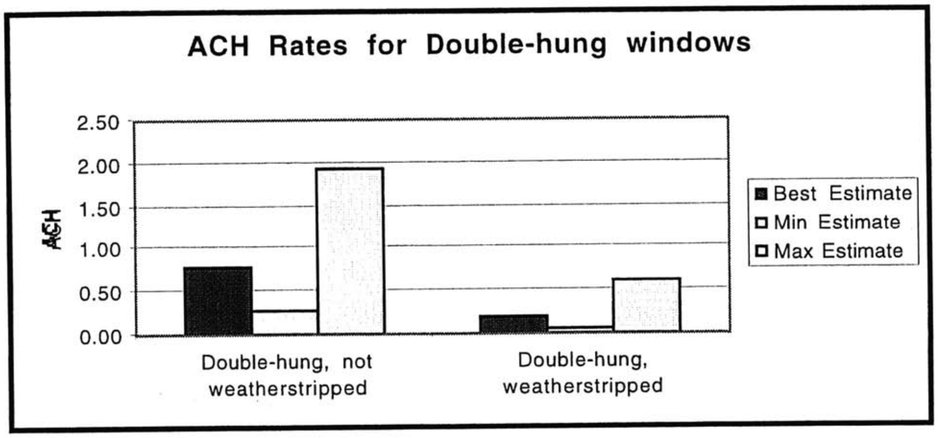


Figure 4.14 Air change per Hour

Economic Analysis of window upgrades

A homeowner can reduce heat loss significantly by investing in window replacement; however, the high capital cost of such an undertaking is potentially far greater than the net present value of the energy savings over a twenty year period. Therefore, the viability of such an investment depends on the reduction of the unit price per window or the increase in the cost of energy. According to the Means Residential Cost data, the standard price of a 2' by 3' double-hung window system with insulating glass is $275.43 per window. The regional price of the window system in the Boston area is $294.70. A 2' by 3' double-hung system with single glass is $240.46 per window.

Given that double-hung window systems are common in many homes, one can assume that there are five variations of these window systems found in Cambridge code and older 1920s residences.

Double-Hung Window Types

1. Single glazing, non weather-stripped, loose fit, (S(L)NW)
2. Single glazing, non weather-stripped, average fit, (S(A)NW)
3. Double glazing (low-e), weather-stripped, average fit, (T(A)W)
4. Double glazing, weather-stripped, average fit, (D(A)W)
5. Double glazing, non weather-stripped, average fit, (D(A) NW)

Based on the maximum, minimum and best estimates for the double-hung window systems, the air changes per hour (ACH) of the five window types can be estimated. For example, a 1920s window can be classified as either a single glazed, non weather-stripped, loose fit window type with a corresponding maximum estimate of 2 ACH. It can also be classified as a single glazed, non weather-stripped, average fit window with a corresponding best estimate of .8 ACH. The following table estimates the annual energy loss due to only infiltration (not conduction) and the air changes per hour of the varying double-hung window systems. Calculations are based on the total estimated linear meter of crack obtained from the Cambridge House for Sustainability.

Table 4.12: Infiltration and ACH for Window Types

	MMBtus /Yr (total) for entire House	MMBtus/yr/per Window	ACH
S(L)NW	178.22 (max)	2.17	2
S(A)NW	73.04 (best)	.89	.8
T(A)W	18.99 (best)	.23	.2
D(A)W	18.99 (best)	.23	.2
D(A)NW	43.59 (min)	.53	.3

From the above table, one can approximate the percentage of energy savings obtained from window replacement. Energy calculations include the losses due to infiltration and conduction. For example, a window built according to Cambridge Code would correspond to a double glazed, non weather-stripped, average fit window (D(A)NW). If a Cambridge code window was replaced by a double-glazed (low-e), weather-stripped, average fit window (T(A)W), it would yield an overall savings of 46%. A homeowner can achieve an 81% energy savings by upgrading a 1920s window with 2 ACH (classified as a single glazed, non weather-stripped, loose fit (S(L)NW)) to a double glazed (low-e), weather-stripped, average fit window (T(A)W).

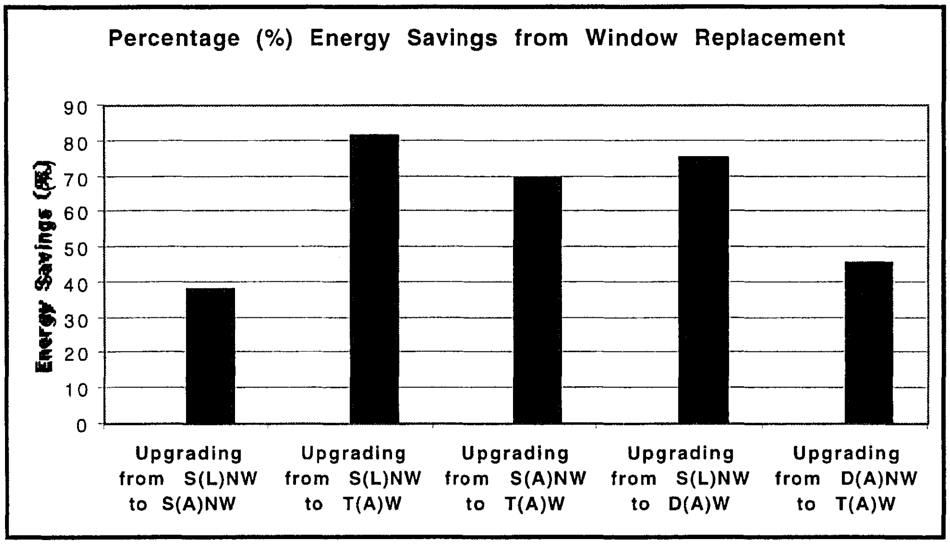


Figure 4.15

If the 1920s window has .8 ACH (S(A)NW), the upgrade to a T(A)W would yield a 70% energy savings. A 1920s window with 2 ACH that is upgraded to a T(A)W would yield 81% savings.

Window Type	Classification	ACH	Replaced By	Percentage savings
Cambridge Code	D(A)NW	.5 - .3	T(A)W	46%
1920s Window(1)	S(L)NW	2	T(A)W	81%
1920s Window(2)	S(A)NW	.8	T(A)W	70%

A homeowner would obtain the smallest savings of only 38% when upgrading from a single glazed, non weather-stripped, loose fit window to a single glazed, non weather-stripped, average fit window. Such an upgrade might occur if the proprietor was interested in repairing damages or addressing a poor fitting between a window and frame. In all of the above case scenarios, there are significant energy savings; however, given the unit price of each window, only a few of the above measures are cost-effective at varying interest rates.

From the figure 4.15 , it is clear that that the two upgrade measures with highest percentage energy savings yield the largest net savings at a 4% interest rate.

Upgrade Measures with the Highest Energy Savings

S(L)NW	to	T(A)W	81% Savings
S(L)NW	to	D(A)W	75% Savings

At higher interest rates, even these upgrades result in a loss over a twenty-year span. Thus, a homeowner with a 1920s window with 2 ACH could obtain a net saving of $113.70 dollars per window at a 4% interest. At an 8% interest, he/she would gain a meager profit of $.35 cents per window and barely break even on the initial investment. At a 10% interest, the upgrade would result in a loss of $-38.87 dollars per window. The least cost-effective measure is the upgrade from the Cambridge Code window to the low-e, weather-stripped window (D(A)NW to T(A)W). Although there is a 46% energy savings, the net loss is in the range of $-215.93 to $-245.36 dollars per window. It is necessary to obtain energy savings greater than 94% in order to have positive net savings at the three interest rates, 4%, 8%, 10%. This would correspond to a negligible energy loss due to infiltration and a window with an R-value greater than 5.5.

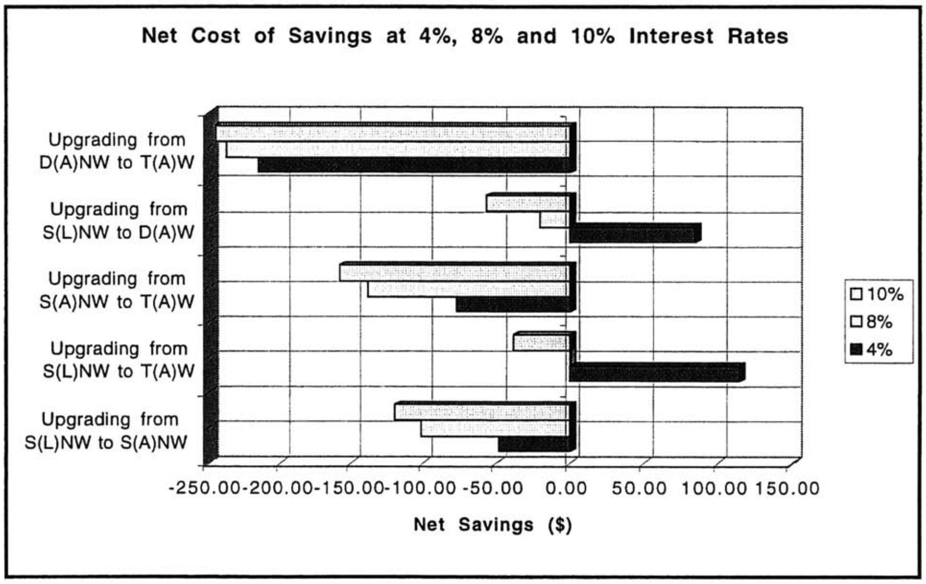


Figure 4.16

Window replacement is cost-effective with a reduction in the unit price or an increase in the cost of fuel. The following graph demonstrates the most economical upgrade measures when the capital cost is decreased by 50%.

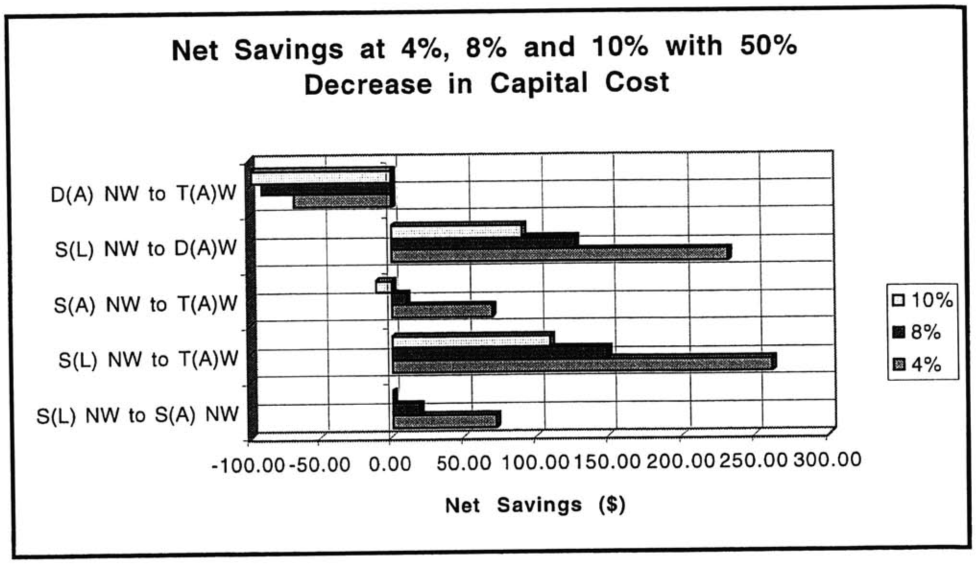


Figure 4.17

If the unit price is decreased by 50%, the owner will obtain a profit for most of the upgraded measures. For example, a bargain-hunting homeowner, interested in renovations, may find a contractor willing to reduce his/her price. In this case, the proprietor will obtain a profit at 4%, 8% and 10% interest rate, by upgrading his 1920s windows from a single glazed, non weather-stripped, loose fit window to a double glazed (low-e) or double-glazed, weather-stripped, average fit window. On the other hand, if he/she chooses to upgrade a Cambridge Code window to a double-glazed (low-e), average fit window, he/she will lose at all interest rates. Interestingly, at a reduced capital cost, a non weather-stripped, loose fit window yields a positive net saving at 4% and 8% interest rates when upgraded to a single glazed, non weather-stripped, average fit window.

Assuming that the unit price per window remains constant, one can determine the increase in the price of fuel ($/therm) necessary for capital to equal the net savings over twenty years. Thus, a homeowner, would break even on his/her investment. In the New England region, the price of gas is around $1.10/therm. At a 4% interest, the upgrade of a Cambridge Code window (D(A)NW) to a double-glazed (low-e), weather-stripped, average fit window would require 274% increase in the price of gas for the net present value of the savings to equal the cost. This percentage increase would correspond to a gas price of $4.11/Therm. On the other hand, a 1920s window with .8 ACH upgraded to a double glazed (low-e), average fit window with a low-e coating would require a 25% percent increase in the price of fuel ($1.50/therm). A 1920s window with 2ACH that is replaced by a low-e window would require a decrease in the price of fuel to from $1.10/therm to $.79/therm. Such an upgrade would indicate that the owner would achieve net savings at the present energy rates.

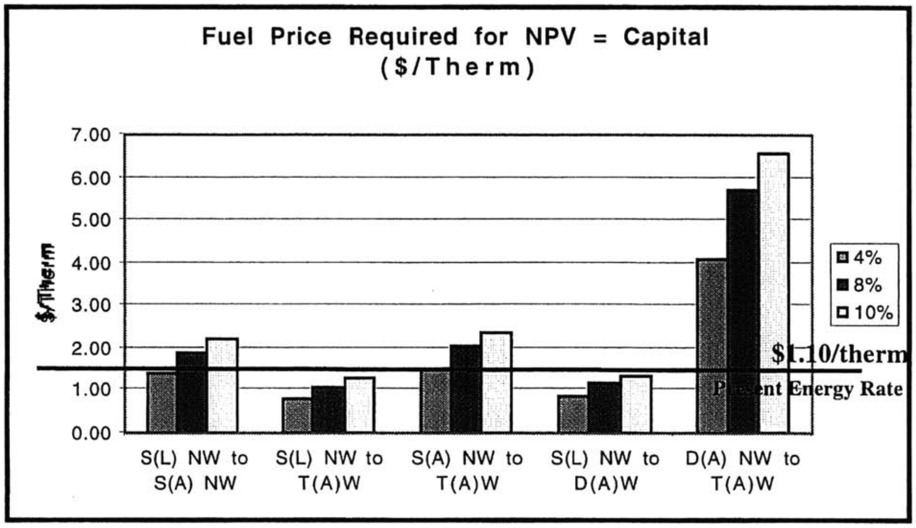


Figure 4.18

From the above graph, it is clear that the upgraded single glazed, non weather-stripped, loose fit windows (S(L)NW) are the most cost-effective at the present energy rates. At a 4% interest, a homeowner would achieve net savings by upgrading the S(L)NW to either a T(A)W or D(A)W. At 8% interest, he/she would obtain a net present value of savings equal to the capital cost. At a 10% interest, the upgrade from S(L)NW to T(A)W would require a 15% percent increase in the price of fuel, and the upgrade of S(L)NW to D(A)W would require a 24% percent increase in the price of fuel.

If the interest rate is set at 8% and there is a projected percentage increase on the price of gas, one can estimate the number of years required for the net present value of the savings to equal the capital cost.

Table 4.13: Increase in Gas Price over a # of Years

	1% Increase in Annual Gas Price # of years	5% Increase in Annual Gas Price #of years	10% Increase in Annual Gas Price # of years
S(L)NW to S(A)NW	74	15	7
S(L)NW to T(A)W	0	0	0
S(A)NW to T(A)W	88	18	9
S(L)NW to D(A)W	8	2	1
D(A)NW to T(A)W	417	83	42

If the energy prices increase at the same rate as inflation and the unit prices remains the same, a homeowner can obtain a net savings by performing most of the window upgrades.

However, he stands to lose by upgrading from double glass (D(A)NW) to low-E window (T(A)W).

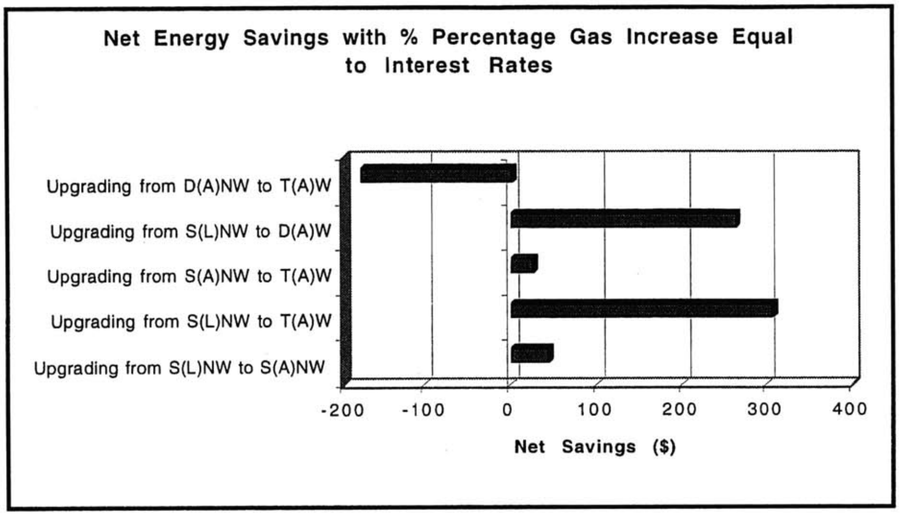


Figure 4.19

Caulking and Weather-stripping Windows

Weather-stripping or caulking a window is an alternative to window replacement. Energy loss due to infiltration can account for more the 70% of the total energy loss. According to the Means Residential Cost Data, the caulking of one window cost $10.91 dollars in the Boston area. Many times, homeowners weather-strip their own windows and do not hire professional labor. Therefore, the prevention of air leakage reduces energy consumption at a reduced capital cost. The graph (4.20) estimates the percentage energy savings of a weather-stripped window versus a non weather-stripped window.

The weather-stripping of a single glazed, non weather-stripped window yields the largest percentage energy savings, reducing energy loss by 45%. One can achieve the second highest energy saving by weather-stripping a double glazed (low-e), non weather-stripped, average fit window, reducing energy loss by 32%. The weather-stripping of a window can lead to an energy saving in the range of 17% to 45%. Whereas, window replacement has a higher range of 38% to 81%. Nonetheless, the huge reduction in capital cost of caulking or weather-stripping yields positive net savings and is therefore a very cost-effective measure of reducing energy consumption.

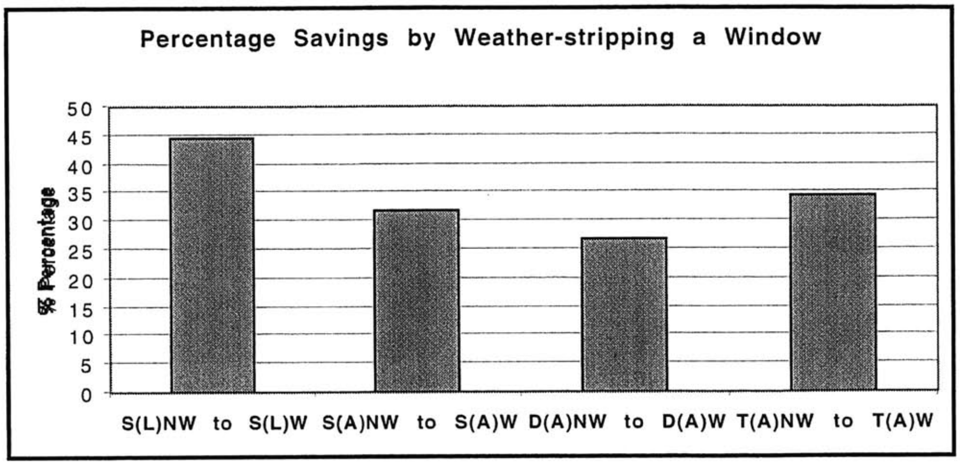


Figure 4.20

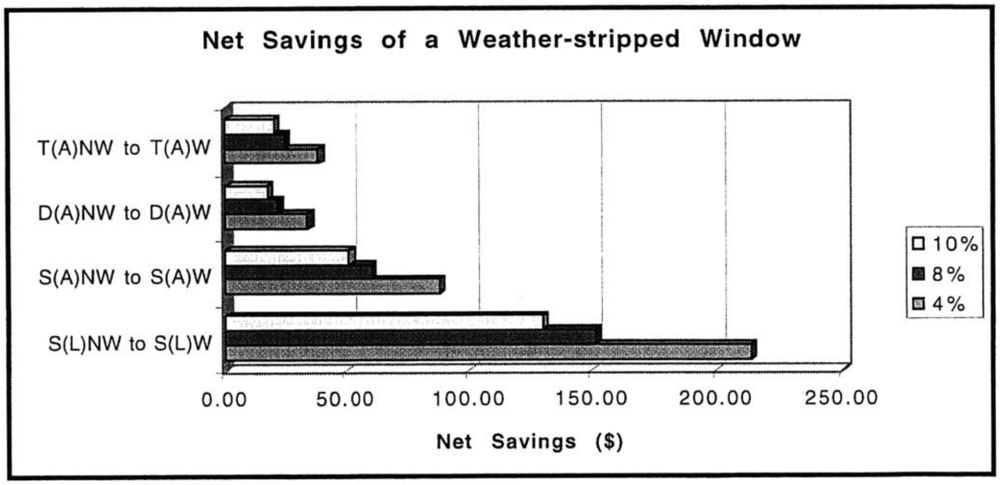


Figure 4.21

Window Replacement in New Construction

In new construction projects, the difference in cost between a single glazed, average fit, window is marginal when compared to a high performance window (double-glazed with low-e). However, the energy saving is substantial. A homeowner that installs double-glazed, low-e window (T(A)W) in place of a single glazed, average fit, weather-stripped window (S(A)W) can obtain a 70% saving. The net saving is in the range of $81 to $162 per window depending on the interest rate.

4.1.7 Conclusions for Building Envelope Upgrade

Cambridge Code

A homeowner interested in retrofitting a house built according to Cambridge code should first address the major areas of energy loss which include the following: windows/infiltration, frame walls, slab floors and doors. The below grade walls comprise a small percentage of the energy loss and can therefore be neglected. Depending on the varying interest rates, the proprietor can obtain the optimal net savings if the frame and masonry walls are upgraded from R-11 to either R-16 or R-20. Slab floors account for a very large percentage of the energy loss and should be insulated to a level of R-13. A homeowner should also insulate the doors in a range of R-9 to R-13 (3" to 4" of insulation).

Although windows and infiltration account for over half of the total energy bill, the replacement of a Cambridge Code window by one with a low-e coating can result in a very large financial loss over a span of twenty years. It is therefore more cost-effective to weather-strip a window built according to Cambridge Code. Such an upgrade can result in a net saving in the range of $17.00 to $33.00 per window and reduce energy loss by 27%.

In new construction projects, the installation of a double-glazed window with low-e (T(A)W) instead of a (S(A)NW) is a cost-effective measure.

1920s Home

A proprietor of a 1920s home should address the following major areas of energy loss: windows/infiltration, the vaulted ceiling, frame/masonry walls and below grade walls. At varying interest rates, a proprietor can obtain an optimal net saving if the vaulted ceiling has an insulation level in the range of R-20 to R-16, frame/masonry walls in the range of R-16 to R-20 and below grade walls in the range of R-11 to R-13.

Windows and infiltration account for a little less than half the energy bill. A single glazed, loose fit window with 2 ACH can yield a positive net saving at a 4% interest rate if upgraded to either double-glazed, or double-glazed (low-e), average fit window. At higher interest rates, the replacement of the loose fit window results in a loss. On other hand, the replacement of a single glazed, loose fit window with .8 ACH results in a loss at a 4%, 8% and 10% interest rate. Although not cost-effective, window replacement has qualitative benefits such as more comfort, less draft, and upgraded windows are , in general, more environmentally friendly..

If either of these two window types (2 ACH or .8ACH) is weather-stripped instead of replaced, a homeowner can achieve very large net savings over a span of twenty years. A weather-stripped loose fit window (2 ACH) uses 45% percent less energy than a non weather-stripped loose fit window. Older windows yield larger net energy savings.

4. 2 Renewable Energy Systems

A photovoltaic and a solar hot water heating system were installed in the Cambridge House for Sustainability. Solar renewable energy systems can reduce household energy consumption. However, their performance is based on unpredictable environmental factors such as the amount of solar radiation, the air temperature and number of clear sky and cloudy day in Boston. With average weather data for Boston, one can assess the likely output and potential energy savings of solar technology in the northern region.

Solar Angles

The efficiency of a solar system is dependent on the position of the sun and the amount of available direct beam radiation. The sun's position is calculated from the solar altitude, ϕ and azimuth ,β. The altitude is angular elevation above the horizon, and the azimuth is angle measured from the local north/south meridian.

$$\sin\beta = \cos l \cos\delta \cos H + \sin L \sin\delta$$

$$\cos\phi = (\sin\beta \sin l - \sin\delta) / (\cos\beta \cos l)$$

(Eq. 4.11)

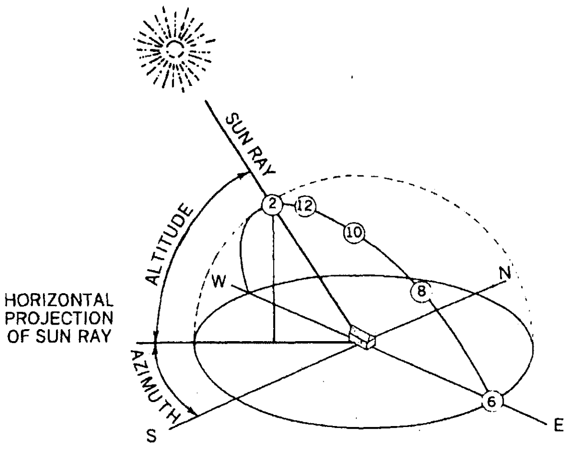


Figure 4.22

l=local latitude, 42°N for Boston
H = apparent solar time
δ = solar declination angle

The equations above allow one to calculate the azimuth and altitude angles based on the apparent solar time, H, and the sun's declination angle, δ. .The apparent solar time is equal to the local standard time plus the equation of time, which is a factor of the orbital velocity of the earth.

The sun's declination angle, δ, is the angular position of the sun at its highest point with respect to the plane of the equator.

Solar Radiation

Boston receives the most radiation during the month of June, and the least amount in December. Figure 4.23 shows the amount solar radiation hitting a surface at varying angles. On a horizontal surface, the daily total radiation is in the range of 433 to 1862 (Btus/ft^2/day)[1]. A horizontal surface receives the maximum amount of radiation during the summer months and the least amount during the winter months. A collector that is oriented at 53° would obtain most radiation in the winter. A south-facing vertical surface would receive the least amount for most of the entire year.

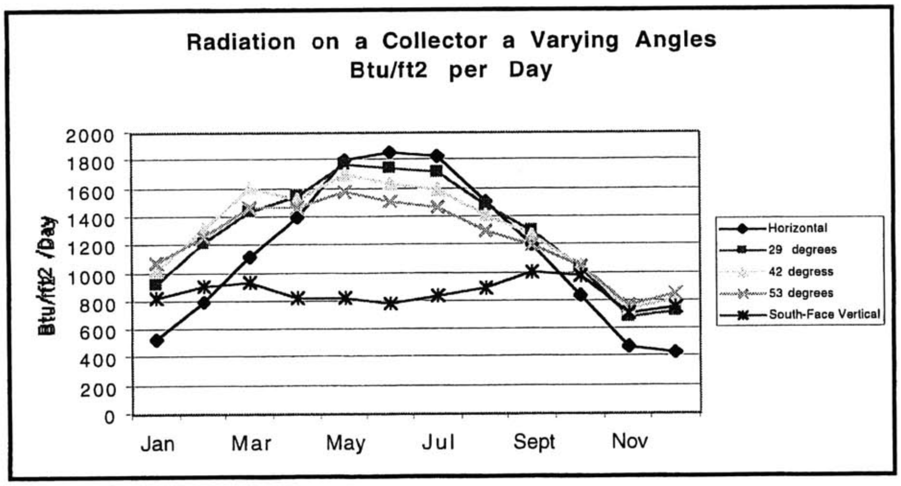


Figure 4.23
Source: NBS Building Science Series

Maximum and Minimum Temperatures in Boston

In Boston, the mean monthly maximum and minimum temperatures are in a range of 23°F to 81°F[2]. The maximum temperature is in July. The minimum temperature is in January.

During the summer, the peak temperatures rarely exceed 80°F. At nighttime and late evening, there is a decrease in temperature to around 60°F. Given that the temperature range is roughly within the comfort zone, there is not a great demand for cooling in the Boston area.

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[1] T.Kasuda, K, Ishii, NBS Science Series 96, Hourly Solar Radiation Data for Vertical and Horizontal Surfaces on Average Days in the United States and Canada, U.S Department of Commerce, April, 1977

[2] Editors, J. Ruffner, F. Bair, The Weather Almanac, Gale Research Company, 1987

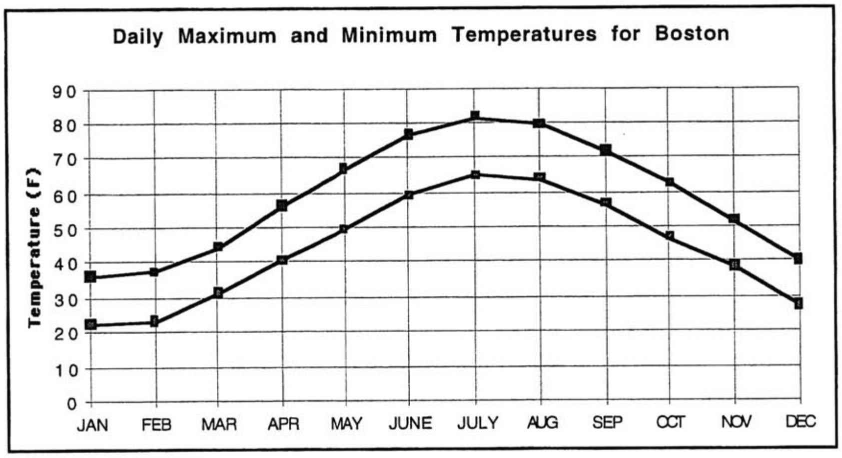


Figure 4.24
Source: The Weather Almanac

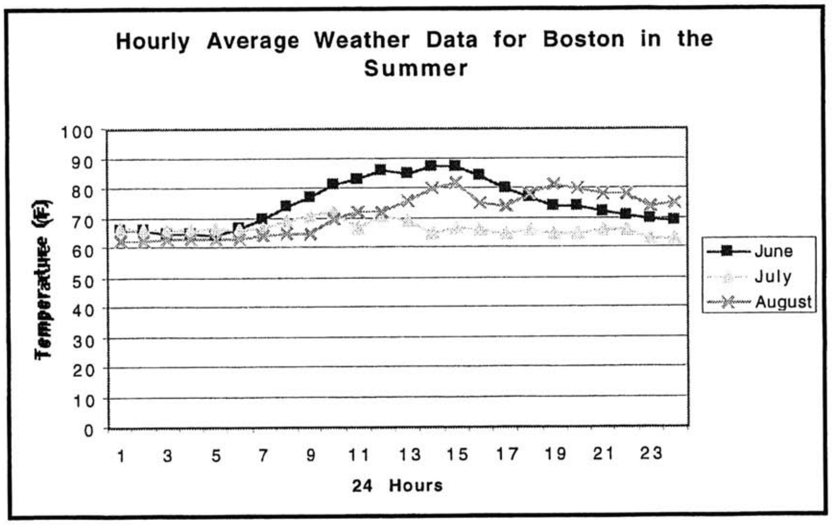


Figure 4.25
Source: Tm2 Data

Average Percentage of Daylight Hours and Sunshine in Boston

Boston receives has the largest percentage daylight hours during the month of May, June and July. Those three months also receive the largest average percentage of sunshine. The overall average annual percentage of sunshine for the city is 59%. This indicates that there is a 59% chance in Boston that the photovoltaic energy system will receive the necessary solar energy for performance.

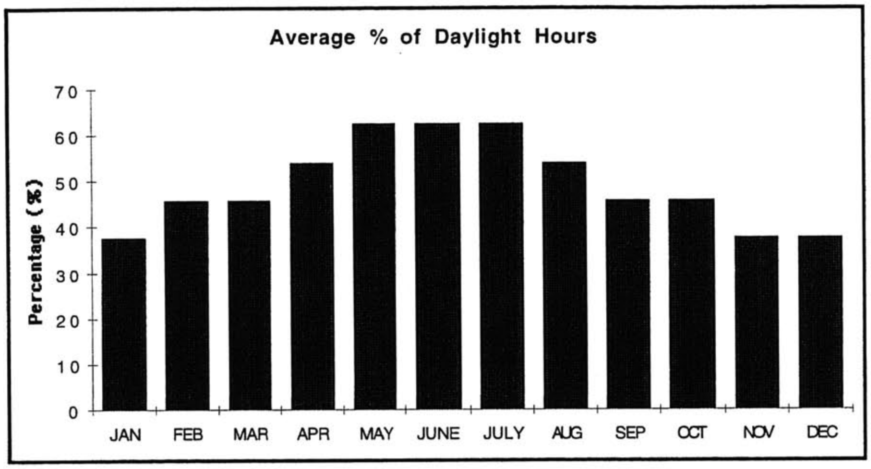


Figure 4.26
Source: Weather almanac

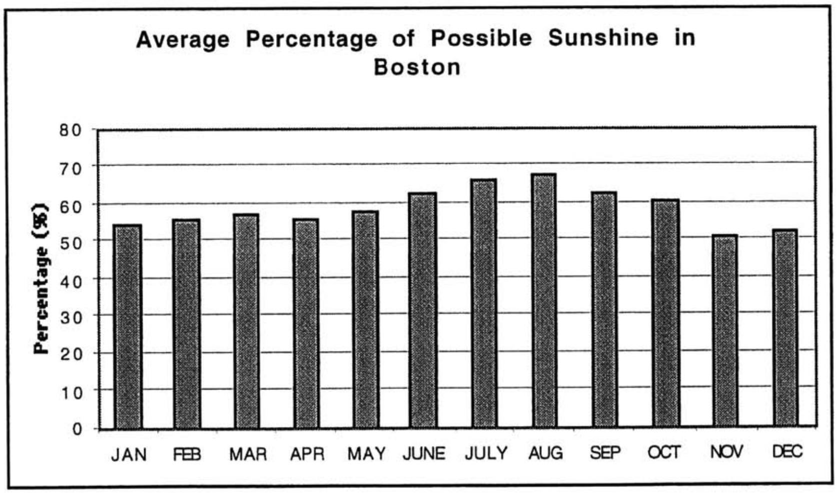


Figure 4.27
Source: Buresch
Photovoltaic energy systems

Ratio of the Solar Radiation on a South-Facing tilted surface to the Horizontal Surface

Based on the average monthly horizontal solar radiation data, one can estimate the likely performance of a solar renewable energy system in Boston. Using the following equations, one can determine the ratio between the average daily total radiation on a tilted south-facing surface and the solar radiation on a horizontal surface. In the Cambridge house, the photovoltaic panels face south and have a tilt angle of 29.74°. The ratio of the solar radiation on a tilted surface to a horizontal surface increases during the winter months and decreases in the summer when the solar altitude is at its highest point.

$$\delta = 23.45\sin\left(360\frac{284+n}{365}\right) \qquad \text{(Eq. 4.12.1)}$$

$$\omega_s' = \min\left[\begin{array}{c}\cos^{-1}(-\tan\phi\tan\delta) \\ \hline \cos^{-1}(-\tan(\phi-\beta)\tan\delta)\end{array}\right] \qquad \text{(Eq. 4.12.2)}$$

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \qquad \text{(Eq. 4.12.3)}$$

$$\frac{H_d}{H} = 1.390 - 4.027K_T + 5.531K_T^2 - 3.108K_T^3 \qquad \text{(Eq. 4.12.4)}$$

$$R_b = \frac{\cos(\phi-\beta)\cos\delta\sin\omega_s' + (\pi/180)\omega_s'\sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega_s + (\pi/180)\omega_s\sin\phi\sin\delta} \qquad \text{(Eq. 4.12.5)}$$

$$R = \left(1-\frac{H_d}{H}\right)R_b + \frac{H_d}{H}\left(\frac{1+\cos\beta}{2}\right) + \rho\left(\frac{1-\cos\beta}{2}\right) \qquad \text{(Eq.4.12.6)}$$

Eqs. 4.12

δ = the sun's declination angle (-23.45° to +23.45°)
n= day of the year (1 to 365)
ω_s=sunset hour angle on a horizontal surface
ω_s'=sunset hour angle on a tilted surface
ϕ = the site's latitude angle (0° to 90°) in the Northern Hemisphere
β= tilt or slope of a south-facing surface (0° to 180°; $\beta > 90°$ indicates that the surface is facing downward)
R_b=the ratio of monthly average daily direct-beam radiation on a tilted south-facing surface to that on a horizontal surface
H = monthly average daily total radiation on a horizontal surface
H_d= monthly average daily diffuse radiation on a horizontal surface
K_T = clarity coefficient; the ratio of insolation on the earth to the insolation directly outside the earth's atmosphere
R = ratio of monthly average daily total radiation on a tilted south-facing surface to that on a horizontal surface
ρ = the reflection coefficient: the fraction of light reflected by a surface (0 to 1)

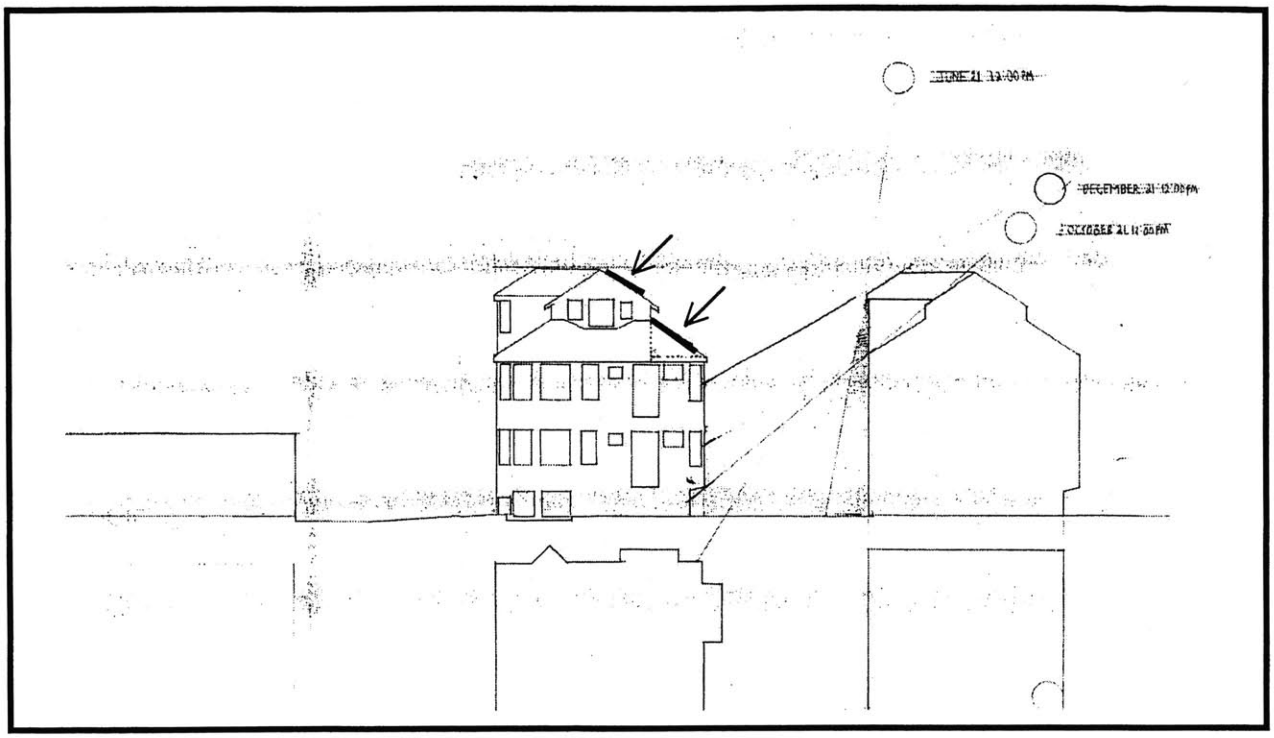


Figure 4.28

West Elevation of the Cambridge House for Sustainability
Solar Angles on October 21, December 21, June 21 12:00pm

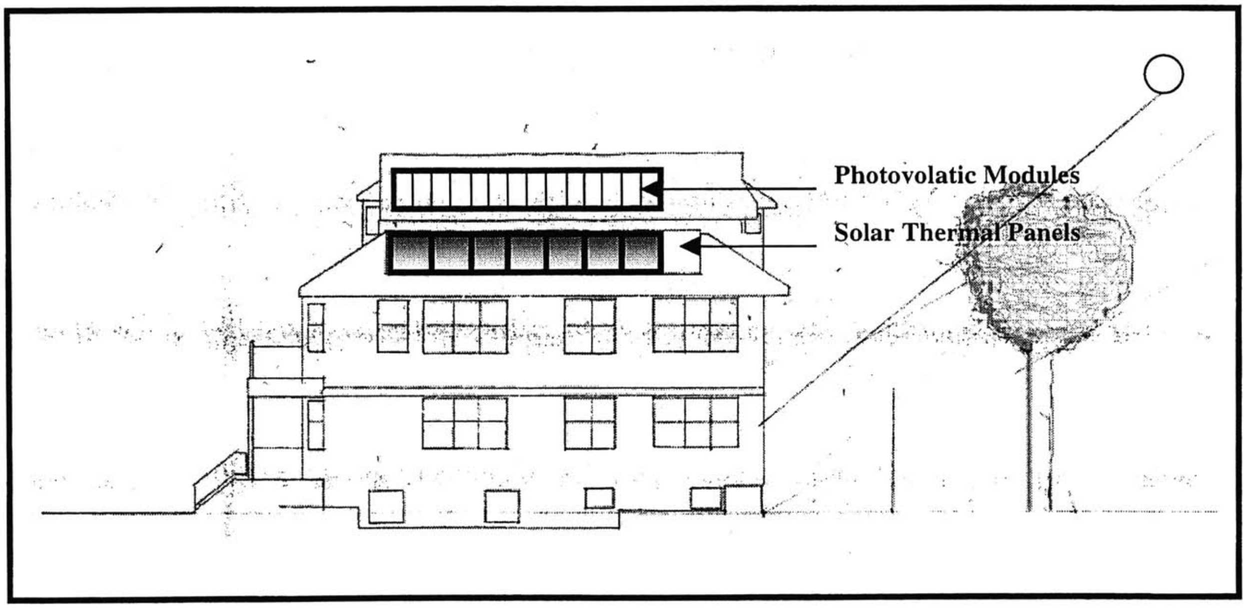
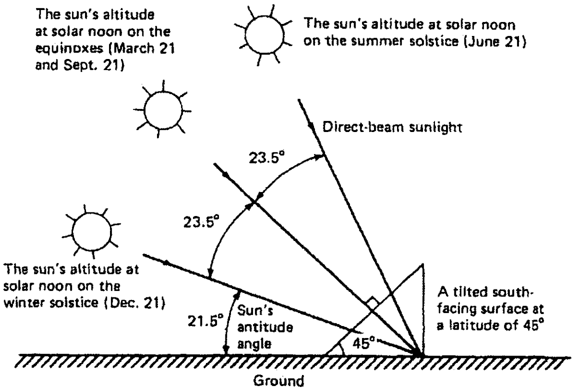


Figure 4.29
South Facade

Optimal Tilt Angles

The optimal tilt-angle for a south-facing panel throughout the entire year is equal to the latitude of the site. At the optimum angle, a panel receives the greatest direct-beam radiation. Therefore, in Boston, the optimal angle is to 42°. However, if a designer of a solar renewable energy system intends to maximize the direct beam solar radiation during the winter, the surface tilt should equal the latitude plus 11°. The optimal orientation in the summer is equal to the latitude minus 11°. The tilt angle for the Cambridge House for Sustainability is 29° indicating that its orientation optimizes the performance in the summer. A tilt angle of 53° optimizes the performance of the winter solar radiation.



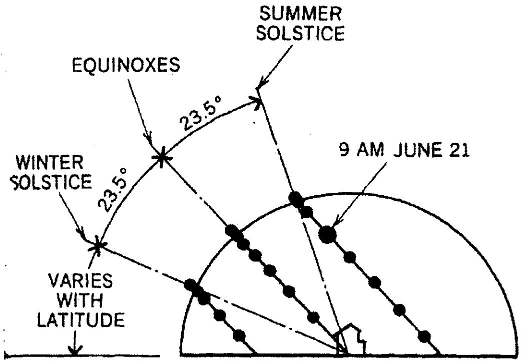


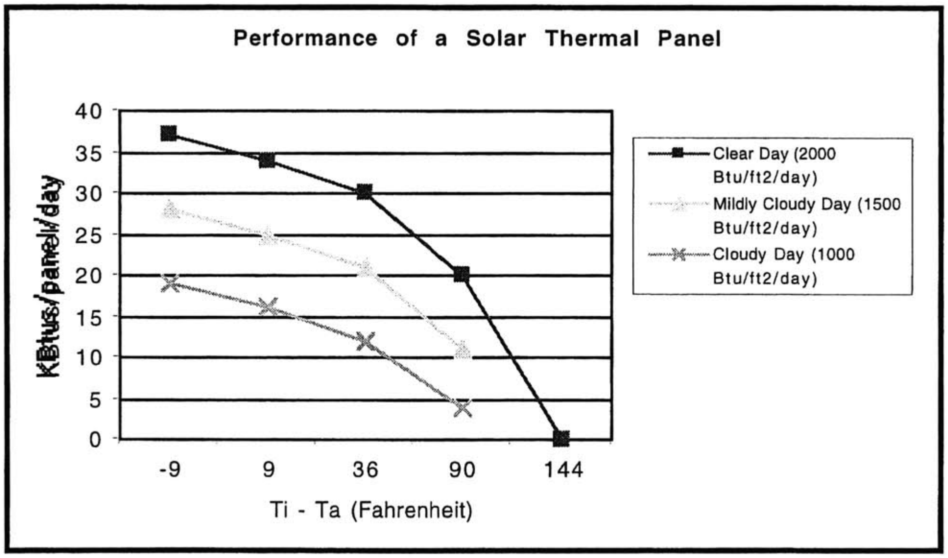
Figure 4.30
Optimal tilt Angles

Figure 4.31

4.3 Solar Thermal Panels

Solar thermal systems are typically used to reduce hot water energy consumption; however, they can also provide additional space heating. Hot water and space heating systems have two basic components: a collector and a storage medium. The function of the collector is to absorb the maximum amount of solar radiation and transfer the majority of that radiation to the fluid. Therefore, materials with a high absorptance at shorter wavelengths and low emittance at longer wavelengths are ideal. Many collectors consist of a composite material with a glass cover plate, black chrome (a high absorber), nickel (a low emitter) and a steel plate to add structural support and prevent deterioration from moisture.

The Cambridge House for Sustainability has seven south-facing solar thermal panels from the American Energy Technologies Inc. Each panel is 32ft^2 with a fluid capacity of 1.3 gallons. According to the specifications of the AET catalog, the maximum output of a 32ft^2 panel is 47,000 Btu/ per panel per day, given a temperature difference (T_i- T_a) of –9°F and a daily total solar radiation of 2000 Btu/ft^2/day. The following graph shows the thermal performance of a collector for various temperature differences between T_i and T_a and weather conditions. The graph categorizes three weather conditions (clear day, mildly cloudy day, cloudy day) and the available solar radiation. The Solar Rating and Certification Corporation (SRCC) determined the ratings.



Data obtained from the AET Solar Thermal Catalog, January 1993.

Figure 4.32

The most optimal storage medium allows the most stratification with the cooler temperatures at the bottom. In most system designs, the temperature from the bottom of the tank functions as the inlet temperature (T_i) to the collector. As the T_i approaches T_a (ambient temperature), the efficiency of they system increases. When T_i is less than T_a, convection and radiation have a positive contribution to the energy gain of the panel and the energy output is increased.

In hot water space heating system, the storage systems have two cycles: the "charge" cycle and the "discharge cycle". The "charge cycle" will begin around 8am in the morning when most of the stored heat has been used during the nighttime. Fluid is recycled from the tank to the collector. The energy is collected and stored at higher temperatures in the middle afternoon and lower temperatures in the early morning and late afternoon. In the discharge cycle, heat is discharged from the tank in the reverse cycle direction and supplied to the space. The energy stored in the late afternoon is used first. Afterwards, the energy from the peak period of the mid-afternoon is used to accommodate the nighttime peak temperatures. Energy from the early morning is used during the period after peak hours.

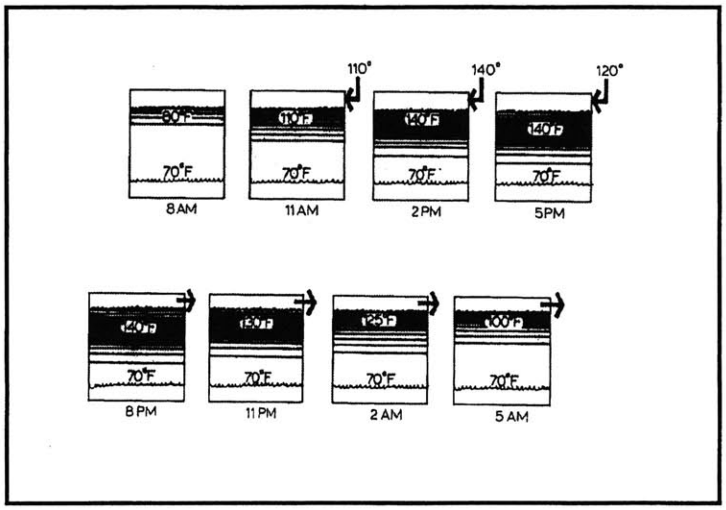


Figure shows the stratification in the tank temperature during the day
Figure 4.33

In domestic hot water systems, the temperature of the storage medium is in a range of 95°F to 212°F in order to meet hot water energy requirements. When the difference between T_i and T_a is less than –9°F, the ambient temperature ,T_a, is at a level greater than or equal to 104°F. Temperatures greater than 100°F are more likely to occur in the southern region of the United States during the summer months. However, they rarely occur in the northern region.

4.3.1 Efficiency of Collector

The efficiency of a collector is based on the inlet temperature of the fluid, T_i, the outside ambient temperature, T_a , and the amount of available solar radiation (Q_{solar}). As the difference between T_i and T_a decreases, the collector efficiency increases. This is due to the decrease in convective and radiative thermal losses. The following equation gives the amount of energy collected per length of the collector surface (Btu/hr ft) during steady state conditions.

$$Q / L = \dot{m} cp \frac{dT}{dx} = \tau \alpha q_{solar} - \bar{u} p(T - Ta) - \varepsilon \sigma p(T^4 - Ta^4) \qquad \text{(Eq. 4.13)}$$

Q/L_p = *the amount of energy collected per foot of panel per hour*
m = *mass flow rate of water*
cp = *specific heat of water*
τ = *cover transmittance*
$\propto$ = *plate absorptance*
ε = *emissivity*
σ = *Stefan-Boltzmann constant*
u = *effective heat transfer coefficient including cover plate*
q_{solar} = *average horizontal radiation per foot*
p = *width of plate*

Based on the energy equation, one can obtain an estimate on the performance of the solar panels in Boston. The following information was used to obtain the energy collected per unit length of panel.

τ = .91	%transmittance of glass plate
$\propto$= .92	%absorptivity of absorber coating
ε = .28	%emissivity of plate
u= .1937(Btus/h ft^2°F)	% heat transfer coefficient for radiation and natural convection
p= 3.93(ft)	%Width of solar panel
L =7.884 (ft)	% Length of panel
m = 648.12 (lbm/h)	% mass flow rate through panel
cp= .998 (Btus/lbm°F)	%specific heat
σ =.1714e-8(Btus/hft^2R^4)	%Stefan-Boltzmann Constant
T = T_I@x=0	%Inlet temperature of collector

The ordinary differential equation solver in Matlab calculates the rise of temperature across the length of panel with input values for the hourly monthly solar radiation, the monthly maximum ambient temperatures and a given inlet temperature. At x = L (the length of the panel) the temperature of the bulk fluid reaches its maximum value at the outlet temperature. The calculations assume that there is enough stratification in the solar tank such that the inlet temperature remains constant during the hours of operation. In addition, the panel only operates when there is enough solar energy to heat the fluid. Calculations also assume that the volumetric flow rate of 1.3 gallons per minute. The following equation determines the amount of energy collected in Btu/hr.

$$Q = \dot{m}cp\Delta T \qquad \text{(Eq. 4.14)}$$

The difference between the inlet temperature ,T_i, and the outlet temperature, T_o, is equal to ΔT. The efficiency of the panel is determined by the following equation:

$$eff\% = Q \,/\, q_{solar} \qquad \text{(Eq. 4.15)}$$

The graphs show the upper and lower limits of performance for a 32 ft^2 panel in Boston. The computer simulations are based on three conditions when the inlet temperature of the collector is at a minimum temperature of 70°F, a medium temperature of 95°F and a maximum temperature of 122°F. For all three conditions, the monthly mean outdoor temperature, T_a, remains constant, and the energy output of the panel varies according to the average monthly and hourly solar radiation on a horizontal surface. When T_i is at its minimum value, the energy collected (*Q*) is an upper limit value on the amount of energy collected. When T_i is at its maximum value, *Q*, is at a lower limit on the panel performance. Most hot water tank have temperature ranges from 70°F to 120°F or greater.

During the month of July, a solar panel in Boston can collect anywhere from 41KBtu to 54 KBtu per panel per day depending on the temperature of the tank. The efficiency of the solar system is dependent on the tank temperature and the amount of solar radiation. During the winter months, there is less average solar radiation and the differences between inlet and ambient temperature are greater than in the summer months. Therefore, the efficiency of the system decreases. In December, a panel can collect solar energy in the range of 12 to 16 KBtu per day.

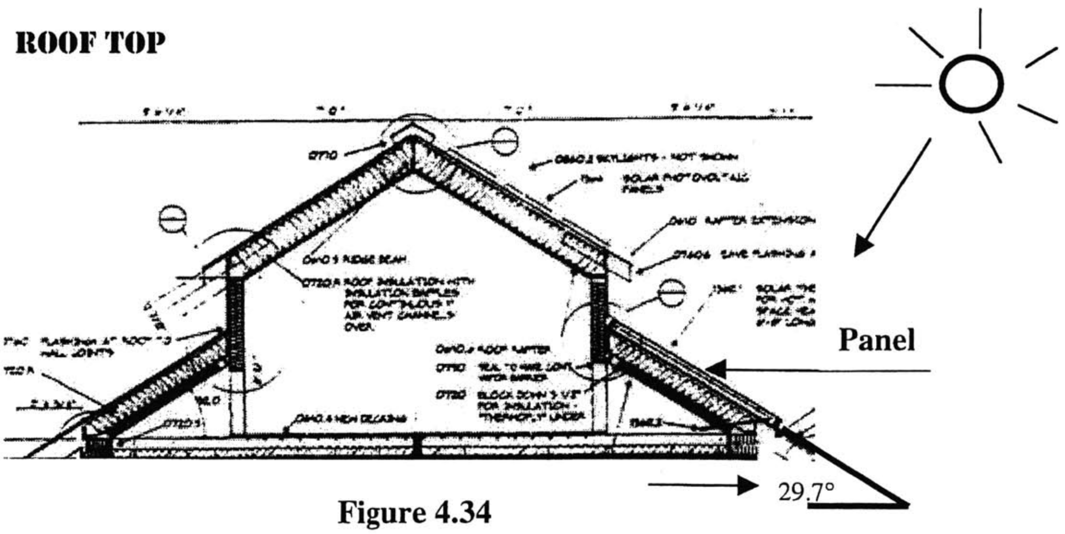


Figure 4.34

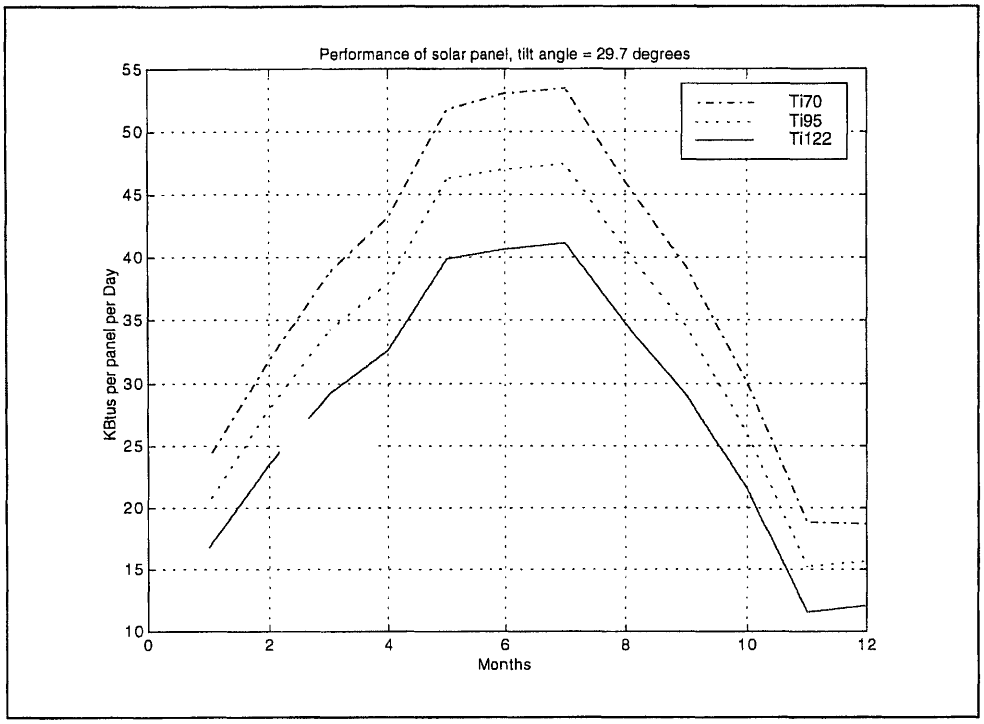


Figure 4.35

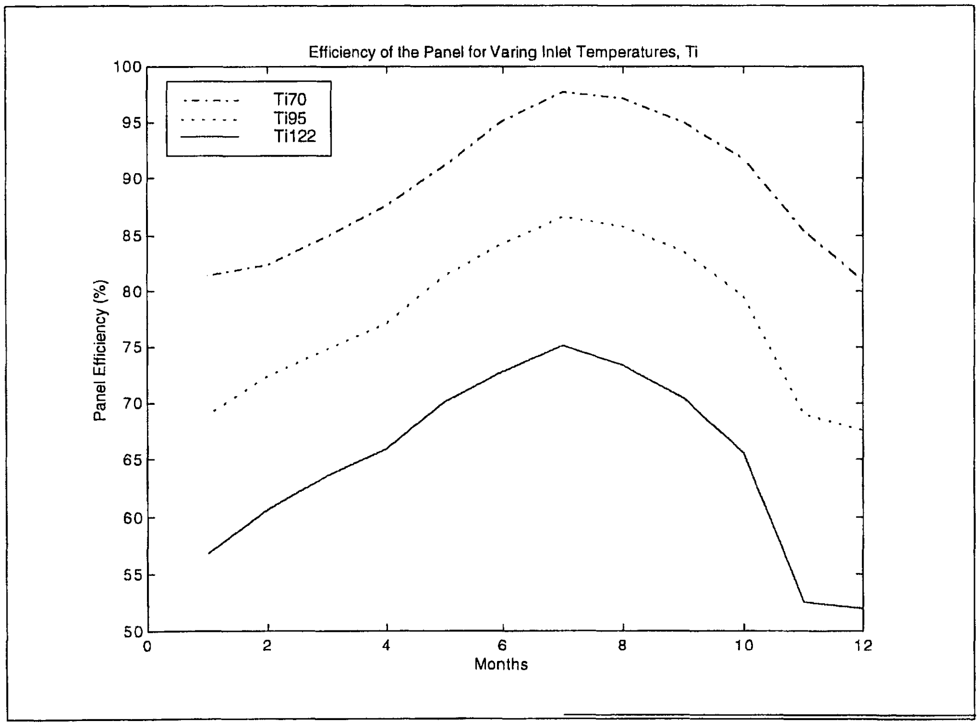


Figure 4.36

Table 4.14: Performances of the panel for varying inlet Temperatures.

Limits	Inlet Temperatures (°F)	Performance of one 32ft^2 panel MMbtu/yr	Energy savings ($)/yr per panel*
Upper	**70**	**13.69**	**150.56**
Medium	**95**	**11.99**	**131.85**
Lower	**122**	**10.13**	**111.45**

*Energy Savings if all the solar energy collected is used for either space heating or domestic hot water

4.3.2 Hot Water Consumption

Estimates on hot water usage for a multi-family dwelling are based on the solar thermal catalog from American energy technologies. Eight occupants use approximately 110 gallons of hot water per day, which is 40,150 gallons of water per year. Assuming that water is heated from 10°C to 80°C, the estimated yearly consumption of energy is 41 MMBtu. The cost is approximately 455 dollars per year. Given that there are seven panels in the Cambridge house, and each one produces energy in the range of 10.13 to 13.69 MMBtu per panel per day, the total annual contribution of solar energy is in the range of 70.92 to 95.8 MMBtu. Clearly, this amount exceeds the consumption requirement, indicating that some additional energy can be used to fulfill space heating requirements.

If a homeowner purchases the solar system to meet the hot water energy demands, the tank temperatures would have to remain within a range of 95°F to 122°F (medium to lower limits of performance). The following charts and graphs compare the monthly domestic hot water loads (DHW), and heating loads (HTG) to the energy contributions of the system (consisting of seven panels). The difference (Diff) between both the domestic hot water load and space heating load and the solar contribution indicates the amount of supplemental energy needed for the house. A negative difference shows that there is an excess amount of solar energy from the panels.

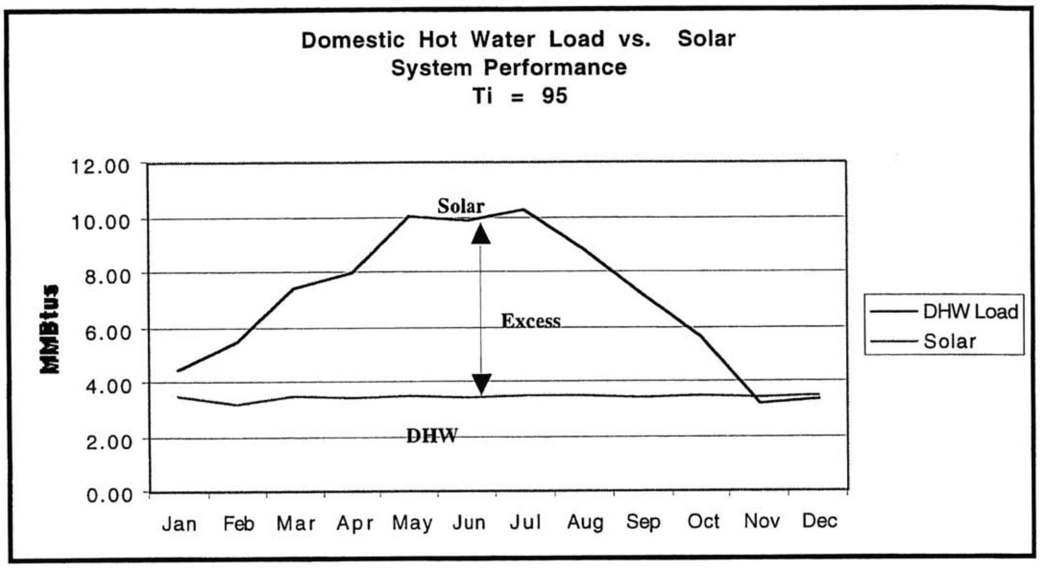


Figure 4.37

Table 4.15: Performance of System when Ti = 95°F

	Solar (MMBtu)	DHW loads(MMBtu)	HTG loads	Diff (MMBtu)
January	4.44	3.54	14.93	14.03
February	5.50	3.20	13.30	11.00
March	7.44	3.54	11.77	7.86
April	7.99	3.43	4.77	.21
May	**10.04**	**3.54**	**1.10**	**-5.39**
June	**9.88**	**3.43**	**0.00**	**-6.45**
July	**10.31**	**3.54**	**0.00**	**-6.77**
August	**8.83**	**3.54**	**0.00**	**-5.29**
September	**7.25**	**3.43**	**0.82**	**-3.01**
October	5.64	3.54	5.33	3.22
November	3.19	3.43	9.12	9.36
December	3.40	3.54	13.49	13.63

When the inlet temperature, T_{i} , is equal to 95°F, the solar energy contribution from the panels exceeds the domestic hot water energy requirements during the months of January through October. In December and November, the solar energy contribution falls slightly below the domestic hot water demand. In May and September, the system appears to satisfy both the domestic hot water and heating loads with an excess amount of energy of 5.39 and 3.01 MMBtu respectively.

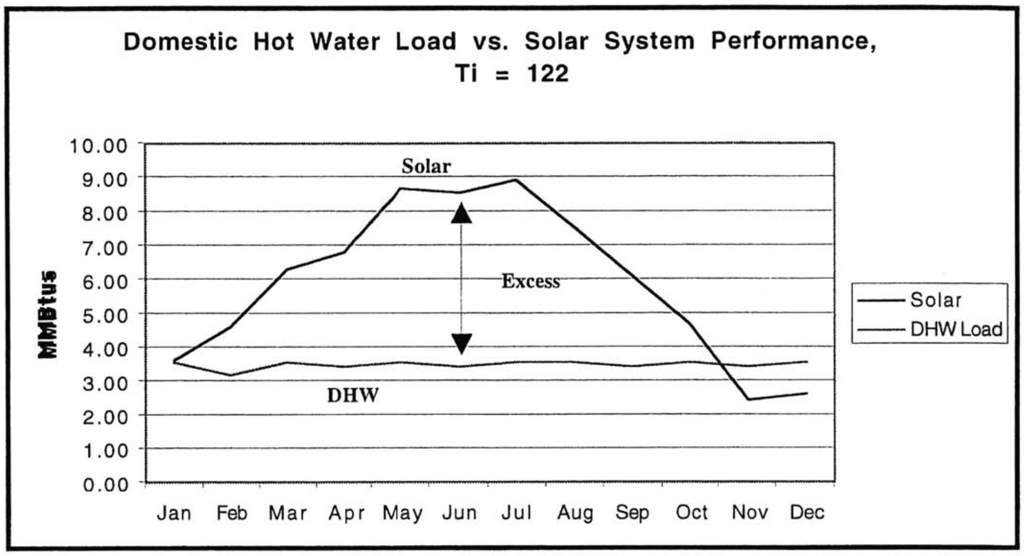


Figure 4.38

Table 4.16: Performance of System with Ti = 122°F

	Solar (MMBtu)	DHW load(MMBtu)	HTG loads	Diff (MMBtu)
January	3.65	3.54	14.93	14.82
February	4.61	3.20	13.30	11.89
March	6.33	3.54	11.77	8.97
April	6.84	3.43	4.77	1.35
May	**8.66**	**3.54**	**1.10**	**-4.01**
June	**8.54**	**3.43**	**0.00**	**-5.11**
July	**8.93**	**3.54**	**0.00**	**-5.38**
August	**7.56**	**3.54**	**0.00**	**-4.02**
September	**6.11**	**3.43**	**0.82**	**-1.86**
October	4.66	3.54	5.33	4.21
November	2.43	3.43	9.12	10.12
December	2.61	3.54	13.49	14.42

At higher inlet temperatures, T_i equal to 122°F, the system still performs quite well and can meet the domestic hot energy loads from January through October. In November and December, a supplemental back-up system is required. The total energy required for backup during those months is 1.93 MMBtu which is about $67 worth of water heating.

4.3.3 Solar Excess and Auxiliary Loads

The solar excess is any additional energy that is not used for domestic hot water that can be used towards space heating. When the inlet temperature is equal to 95°F, the solar excess can reduce the space heating load by 21%. When the inlet temperature is equal to 122°F, the solar excess reduces the space heating load by 11%. Thus, the temperature of the tank significantly affects the performance of the solar system and percentage of energy savings. A change in the tank temperature from 95°F to 122°F reduced the space energy saving by one half.

During the summer months, the house will have a cooling load; therefore, the heating load is equivalent to zero. In June, July and August, the solar excess contribution greatly exceeds the energy demands. Therefore, the energy is wasted. The auxiliary load graphs show the cost for heating the house with a solar thermal system that provide both domestic hot water heating and space heating. When the auxiliary is less than zero, the solar energy supplied exceeds the hot energy demand.

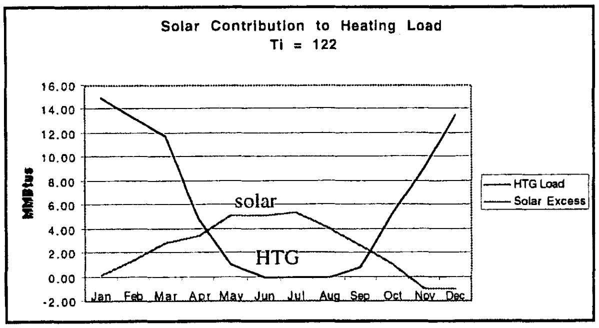


Figure 4.39

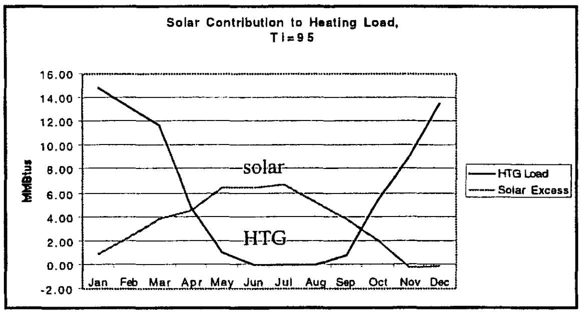


Figure 4.40

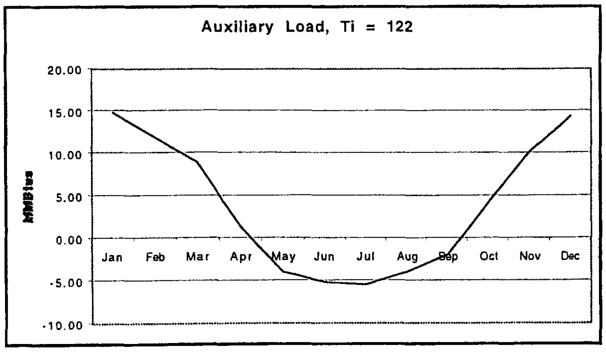


Figure 4.41

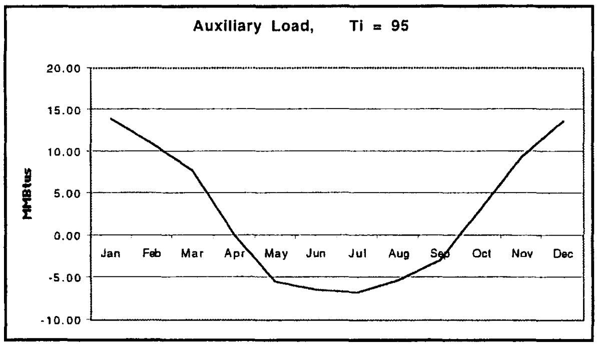


Figure 4.42

Solar hot water systems can be used exclusively for space heating, the temperature of the tank can fall below the constraints of 95°F and 122°F. If the tank is maintained at 70°F, the system collects as much as 95.8 MMBtu/yr. If none of the total energy collected is used for domestic hot water, then the solar thermal system can significantly reduce the space heating energy bill. A certain amount the excess energy collected may not serve any use during the summer months.

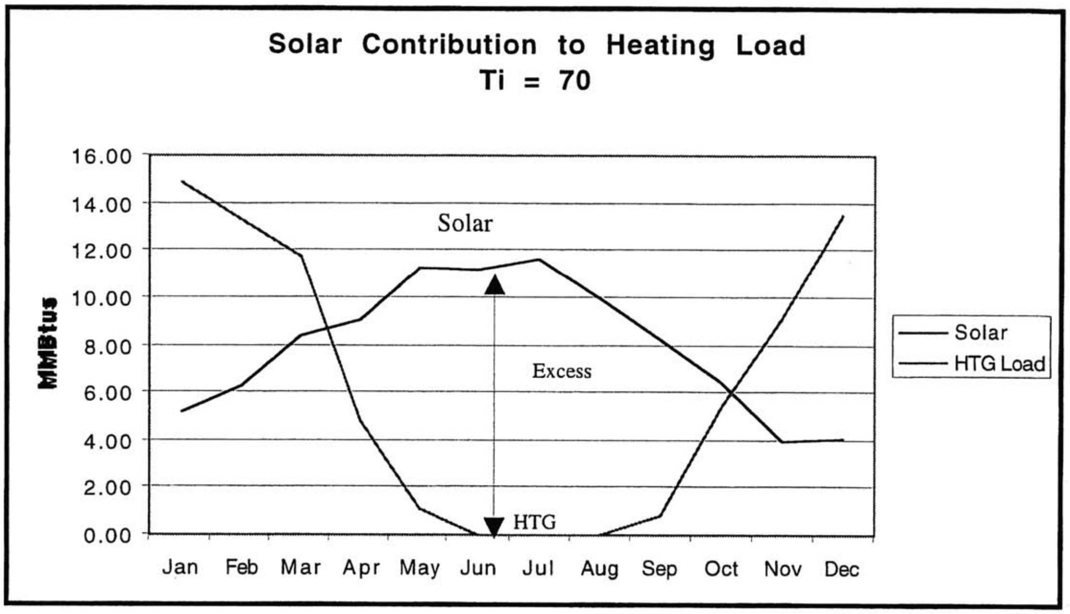


Figure 4.43

Table 4.17: Performance of Solar System with Ti = 70°F

	Solar (MMBtu)	DHW load(MMBtu)	HTG loads	Diff (MMBtu)
January	5.22	3.54	14.93	13.25
February	6.26	3.20	13.30	10.24
March	8.45	3.54	11.77	6.86
April	**9.09**	**3.43**	**4.77**	**-.89**
May	**11.25**	**3.54**	**1.10**	**-6.61**
June	**11.16**	**3.43**	**0.00**	**-7.73**
July	**11.62**	**3.54**	**0.00**	**-8.07**
August	**10.00**	**3.54**	**0.00**	**-6.46**
September	**8.24**	**3.43**	**0.82**	**-3.99**
October	6.52	3.54	5.33	2.35
November	3.95	3.43	9.12	8.60
December	4.07	3.54	13.49	12.97

4.3.4 Economic Analysis of Solar Thermal Systems

If ***all of the solar energy collected*** is used either for space heating, domestic hot water heating or both, an analysis of the net savings over a twenty year span appears very impressive and promising. The initial investment of an entire system with seven panels is approximately $6,000. Each panel is $500 plus the cost of labor. The total is $857 per panel. The following graph shows the net savings over a twenty year span at a 4%, 8% and 10% interest rates.

The lower limit estimate suggests net savings in the range of $657.46 to $91.63 per panel depending on the interest rates. The upper limit estimate suggests a net saving in the range of $1188.99 to $424.59 per panel. At a 4% interest rate, the solar system will pay for itself in seven years.

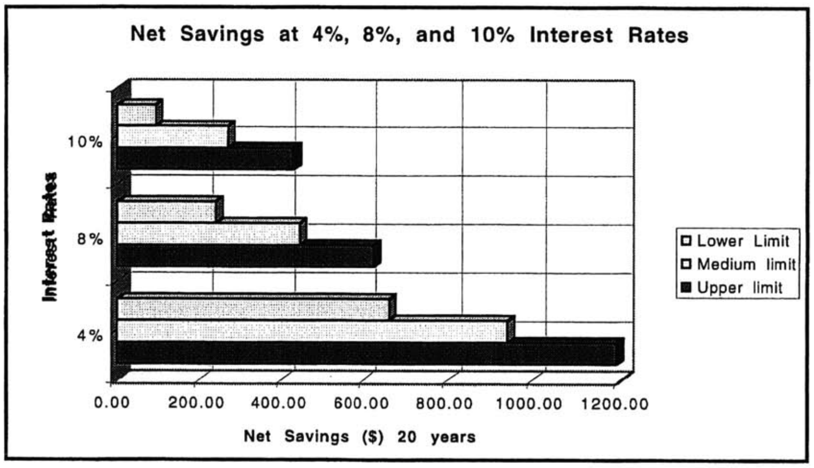


Figure 4.44

On the other hand, if the solar thermal system is used exclusively for all of the domestic hot water heating, then a large percentage of the energy collected is wasted particularly during the summer months. Consequently, the net savings over a twenty-year span will result in a financial loss at higher interest rates. The payback is better for a smaller system that meets part of the domestic hot water needs all year round.

Solar Thermal Panel used <u>only</u> for Domestic Hot Water

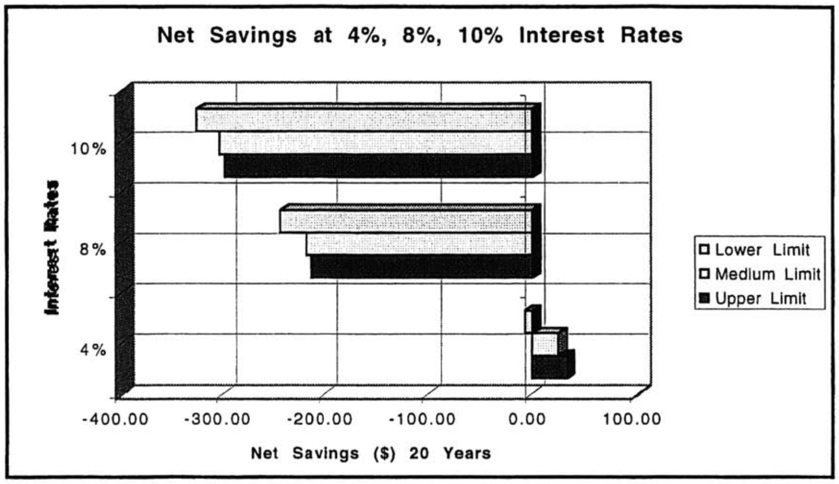


Figure 4.45

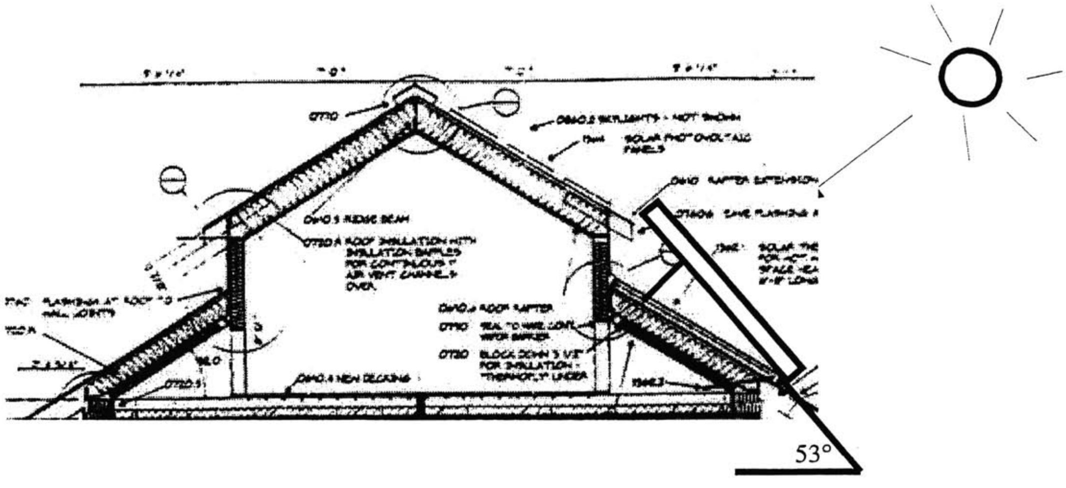
At a 4% interest rate, there is a net savings in the range of $-7.98 to $33.15 dollars per panel. At an 8% and 10% interest rate, the result is a large negative net saving.

Optimizing Winter Solar Radiation

Given that the majority of the energy collected is wasted during the summer, it might make more sense for a designer to tilt the panel such that it maximizes winter solar radiation. The optimal angle for winter solar radiation is equal to the latitude plus 11°. In Boston, it is equal to 53°.

ROOF TOP

Figure 4.46



Performance of Solar Panel at Varying Tilt Angles

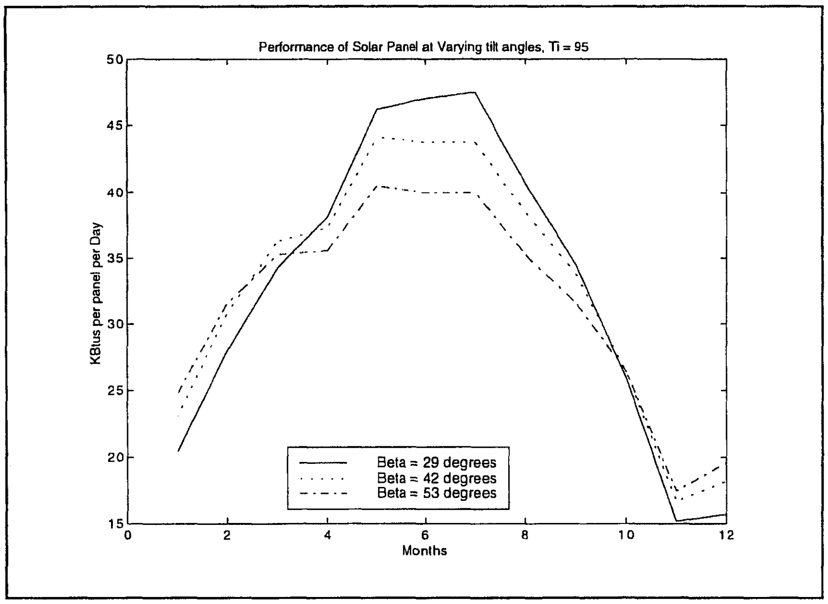


Figure 4.47

Because altitude of the sun is at lower angle in the winter than in the summer, the tilt angle of 53° is closer the perpendicular rays of the sun. From the graph, it has the maximum performance during the winter months and the minimum performance during the summer months.

If the solar thermal system was used exclusively for domestic hot water heating, it would fair slightly better than at a lower tilt angle. At a 4% interest rate, the panel has positive net savings in the range of $20.37 to $33.15 per panel. There is still a loss at an 8% and 10% interest rate.

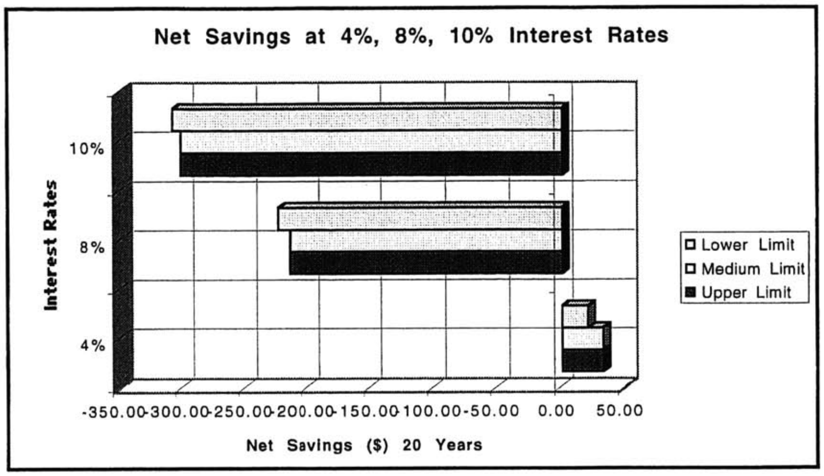


Figure 4.48

4.3.5 Conclusions: Solar Thermal Systems

Based on the average solar radiation data in Boston, it appears the solar thermal systems can potentially meet all of the domestic hot water loads. Even at a high tank temperature of 122°F, the system performs well except in the months of November and December when electric back-up is needed. There is even an excess amount of energy available for space heating. If the tank temperature is maintained in a range of 95°F to 122°F, the solar excess may reduce space heating in a range of 11% to 21%.

If all of the solar energy collected is used, then solar thermal system are cost-effective with a payback of 7 years. However, if the system is used for only domestic hot water, the majority of the energy is wasted. The net present value analysis indicates that there is a net loss at 8% and 10% interest rates. There are some minimal net savings at a 4% when the tank temperature is 70°F or 95°F. (Fig 4.45).

When the panels are tilted at an optimal angle of 53°, it can minimize the solar gain during summer and maximize the gain during the winter. The tilting of the collectors at optimal angles can make the solar thermal systems more cost-effective. According to figure 4.48, both the medium and upper limits (95°F, 122°F) have net gains at a 4% interest rate.

Given that this analysis is based on average solar data, it may over estimate the system performance. Most likely, solar thermal collectors will require some electric backup during extremely cold outside temperatures and cloudy days.

4.4 Photovoltaic Modules

Photovoltaic modules reduce energy consumption by converting solar radiation directly in electricity. These systems usually have efficiencies in the range of 3% to 15%.
The Cambridge House for Sustainability has fourteen architectural standing seam panels from the Uni-Solar Inc. The solar modules are integrated into the roof following the specifications of conventional architectural standing seam panels. According to the specifications and performance of the catalog, each panel has a rated power of 64 watts with a solar input of 1000 W/m^2, and a solar cell temperature of 25°C. The panels are 12ft^2 each, and supply 20 – 30 Wh/ft^2 per day under the specified design conditions.

The output of the panel is directly proportional to the light intensity. Therefore, on sunny days, the panels perform optimally. Cloudy and overcast days can reduce the panel output by as much as 50%. During peak hours of insolation, there is an increase in the temperature of the solar cells of each module. Increases in the temperature of the cell are inversely proportional to the output of the panel[1]. The Uni-Solar panels have solar cells made from an amorphous thin film structure with a high emissivity. Therefore, they can emit heat that is produced when the solar energy is converted into electrical energy. The decrease in temperature improves the performance of the solar cell. In cold climates, the amorphous thin film panels have an efficiency of 7%.

System Performance

From the monthly average daily total radiation on a horizontal surface, the average ratio of tilted radiation to horizontal radiation, and the efficiency of the each panel, one can estimate the likely performance of the photovoltaic system in Boston. The total output for a system with fourteen south-facing panels, 12 ft^2, is 1639 kWh per year which corresponds to a savings of \$196.68 or \$1.17/ft$^{2.}$

Month	Output (kWh)	Savings($)
January	98.2	11.86
February	117.06	14.05
March	154.23	18.51
April	159.91	19.19
May	191.40	22.98
June	182.01	21.84
July	183.06	21.97
August	159.45	19.13
September	133.78	16.05
October	110.06	13.21
November	71.32	8.56
December	77.86	9.34
Total	**1639.04**	**196.68**

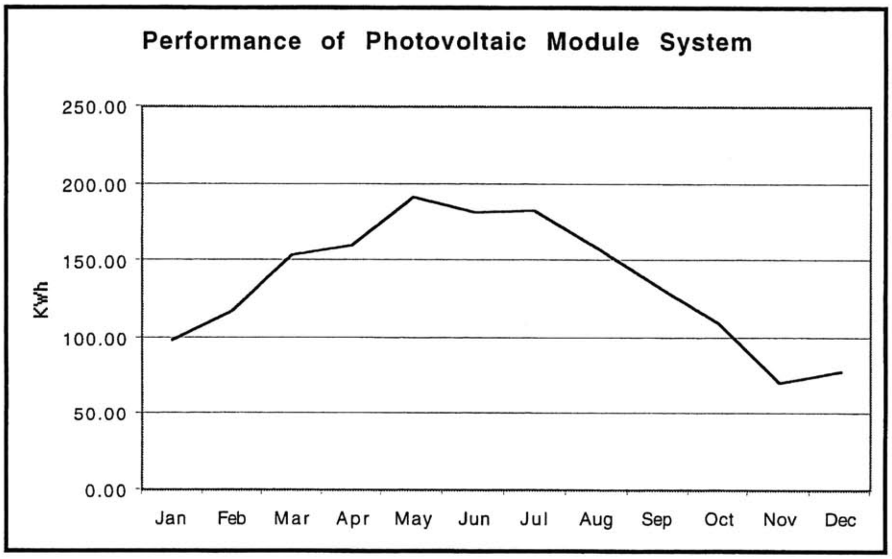


Figure 4.49
Performance for panel system at 29.7° Degrees

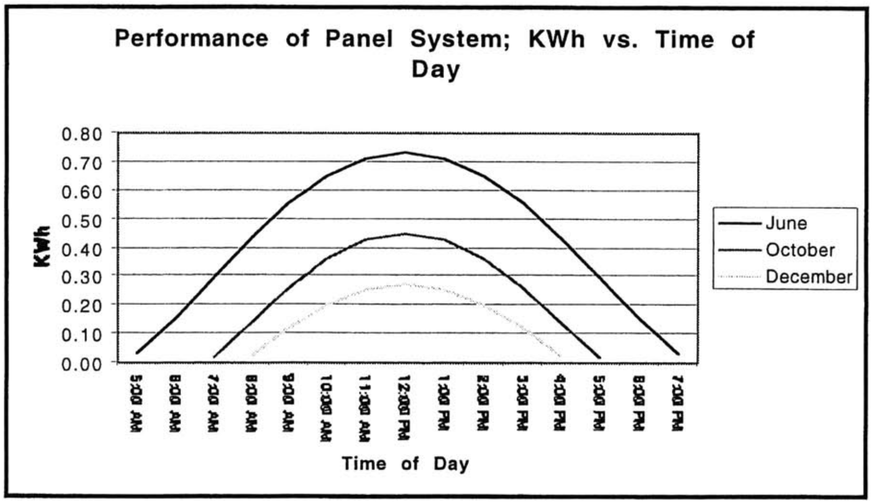


Figure 4.50
Solar Power on a Horizontal Surface

4.4.1 Consumption Patterns of a Multi Family Dwelling

The consumption patterns of a multi family dwelling vary according to the season and the individual lifestyle of the occupants. However, one can approximate the daily consumption of a house with four apartments based on an estimated number of appliances and lights.

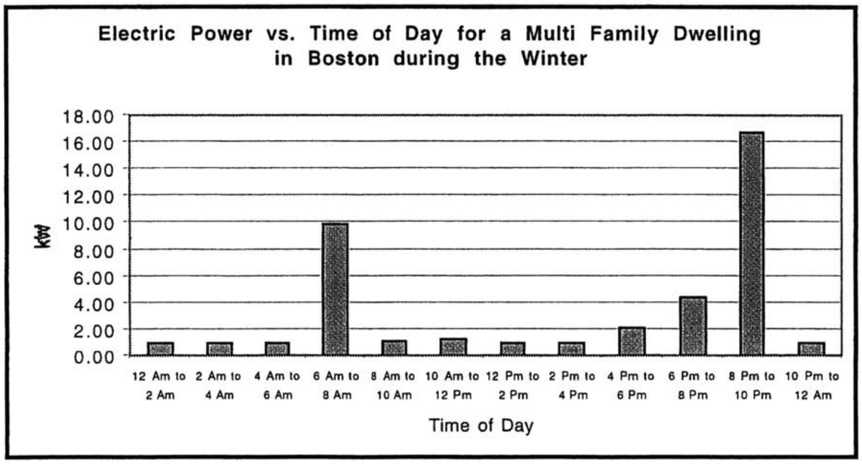


Figure 4.51 Consumption Pattern

During the winter, a multi-family dwelling may consume a total of 42 kWh per day for lighting and appliances. In a year, the occupants of the Cambridge house may consume a total of 12,397 kWh of electricity for both lighting and appliances. This translates to an amount $1485.76 per year.[2]

If a photovoltaic system can supply 1639 kWh per year, it can meet 1/8 the load of the house, which is a 13% energy savings. The total surface area of the system must increase by a factor of 8 to meet the total electrical demand for the house. The total surface area of the photovoltaic system is 168 ft^2 ,which is approximately 1/3 of the total south-facing roof area. If the entire south-facing roof area was covered with photovoltaic panels, then it could potentially meet 35% of the electrical load for lighting and appliances.

The following graph shows output of a fourteen-panel system versus the electrical load for a multi-family dwelling. The panels receive most of their energy during the mid-afternoon when the electrical load is at a minimum.

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[2] The total annual consumption for lighting and appliances for a multi family dwelling was taken from the analysis report on the Cambridge House for Sustainability, by the Building Science Engineering Company

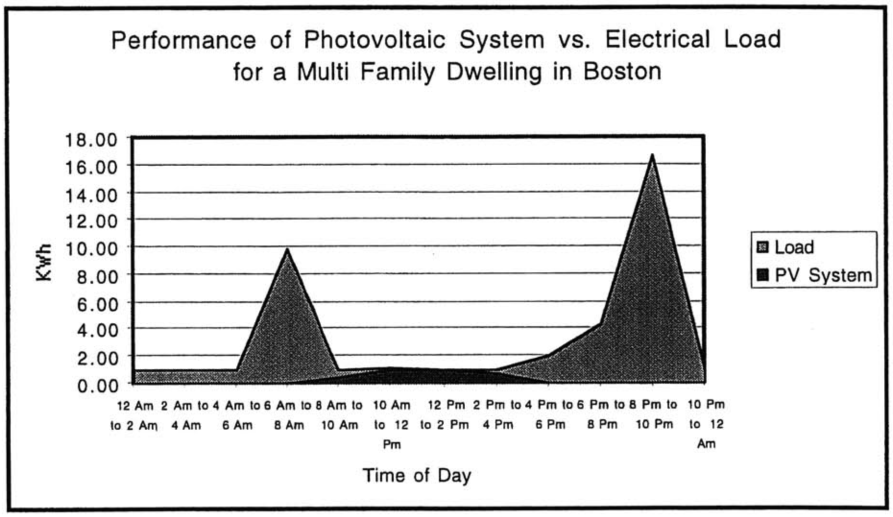

Figure 4.52

Output of panel vs. electrical load during the month of January

4.4.2 Cost Analysis

The cost of photovoltaic electricity is on average five times greater than conventional electricity: \$.50/kWh[4] compared to the standard \$.10/kWh. A system module consists of the following components; prices are based on the dollars per rated power (\$/Watt). The following figures were taken from a lecture sponsored by the Northeast Energy Association.

Table 4.18: Cost/ Peak Watt Photovoltaic Module

Cost	AC Module		DC Module	
	Low	High	Low	High
Laminates	\$5.00	\$6.00	\$5.00	\$6.00
Inverters	\$1.00	\$3.00	\$.75	\$1.00
Connectors	\$.10	\$.15	\$.10	\$.15
Electrical	\$.50	\$1.16	\$.75	\$1.50
Cost of good	\$6.60	\$10.15	\$6.60	\$8.65
+ Installation	\$9.94	\$15.80	**\$10.52**	**\$14.74**

A DC Module has cost range of \$10.52 to \$14.74 per peak watt. Therefore, a 64-watt panel has a price range of \$683 to \$953 per panel or \$60/ft^2 to \$79/ft^2. An entire photovoltaic system with fourteen panels may have a price range of \$9560.32 to \$13,341. Each panel provides an annual saving of \$14.

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[4] Cost obtained from a lecture sponsored by the Northeast Energy Association

At varying interest rates, the net present value of the energy savings results in a loss over a twenty year span.

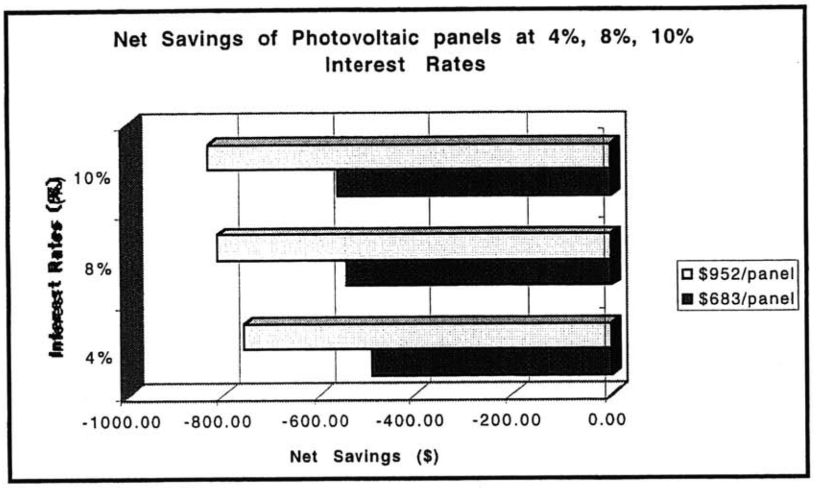

Figure 4.53

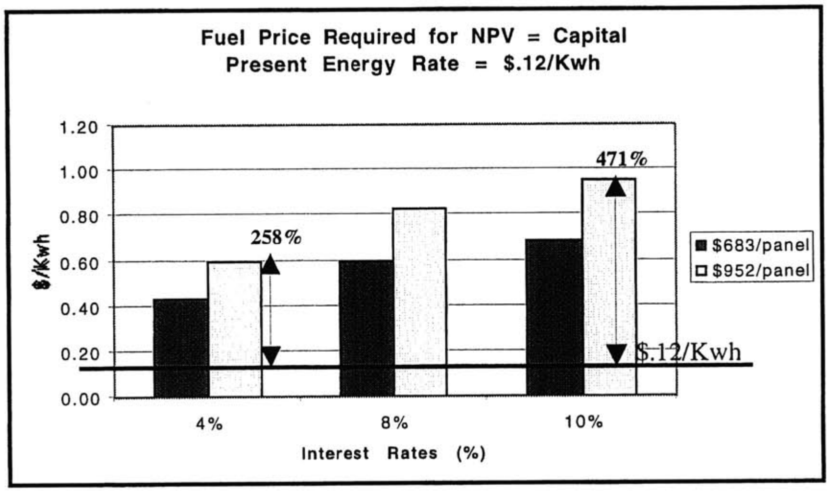

Figure 4.54

From graphs above, the capital is far greater than the net present value of the savings over twenty years, indicating that an investment in photovoltaics is not cost-effective at an energy rate of $.12/kWh. At $683/panel, the energy rate must increase by 258% to 471% for the net present value of the savings to equal the capital cost.

The actual cost of energy has risen in some regions of the United States to as high as $.33/kWh. However, the government has provided subsidies to lower the cost to a conventional rate of approximately $.10/kWh to make prices more affordable for the average citizen. Thus, renewable energies are competing with a subsidized energy rate as opposed to an actual rate. If the actual cost of electricity is $.33/kWh, then the percentage increase for the net present value of the savings is significantly lower. For example, a 30% increase over the cost of $.33/kWh (at a 4% interest rate) is required for the net present value of the savings to equal the capital cost (at $683/panel). A larger market for photovoltaics would increase demand and decrease the capital cost. Thus, use of such a system dependent on successful marketing strategies as well as government incentives. In addition, if the price of energy increased by 4% every year over the next twenty years (over a base cost of $.33/kWh), then a homeowner would achieve a profit given a fixed capital cost of $683/panel.

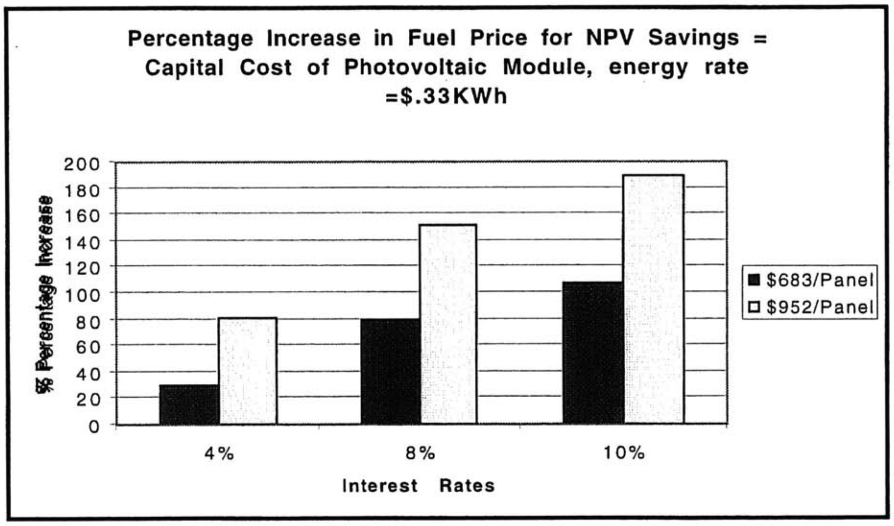

Figure 4.55

4.4.3 New Construction and Replacement of Roofing System

In new construction and rehabilitation projects, a proprietor may consider the relative cost of a roofing system with a photovoltaic energy system to the net energy savings.
A photovoltaic module excluding installation cost is $6.60 to $8.65 per peak watt. The cost of a fourteen-panel system is approximately $5913.60 to $7750.40. If the proprietor achieves savings on roofing materials from the photovoltaic system, then he/she can obtain a credit of $1636.32 (a roofing system with shingle is estimated at $9.74/ft^2) towards the overall construction cost. Therefore, the entire photovoltaic system has a cost of $4277.28 to $62114 above the base cost of construction. Each panel has a price range of $305.52 to $436.72.

Unfortunately, the reduction in price is not enough for the net savings to equal the capital cost over a twenty year span at an energy rate of $.12/kWh. The price per panel must equal a minimum of $120 in order for an investor to break even at a 10% interest rate and have a meager profit at a 4% and 8% interest rate.

If the actual cost of electricity is $.33/kWh, a homeowner of a multi family dwelling can obtain a net savings at all three interest rates if the cost is $305.52/panel. (Figure 4.56). If the cost is $436/panel, then he/she achieve a profit at a 4% interest rate, but will lose at 8% and 10% interest rates.

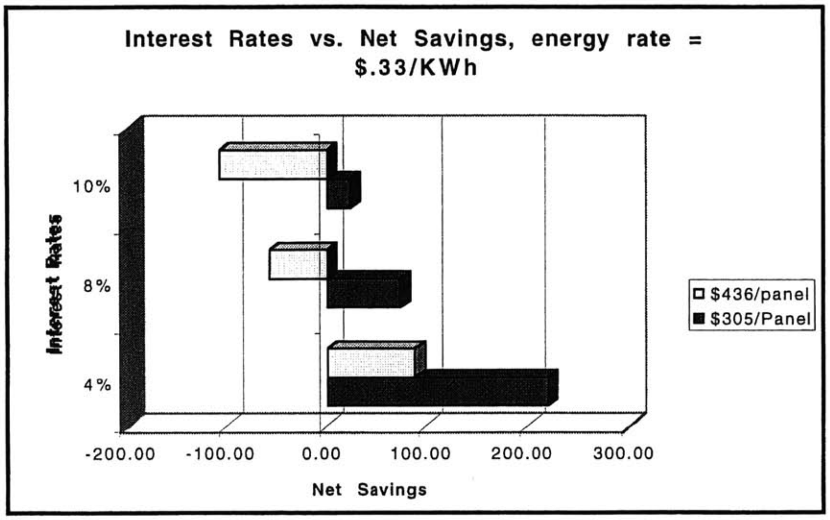

Figure 4.56 New Construction

4.4.4 Conclusions: Photovolatic Systems

The fourteen-panel system in the house meets approximately 13% of the total annual electrical load. This translates to an annual energy saving of $196.68. Unfortunately, the system is not cost-effective at a present energy rate of $.12/kWh. At an energy rate of $.33/kWh, there is still a financial loss over a twenty year span. However, the percentage increase required for the capital cost to equal the net savings at $.33/kWh is significantly lower than at $.12/kWh. (See 4.55).

In new construction projects, photovoltaic systems still result in a huge loss at $.12/kWh. At $.33/kWh, the system is cost-effective at a lower limit cost ($305/Panel). (Fig 4.56)

4.5 Ground Source Heat Pumps

Ground source heat pumps extract energy from the earth and use the relatively stable temperatures of the ground as both a source and a sink. Geothermal systems have a coefficient of performance in the range of 3 to 3.8 or even greater depending the temperature differences between the ground and the fluid circulating through the pipes. Although these systems significantly reduce energy consumption, the energy saving is offset by the high cost of electricity in New England. Heat pumps use electricity, which is equal to $.12kWh. Electricity is roughly three times the cost of gas, which is around $1.1/therm or $.037 kWh.

The Cambridge House for Sustainability has an annual heating and cooling load of approximately 95 million Btu. If the ground source heat pump (gshp) has a coefficient of performance of 3.8, the work energy input to the pump is 25 million Btu or 7326 kWh per year. The following table shows a comparison between the annual cost of running a ground source heat pump versus an electric AC/gas-fired furnace.

Table 4.19: Comparison of Annual Cost

	Annual Energy Use for Heating/Cooling	$cost
A/C gas-fired furnace	95 MMBtu	1057
GSHP	7326 kWh	880
Savings		176

The cost of savings of a ground source heat pump relative to an electric AC/gas-fired furnace is a meager annual sum of $176.00. The following table shows the cost of ground source heat pumps plus the cost of installation. Water to water systems are more costly than water to air systems.

Table 4.20: Cost of GSHP Systems[1]

	Inside Work: ductwork,unit plumbing, $/ton	$Cost
Water to Water	6000	10000
Water to Air	3500 - 4300	3500 - 5000

A water to water system was installed in the Cambridge House for Sustainability. Therefore, the cost was more expensive than an average system. The system requirement was sized to meet a maximum load of 52 MBH, which is approximately 4.2 tons for 3457 ft^2. The

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[1] Price estimate from a thermal Consultant, a Climate Master Distributor from Water & Energy System Corporation

cost per ton is $6000/ton plus the outside work, $10,000. The grand total is $36,000 for the entire system.

At a 4% interest rate, the net present value of the annual savings is $2,393 over a twenty year span. Clearly, the sum total of the savings is much smaller than the initial investment. The capital cost must decrease by $33,606 in order for the net present value of the savings to equal the investment at a 4% interest. From another perspective, the annual savings must be greater than $2,649 for the net present value to equal a fixed capital cost of $36,000 at a 4% interest rate. The annual saving of $2,649 is greater than the annual cost of heating and cooling a building using a gas-fired furnace and electricity. The cost of energy must increase to astronomical figures in order for a proprietor to break even on his investment, without the rebates or tax incentives.

In some retrofit projects, it is possible to use the existing ductwork of the house when replacing a conventional system with a ground source heat pump. This, in turn, reduces the capital cost of the system such that it only includes the cost of the unit, plus the outside work. If the estimated cost for installation (including the unit and outside work) is $3480/ton, then the total cost of the entire system is reduced from $32,000 to $14,616. Unfortunately, the price reduction is not enough to make the overall system economically feasible in New England. The following table shows the increase in the cost of electricity required for the net present value of the savings to equal the capital cost of the geothermal system with or without inside duct work.

Table 4.21: Net Present Value of Savings equal to Cost

Capital Cost ($)	$/kWh (4%)	$/kWh(8%)	$/kWh(10%)
36,000	1.80	2.50	2.88
14,616	**.73**	1.01	1.17

4.5.1 Energy Crafted Homes in Connecticut

If a water to air system had been used in the Cambridge House for Sustainability, the capital cost would decrease from $36,000 to $18,886. Clearly, the decrease in the initial investment is not enough for a homeowner to break even on his investment. Nonetheless, it represents a more realistic price for a ground source heat pump in the New England area.

The Northeast utilities in Hartford, Connecticut, sponsors a program called the "Energy Crafted Home" or (ECH) to provide rebates and technical assistance to people interested in building an energy-efficient home. A ECH representative will evaluate drawing submitted by the homeowner to insure that the houses meet a set performance standard. Energy Crafted homes have extra air sealing, insulation and improved indoor air quality.

According to a case study in Connecticut (the Palmer residence), a two-story colonial home with 3,537 square feet required a 4.2-ton system to supply 49,614 Btuh. The cost of the equipment and duct work for unit was approximately, $10,541, and the cost of the installation cost of the ground loop system was $8,742 yielding a total cost of $19,283. The following table shows the annual operating cost for the Palmer residence in comparison to alternative systems. Costs are based on an electric rate of 9.884 cents/kWh.

Table 4.22-Operating Cost Estimates

	Heating($)	Cooling($)	Water($) heating	Domestic($)energy	Total($) Operating
GSHP	978	189	243	537	1947
Electric AC, Gas fired furnace	1025	247	169	572	2013
Electric AC, Electric Resistance Heating	2983	230	626	537	4376

A comparison of the total operating cost of the geo-exchange system with the electric air conditioning system with the gas fired furnace, shows an annual saving of $66. A comparison of only the heating and cooling cost yields a slightly larger saving of $105.

The Palmer residence qualified for a rebate under the Energy Crafted Home program. The total rebate of $5,958 reduced their overall cost from $19,283 to $13,325. An analysis of the net saving over a twenty-year span yields a substantial loss with an $105 dollar annual net gain. Figures indicate that an annual savings of $980 or greater is required for the net present value of the savings to be equal or greater to the capital cost at a 4% interest rate. Thus, when the geothermal system is compared to the electric air conditioning and electric resistance system, the savings is $2046 per year. This value exceeds $980; thus, the proprietor obtains profit and the system is cost-effective. Clearly, the comparison is unrealistic because electric resistance heating is uncommon in northern regions due to the high cost of electricity.

4.5.2 Electric Resistance Heating

Although uncommon in the North, electric resistance heating is used in the southern region of the United States. Many homes have both electric resistance and air conditioning systems. If the Cambridge House for Sustainability were moved to a Jacksonville, Fl, the size of the system would be reduced from 4.2 tons to 2.6 tons. In addition, the annual heating and cooling load would decrease from 95 to 77 MMBtu, approximately. The cost of the system would run approximately $10,687[2] including installation and work done inside the house (duct

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[2] Means Residential Cost Data

work, etc.). The replacement of the system would substantially reduce the energy load with a 74% reduction in heating and cooling cost. In Cambridge, the percentage reduction was only 17%.

If electric rate are around $.068 cents/kWh, the annual savings is significant amount of $1135 dollars. After twenty years, the net saving at a 4% interest rate is roughly $2,000 per ton, indicating that it is a very cost-effective measure. At an 8% interest rate, the net savings decrease significantly to $176/ton. There is a loss at a 10% interest rate. This indicates that ground source heat pumps are more economically feasible in warmer climates at present energy rates than in colder climates.

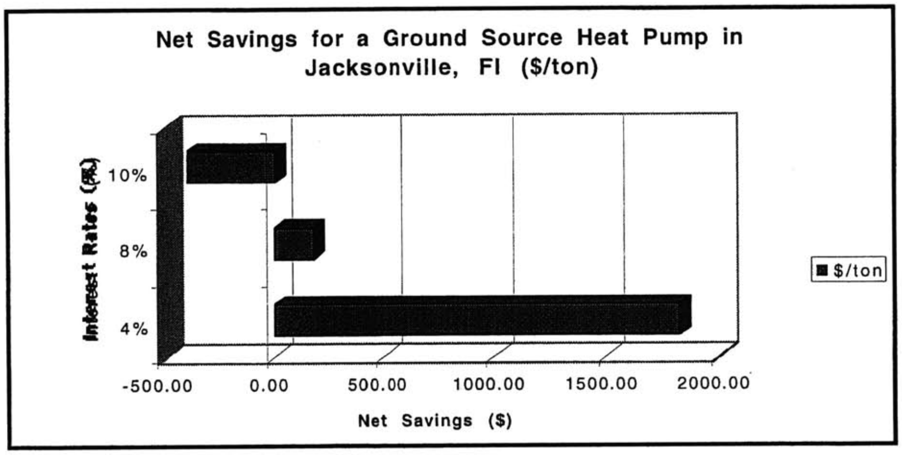

Figure 4.57

If a homeowner in Jacksonville, Fl, installed an air to air heat pump, he/she would obtain an annual energy savings of $432. This amount is roughly half the annual energy savings of a ground source heat pump. On the other hand, the cost of the system is reduced to approximately $2500 /ton. At a 4% interest rate, the net savings yield a profit. However, at higher interest rates, there is a net loss. This indicates that ground source heat pumps are most cost-effective in warmer regions of the United States that air to air heat pumps.

4.5.3 Installation of Ground Source Heat pumps in New Construction

Clearly, the replacement of an entire heating and cooling system is not cost-effective when compared to the energy savings in the Northeast. In new construction or in projects where rehabilitation is required, a proprietor can compare the differences in cost between a heat pump system versus a conventional system relative to the energy savings. Geothermal systems cost more, but can provide greater energy savings.

The Palmer family in Connecticut received a quote of $16,200 for an oil-fired furnace and air conditioning system. Without a rebate, the difference in cost between the heat pump and conventional system in the New England area is around $2500. An analysis of the price difference versus the net present vale of the annual saving (annual savings of $176) results in a loss of $73.00 at a 4% interest rate. There is an even greater loss at a 10% interest rate.

On the other hand, a rebate of $6000 would make the heat pump less expensive than the conventional systems. The difference in cost is added to the long-term energy saving, resulting in a net gain of $5,885 at a 4% interest rate in twenty years. Clearly, a rebate is required for new construction and rehabilitation projects in New England.

4.5.4 Upgrade of Furnace vs. Heat Pump

A homeowner may consider the relative energy savings of upgrading an inefficient furnace versus a ground source heat pump in New England. The following graph compares the annual energy savings of the upgrade to a furnace of higher efficiency versus a ground source heat pump.

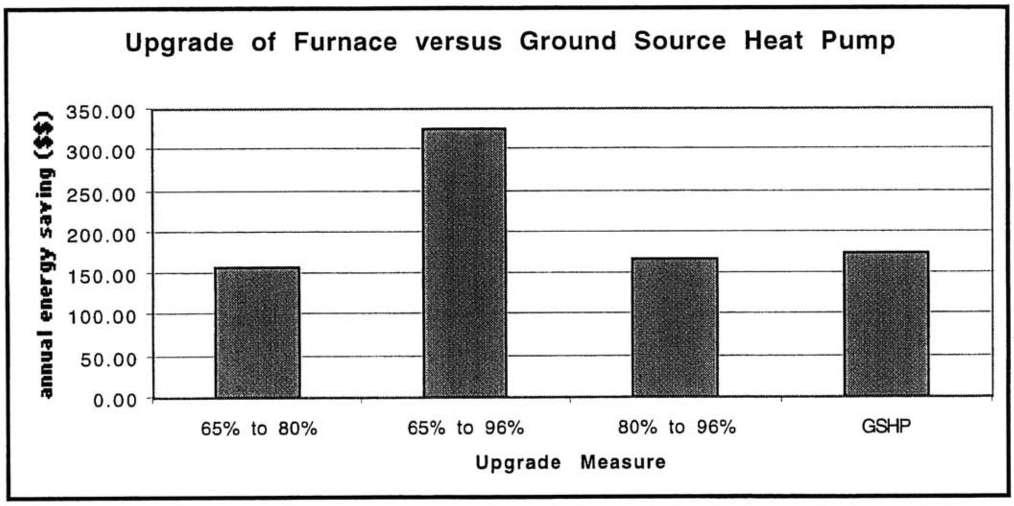

Figure 4.58

From the graph, it is clear that a homeowner obtains the greatest energy savings by upgrading a furnace from 65% efficiency to 96%. A ground source heat pump provides a slightly greater saving than the upgrade of a furnace from 65% to 80% or from 80% to 96% efficiency.

According to the 1996 Means Mechanical Cost Data book, the cost of a gas fired furnace, combination system supply 120 MBH of heating and 42MBH of cooling is around $4,100. If one assumes that a homeowner simply replaces a furnace and not the entire system, then he/she obtains a net saving at a 4% interest rate by upgrading from 65% to 96%. This upgrade measure is more cost-effective than a heat pump system.

Table 4.23: Furnace Replacement

Furnace Replacement %	**Net savings 4% interest ($)**	**Net savings 8% interest ($)**	**Net savings 10% interest ($)**
65% to 96%	308.98	-914.77	-2763.62
65% to 80%	-1966.62	-2558.76	-2763.62
80% to 96%	-1824.40	-2456.01	-267453

As an alternative to furnace replacement, a homeowner may consider a few modifications that can increase the efficiency of a furnace. Some modifications include the following:

1. The installation of a flue damper to prevent heat that is lost up the flue,
2. The installation of two speed fan with a temperature sensor to change the rate of heat delivery depending on the outside temperature
3. Altering the circulating fan in the furnace such that it remains turned on when the furnace is turned off to maximize heat supply to the building.

These measures may reduce about 5% to 10% of fuel consumption.[4]

4.5.5 Ground Source Heat Pumps versus Air to Air Systems

Ground source heat pumps extract energy from the ground; however, air to air systems obtain energy based on the temperature difference between the circulating antifreeze in the pipe and the outside air. The coefficient of performance (COP) of an air to air heat pump will vary according to the outside temperature. For example, the COP a system with an outdoor air temperature of 47°F degrees is 2.5; whereas, the COP of the same system with an outdoor air temperature of 17°F degrees is 1.7. The following analysis demonstrates that air to air pumps use more energy than conventional systems (electric a/c, gas-fired furnace) in colder climates. Therefore, they are not cost-effective.

The Cambridge House for Sustainability is 3,457 ft^2 home with 4 family dwellings, approximately 750 ft^2 per unit. Based on a quote from a local company, each apartment or unit would require a 2-ton air to air heat pump, with a minimum of 100 - 400 amps necessary for operation. Assuming that a homeowner chooses to replace his conventional heating system (possibly gas, furnace) with four air to air heat pumps, he would need to run servicing from the street. The cost of each unit plus the cost of electric wiring is $5,000 + $2,200(service fee) which yields a total installation cost of $7, 200 per apartment dwelling. The total installation cost (based on an estimate from Royal Air Company) is $28,800.

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[4] The Scientific Staff o the Massachusetts Audubon Society, City Lights, a Handbook of Energy Conservation and Renewable Energy for City Housing, Massachusetts Audubon Society, November, 1980

A typical air to air pump will have a heating seasonal performance factor (HSPF) of 6.8 and a seasonal energy efficiency ratio (SEER) of 10. The HSPF and SEER are defined as the total heating/cooling output during a heating/cooling season in Btu divided by the total electrical input during the same period in watt-hours. Based on the SEER and HSPF, the air to air heat pump consumes more electrical energy than a conventional system with electric a/c and furnace. The annual energy cost of $1597.00. The annual cost using a gas-fired furnace and electric air conditioner is $1056.00. Therefore, a homeowner has a net loss of $540.00 per year.

In moderate to warm climates, air to air heat pumps are more cost-effective because they have a higher coefficient of performance. As in the case of Jacksonville Florida, there is an annual energy savings of $432 when compared to the standard system.

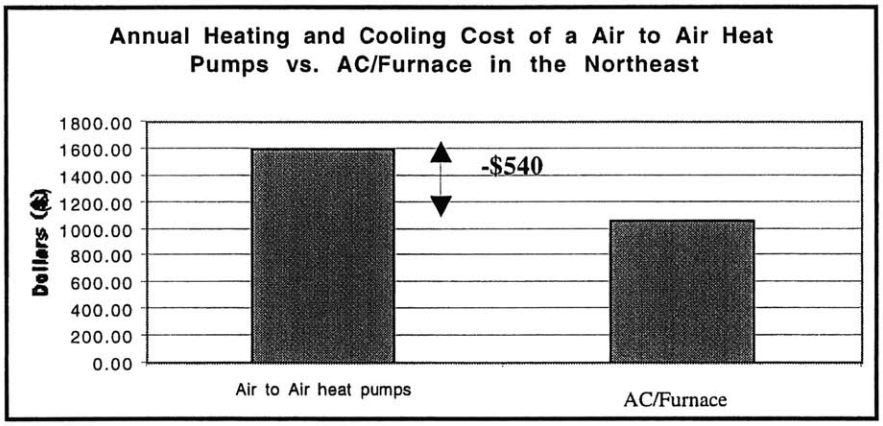


Figure 4.59

Thermal Comfort Considerations with an Air to Air Heat Pump

In addition to the high energy costs, air to air heat pumps are more uncomfortable when compared to a conventional system. Many pumps will blow air at a maximum temperature in a range of 90°F to 110°F. Given that the human body temperature is 98°F, residents will most likely feel discomfort. An air to air system with a gas-fired furnace will blow air at temperature in the range of 130°F to 140°F, which consequently has a warming effect on the occupants within a space.

4.5.6 Conclusions: Ground Source Heat Pumps

The annual saving of $176 per year is an insufficient amount for ground source heat pumps to be cost-effective in New England. In retrofits, the replacement of a conventional system by a ground source heat pump yields a very large negative net saving over a twenty-year span. The systems are only cost-effective in new construction projects with an additional rebate.

On the other hand, ground source heat pumps are cost-effective in the southern region of the United States.

When compared to furnace replacement, the cost of energy savings obtained from a ground source heat pump is slightly less than the cost of energy savings from upgrading of a furnace from 65% to 96%. Therefore, the replacement of a very inefficient furnace is more cost-effective at present energy rates, than the installation of a ground source heat pump system.

Air to Air systems yield a huge energy loss in the northern region when compared to a conventional systems. However, they do provide an annual energy savings in warmer regions of the U.S. On the other hand, air to air systems may not be cost-effective in the South because of the high capital cost.

4.6 Radiant Floors, Walls and Ceilings

The Cambridge House for Sustainability has a radiant heating system with a floor, wall and ceiling. Radiant systems distribute heat from hot water tubes to the surrounding air and objects inside of an interior space. These systems are an alternative to baseboard heating and fan coil units and have some benefits such as increased thermal comfort, energy efficiency, greater space availability, less stratification and an ideal temperature distribution.

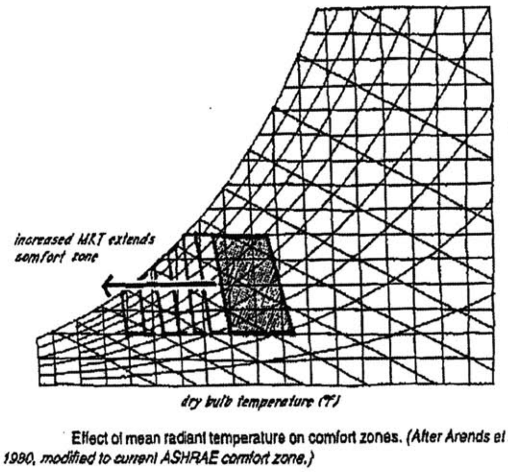
Energy efficiency

Many manufacturers of radiant heating systems claim that homeowners can obtain an energy saving in the range of 20% to 40% when compared to traditional systems with fan coils and baseboard heating units. This due to that fact that radiant floors will heat not only the air, but the surrounding objects, thus increasing the mean radiant temperature, T_{mrt}, of a space. Occupants will feel more comfortable at lower thermostat settings. In addition, inlet temperature of water in radiant floors is lower than that of baseboard heaters or radiators.

4.6.1 Thermal comfort Criteria for Radiant Systems

If a resident with a radiant heating system is comfortable at a lower thermostat setting, then he/she can obtain some energy savings when compared to conventional forced air systems. The following analysis is intended to determine how far a person can set his/her thermostat back and still remain comfortable within a space.

Radiant floors increase the mean radiant temperature, T_{mrt}, of the surroundings. Therefore, occupants within a space can feel comfortable at lower operative temperatures. The comfort zone shifts to lower temperatures when the mean radiant temperature is increased.



Effect of mean radiant temperature on comfort zones. *(After Arends et al., 1980, modified to current ASHRAE comfort zone.)*

Figure 4.60 Shifted Comfort Zone

The mean radiant temperature, T_{mrt} , is defined as the temperature of an imaginary isothermal black enclosure in which the occupant would exchange the same amount of heat by radiation as in the actual non uniform environment[2]. One can determine the mean radiant temperature within a room with the following equation.

$$A_p\sigma\left[T_p^4 - T_{mrt}^4\right] = A_p\sigma\left[f_{pf}(T_p^4 - T_f^4) + f_{pw}(T_p^4 - T_w^4) + f_{pc}(T_p^4 - T_c^4)\right] \qquad \text{(Eq. 4.16)}$$

A_P = area of the person
σ = Stefan-Boltzmann Constant
T_p = temperature of person
T_{mrt}= mean radiant temperature
T_f = floor temperature
T_w = temperature of wall
T_c = temperature of ceiling
f_{pf} = view factor of person to floor
f_{pw} = view factor of person to wall
f_{pc} = view factor of person to ceiling

At steady state, the temperatures of the walls and ceiling can be calculated by equating the convective energy loss to the net radiant exchange between the wall and ceiling and the radiant floor. All of the equations assume a uniform temperature for wall and ceilings.

$$q_{conv} + q_{rad} = 0 \qquad \text{(Eq. 4.17)}$$

$$hA\left[T - T_{air}\right] + h_r f A\left[T - T_f\right] = 0 \qquad \text{(Eq. 4.18)}$$

q_{conve} = convective loss
q_{rad} = radiative loss
A = area of wall or ceiling
h_r = radiative heat transfer coefficient
f = view factor between wall and floor, ceiling and floor
T= temperature of ceiling or wall
T_{air}= air temperature

From the equations above, the T_{mrt}, of a space can be determined for varying floor temperatures. Calculations are based on the room dimensions of the dining room in the Cambridge House for Sustainability. The outdoor air temperature is 20 °F and the air temperature of the surrounding rooms is 70°F.

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[2] 1995, ASHRAE handbook, HVAC Applications

Table 4.24

Floor Temperature (F)	T_{mrt} (F)	Interior Walls (F)	Ceiling(F)
80	72	78	74
77	70	75	73
75	69	74	72

Varying floor temperatures affect the temperatures of the ceiling, inside and outside walls. The thermal comfort of the occupant within a room is dependent on temperature of the surrounding walls, the dry bulb temperature, the humidity and the relative air velocity of the surrounding air.

A few thermal comfort models can determine the predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) of an occupant within a space. These equations take into account the heat generated by the body versus the radiative, convective and evaporative losses that occur through the skin. One may assume than an occupant in a residence is relatively sedentary with a metabolic rate less than 1.2,and an average clothing insulation thickness equivalent to .6 (trousers long sleeve shirt). Calculations also assume a 50% relative humidity and an air velocity of 30 fpm.

$PMV = [.303\exp(-0.036M) + 0.028]L$

$PPD = 100 - 95\exp[(-0.03353PMV^4 + 0.2179PMV^2)]$

L = Heat loss to the actual environment

M = Rate of metabolic heat production (W/m^2)

PMV =

+3	hot
+2	warm
+1	slightly warm
+0	neutral
-1	slightly cool
-2	cool
-3	cold

The acceptable range of PPD is 20% or less. When the floor surface temperature is equal to 80°F, the air temperature can decrease to 65°F, with a disapproval percentage of 23% and a predicted mean vote of -1.3, indicating that occupants are slightly cool. When the air temperature is in the range of 69°F to 67°F, the PPD is 8% to 13%. Interestingly, when the air temperature is 77°F, the PPD is 18.67% and the PMV is .81 indicating that residents are slightly warm. Any temperature higher that 77°F will result in a PPD of 23% or higher.

A fixed floor surface temperature of 77°F yields 41% PPD when the air temperature is 65°F. The lowest acceptable range of air temperature is 70°F to 68°F, which results in a disapproval of 13% to 21%.

When the floor surface temperature is equal to 75°F, the PPD is equal to 55.38% when the air temperature is 65°F and the PMV is -1.58, indicating that occupants are in the range of slightly cool to cool. The lowest possible acceptable range of air temperature is 71°F to 70°F degrees yielding a PPD of 16% to 22%.

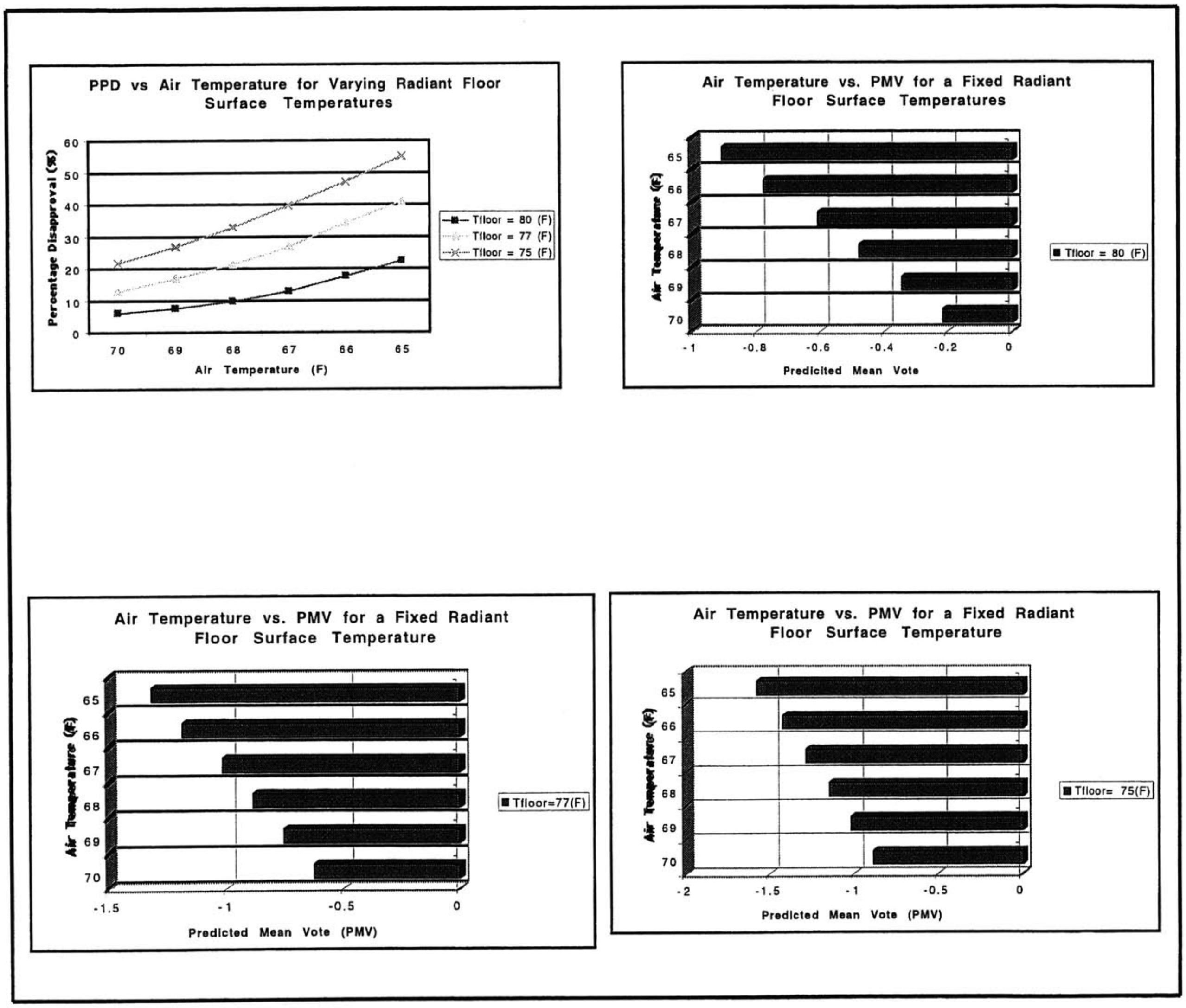
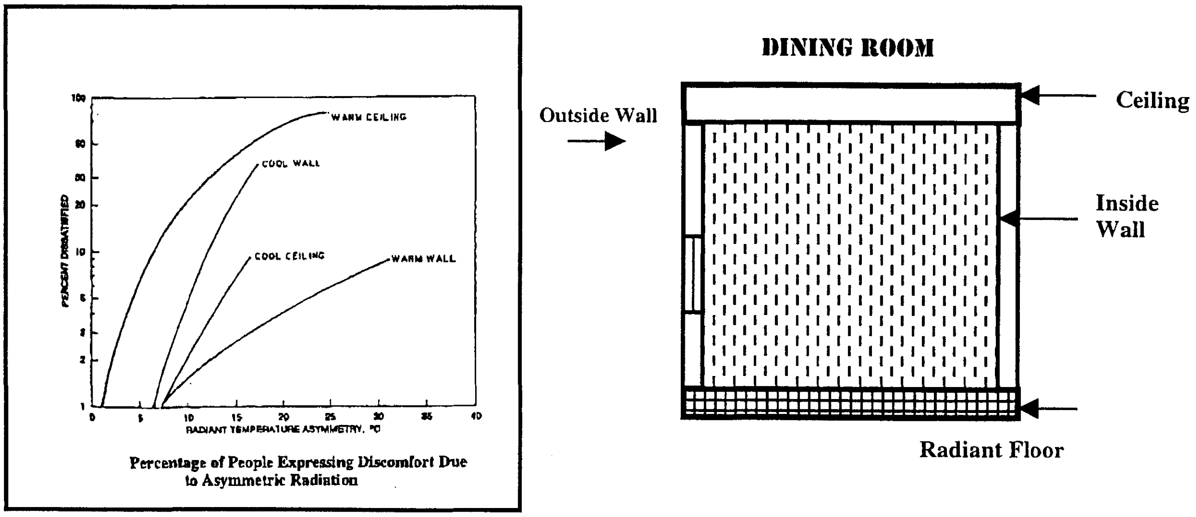


Figure 4.61

Asymmetric Thermal Radiation

The degree of thermal comfort is also determined by the non-uniform thermal radiation caused by cold doors, windows and uninsulated walls. A room containing several windows on one side and a radiant wall, floor or ceiling will affect occupants differently. A radiant floor creates a more uniform distribution of temperature with warmer temperatures closer to the occupants. However, in radiant ceilings, it is exactly the reverse with warm temperatures above the subjects. Studies by Fanger demonstrate that people are more dissatisfied by a warm ceiling than a cool wall. They are affected the least by a warm wall. For example, radiant wall with a temperature of 23°C would yield a PPD of 4%. A warm ceiling of 23°C would yield a PPD of 50% or greater.

In the dining room of the Cambridge House for Sustainability, the greatest temperature difference is between the inside and outside walls.



Percentage of People Expressing Discomfort Due to Asymmetric Radiation

Figure 4.62

When the radiant floor surface temperature is equivalent to 80°F, the inside walls have a temperature of 78°F and the outside wall is approximately 65°F. The difference in radiant temperature is 13°F from the outside to inside wall. According to the graph, the percentage dissatisfied by the warm inside walls is in the range 2% to 3%.

The ceiling temperature is 74°F. Therefore, the difference between the floor and the ceiling is 6°F resulting in a zero percentage disapproval rating. Overall, the occupants in a room with a radiant floor are not affected greatly by asymmetric radiation.

Typical Floor Surface Temperatures and Thermostat Settings

Table: 4.25

Room Set-Point	Radiant Floor Surface Temperature									
75	80	82.5	85	87.5	90	92.5	95	97.5	100	102.5
72	77	79.5	82	84.5	87	89.5	92	94.5	97	99.5
70	75	77.5	80	82.5	85	87.5	90	92.5	95	97.5
68	73	75.5	78	80.5	83	85.5	88	90.5	93	95.5
65	70	72.5	75	77.5	80	82.5	85	87.5	90	92.5
60	65	67.5	70	72.5	75	77.5	80	82.5	85	87.5
	10	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**

BTUH/Square Foot

Radiant Floor Heating by Dodge Woodson

The colored cells of the above table indicate that the radiant floor temperature exceeds the maximum recommended surface temperature for hardwood floors (lighter color) and all floors (darker color).

The Cambridge House for Sustainability has a heating load of approximately 45,147 Btu/h.[1] When the load is divided by the square footage of the house; the required heat input per square footage is between 10 Btuh/ft^2 to 15 Btuh/ft^2. According to the table above, the required surface temperature of the floor is 80°F to meet a room set-point temperature of 75°F (at 10 Btuh/ft^2). If the room set-point temperature is 70°F, the required radiant floor surface temperature is 75°F.

4.6.2 Energy Savings

Assuming that the Cambridge House for Sustainability was heated solely with radiant floors, residents can maintain their thermostat settings at 67°F to 68°F. A forced air system, on the other hand, may require an operative temperature around 75°F. If steady state temperature is maintained throughout the season; the following equation is applicable:

$$Savings = \frac{\Delta T_c - \Delta T_r}{\Delta T_c} \times 100 \qquad \text{(Eq. 4.19)}$$

ΔT_c= *difference between inside temperature (75°F) and outside temperature with forced air system*

ΔT_r= *difference between inside temperature with radiant floor (67°F to 68°F) and outside temperature*

A homeowner may therefore obtain a saving in the range of 13% to 15% during a heating season. The amount of savings will vary according to house design and location.

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[1] Value for heating load was taken from the energy cost and feature report for the Cambridge House for Sustainability

4.6.3 Comparison with Night Set-Back

Many homeowners will use night set back to obtain some energy savings at night time by setting back their thermostats to lower temperatures and reducing the amount of heat that is lost to the outside air. When the radiant system is installed, it interferes with the savings gained by night set back because the overall mass of the house is increased. Therefore, the energy given off at night from the radiant floor is equal to extra energy needed to reheat the house during the early morning hours. Lightweight to medium-weight homes have greater energy savings when using night set back than heavy weight homes.

Three lumped capacitance models can be used as first approximations to simulate the changes in the air temperature of the house and the energy savings gained by night set back. The R and C correspond to the resistance and the capacitance. In these models, it assumed that the house is heated only by the radiant system. There are no additional fan coil units or baseboard heaters. In a radiant only system, a boiler or water tank, located in the basement will supply hot water to plastic tubes located within a radiant walls and floor. The air in the house is heated from radiation and convection.

The three models (model 1, model 2, model 3) describe some upper to lower limits on the amount of energy that is emitted from the radiant system to the air in the house. The more energy that is given off, the smaller the saving achieved with night set back. Model 1 is a 2R2C model with two resistances and two capacitances. In model 1, a certain amount of energy supplied (from the hot water tank) is stored in the mass of the radiant system and there is a convective and radiative resistance between the radiant system and the air, which reduces the amount energy emitted at night. Consequently the air temperature of the house decreases more rapidly during night set back. Model 1 is a lower limit on the amount of energy emitted from the radiant system.

Model 2 is a 2R1C with two resistances and one capacitance. In this model, the temperature of the radiant system remains fixed. During night set back, the difference of temperature between the air and the radiant system increases as the air temperature decreases, thus maximizing the convective and radiative losses. Model 2 is an upper limit on the energy emitted from the radiant system to the air.

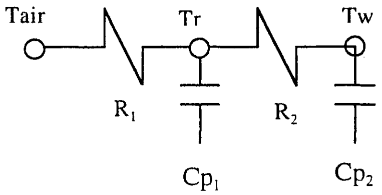
Model 3 is a 1R1C model with one resistance and one capacitance. In model 1, the resistance between the radiant system and the air is equal to zero, or convective and radiative heat transfer coefficient is equal to infinity. This indicates that the temperature of the air and the wall are the same. Model 3 is another upper limit on the energy emitted from the radiant system.

The upper limit models indicate that there is a decrease in the energy savings from night set back. The lower limit model indicates an increase in the energy savings gained from night set back. The following pages describe each of the models in greater detail.

Model 1. (2R2C)

$$1. \quad m_w cp_w \frac{DT_w}{dt} = -h_w a_w (T_w - T_r) - \varepsilon \sigma a_w (T_w{}^4 - T_r{}^4) + Q \qquad \text{(Eq 4.20.)}$$

$$2. \quad m_r cp_r \frac{DT_r}{dt} = h_w a_w (T_w - T_r) + \varepsilon \sigma a_w (T_w{}^4 - T_r{}^4) - u a_r (T_r - T_{air}) \qquad \text{(Eq. 4.21)}$$



Q= energy supplied from tank
T_w = temperature of brick
h_w= Heat Transfer coefficient
ε = emissivity of brick
cp_w = specific heat of brick
m_w = mass of brick
a_w = area of wall
cp_r = specific heat of materials in house excluding brick
m_r = mass of lumped materials in house excluding brick
T_r = temperature of air
R_2= convective and radiative resistance
R_1= conduction resistance
T_{air} = outside air temperature
σ = stefan-Boltzmann constant

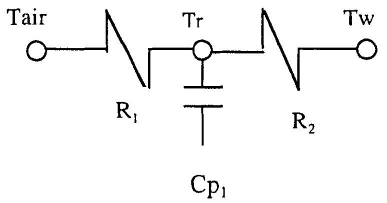
Model 1 has two equations to describe change in air temperature in the house as it relates to the change in the radiant floor/wall temperature and a fixed outside air temperature. The first equation describes the behavior of the radiant system as energy is supplied and emitted by way of convection and radiation. It includes only the mass and specific heat of the radiant system. The second equation describes the behavior of the room air temperature as it receives energy and loses it to the outside air. It includes the mass and specific heat of the air and the materials of the house.

While the house is being heated, the heating energy, **Q** (Btu/h), is supplied to the radiant wall/floor from the water tank in Eq. 4.20. The model assumes that entire wall is at a uniform temperature (in fact the actual temperature will vary in the X and Y direction, this model treats it as a lumped sum). As the temperature within the wall increases, it emits radiative and convective energy to the inside air. The convection and radiation are in a series resistance net work, which consequently over estimates that actual amount of energy emitted to the air in building. The second equation, Eq. 4.21, lumps both the room air temperatures with the materials in the house into one uniform temperature.

When the heating system is turned off, Q is equal to zero. The energy that is stored in the mass of the wall of Eq. 4.20 is emitted to air in Eq. 4.21, which will cause its temperature to a rise at first and then fall. Consequently, Model 1 functions as a lower limit on the energy emitted from the radiant system.

Model 2 (2R1C)

$$mcp\frac{DT_r}{dt} = ha(T_w - T_r) + \varepsilon\sigma a(T_w^4 - T_r^4) - ua(T_r - T_{air}) + Q \qquad \text{(Eq. 4.22)}$$



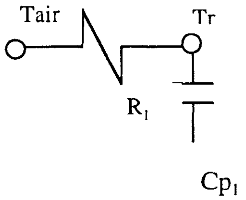
T_w = *temperature of brick wall equal to a constant*
cp_1 = *specific heat of materials in house including brick*
m_r = *mass of lumped materials in house including brick*
T_r = *temperature of room air*
R_2= *convective and radiative resistance*
R_1= *conduction resistance*

In Model 2, the radiant floor/wall is maintained at a constant temperature and contributes both convective and radiative energy to the room air. The mass, *m*, and the specific heat, *cp*, are lumped values for the house materials and radiant floor/wall. The equation is based on the assumption that the radiant system has a very large mass and does not change in temperature over twenty four hours. The increase in mass and specific heat of the lump sum temperature reduces the amount of energy that is lost to the outside air from conduction.

During night set back, as the lumped temperature decreases, (Q = 0), it gains additional energy from the convective and radiative contributions from the fixed wall temperature. Thus, it functions an upper limit on the total energy emitted from night set back.

Model 3 (1R1C)

$$mcp\frac{DT_r}{dt} = -ua(T_r - T_{air}) + Q \qquad \text{(Eq. 4.23)}$$



cp_l = specific heat of materials in house including brick wall
m_r = mass of lumped materials in house including brick wall
T_r = temperature of air
R_1 = conduction resistance, convective resistance equal to infinity
T_{air}= temperature of outside air

Model 3 is similar to Model 2 because it has a lumped-sum temperature of the room air, which includes the materials in the house, and the radiant floor/wall, and the room air. In this model, there is an infinite conductivity between the radiant system and the air or zero resistance. This indicates that all of the energy from the radiant system is transferred to the room air. Consequently, it is the same temperature. The lumped-sum-temperature changes as function of the conductive losses to the outside air. During night set back, the increase in mass and specific heat decreases the rate of conductive loss to the outside air, thus decreasing the possibility of energy savings gained by night set back. Model 3 is also an upper limit model, but slightly less than model 2 because the temperature of the radiant system is not constant.

Materials and Properties in House

h = 3 Btu/hr ft^2	%heat transfer coefficient
ua = 594 Btu/hr °f	% effective heat transfer coefficient multiplied by area (house with .2 ACH)
ua = 951 Btu/hr °f	% effective heat transfer coefficient multiplied by area (house with 2 ACH)
c1 = 1.82 Btu/lb_m°F	% specific heat of lumped materials including brick
m1= 173,157 lb_m	%mass of all material including brick wall
m2 = 143834	%mass of brick wall
tair = 20 °F	%outside air temperature
e = .93	%emissivity of brick
σ = .1714 e-8	%Stefan-Boltzmann constant

Table 4.26: Properties of Material in House

	ρ (lbm/ft^3)	C_p (Btu/lbm °F)	Th(ft)	Volume (ft^3)	Mass (lbm)
Studs	34.02	.57	.44	111.76	3802.44
Batt	1.00	0.00	.44	899.36	898.32
EPS	3.43	.29	.02	23.61	81.07
Gypsum	49.94	0.00	.05	102.2	5104.11
Brick	119.86	.20	1.00	1200	143834.11
Glass	138.9	.20	.17	104.17	14468.99
Air	.07	.24		33813.00	2448.62
*Furnishings	0.00	.33		0.00	2520
gypsum/plaster	116.12	.26	.13	432.13	50176.66
Styrofoam	1.00	0.00	.17	576.17	575.50

** Assumed that that weight of the furnishing is 120lbm per room*

Using the equations on the previous pages, the changes in the room air temperature can be calculated over a twenty four hour period. The models can simulate two cases in a home. In one case, the house is heated solely by a massive brick wall. In another case, a radiant floor heats the house. The difference in the two is dependent on the change in mass and the specific heat of the materials. One may assume that the radiant floor consists of gypsum plaster with a given thickness and a layer of Styrofoam underneath. The brick wall, on the other hand, consists of only brick of a given thickness. The two also differ in surface area.

The energy saving obtained with night set back is computed with the following equations.

$$Q_{lost} = \int_{0}^{24} ua(t_r - t_a)dt \qquad \text{(Eq. 4.25)}$$

$$Q = ua \times (t_r - t_a) \times 24 \qquad \text{(Eq. 4.26)}$$

$$Q - Q_{lost} = Q_{saved} \qquad \text{(Eq. 4.27)}$$

$$\%Q = Q_{saved} / Q \times 100 \qquad \text{(Eq. 4.28)}$$

The following graph, based on Model 1, shows the change in temperature of both the brick wall and air over a 24 hour period using night set back. In a radiant only system, the house is heated solely by the radiant wall. During the heating phase, energy supplied from the hot water tank is supplied to the tubes, which are inside of the brick wall. The energy is then radiated out to the space.

It is assumed that night set back occurs from 10 PM at night until 8 am. At 10 PM, the air temperature is 70°F and the brick wall is at 78.3°F. Exactly at 10 PM, the heating system is turned off, (Q =0) and both the brick wall and the air temperatures drop over a ten hour period. At 8am, the air temperature reaches a minimum of 67.8°F. At 8 am, the heating system is turned on ($Q \neq 0$), until the brick wall exceeds its original steady state temperature of 78.3°F. It reaches a maximum temperature of 86°F. It then drops as the air temperature rises to its original set point of 70°F. The overall energy saving over 24 hours is 1.3%.

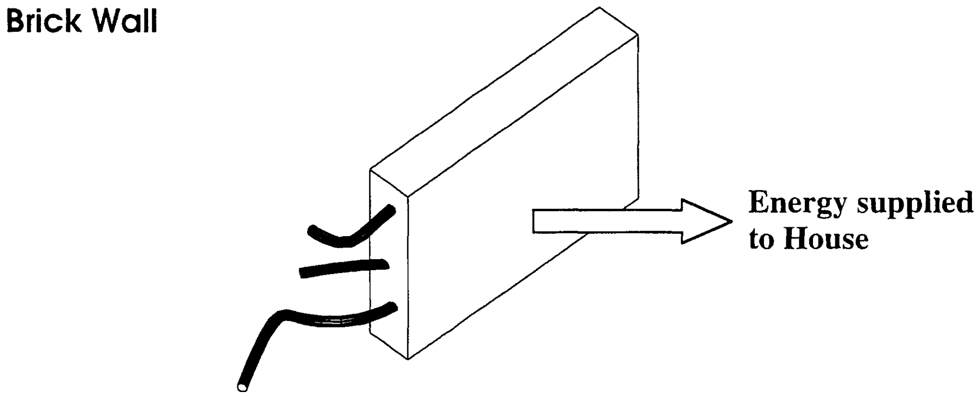


Figure 4.63

Model 1 (Room Air Temperature with Brick Wall and Night Set Back)

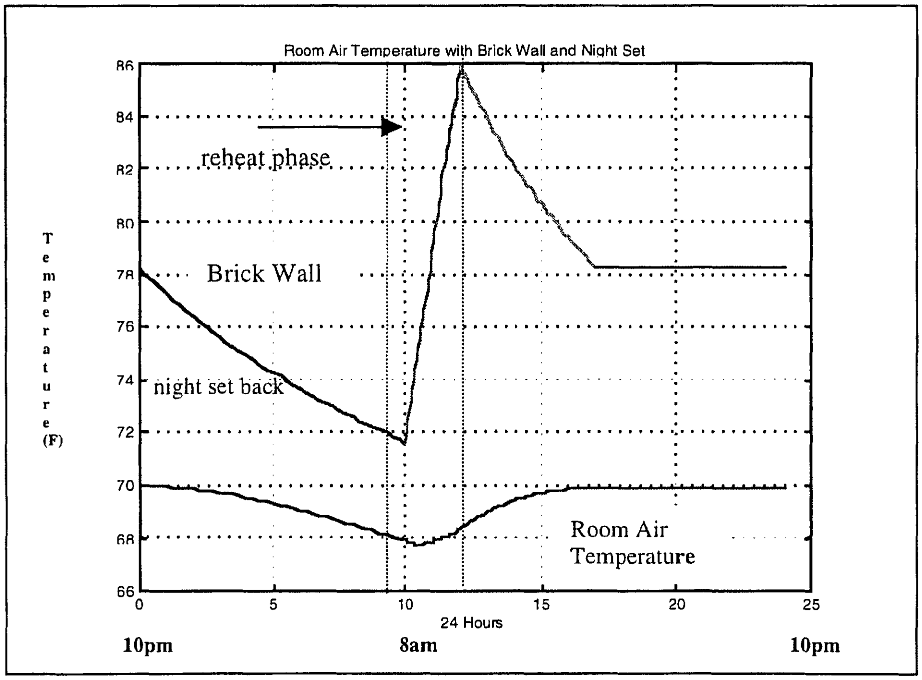


Figure 4.64

Model 1 (Room Air Temperature with Radiant Floor and Night Set Back)

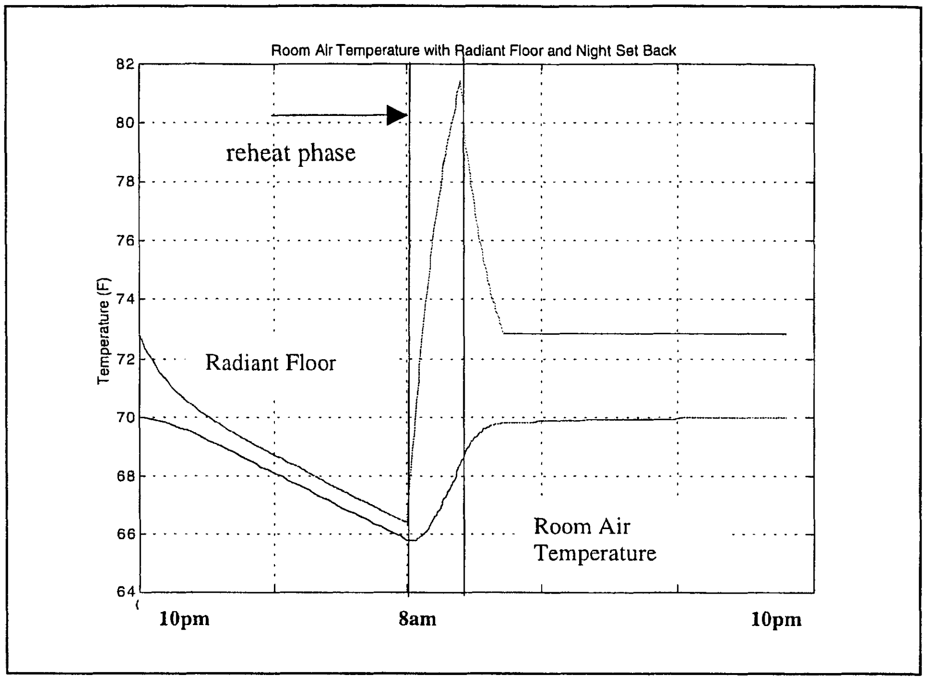


Figure 4.65

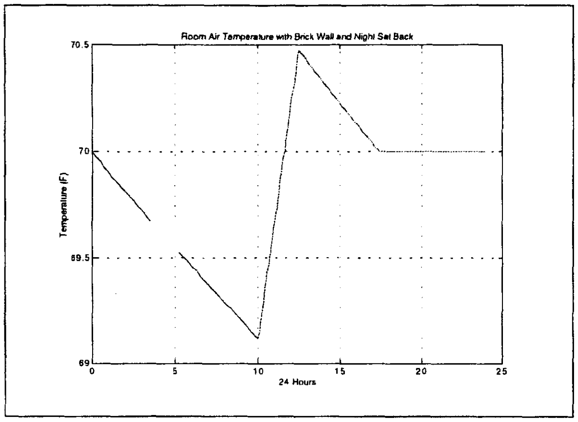
In this graph, a radiant floor is heating the house. During the reheat phase, hot water from the tank supplies the energy to the system. When the house is heated by a radiant floor, there is a faster transient response to night set back. At 8am (10 hours on the graph), the room air temperature has a minimum value of 65.8°F. During the reheat phase, the radiant floor increases to a maximum temperature of 81°F, and then decreases rapidly to its steady state temperature of 72.9°F. Unlike the brick wall, the radiant floor and room air temperature appear to move more rapidly towards convergence over a ten hour period. As a result, the overall energy saving is slightly greater with a percentage equal to 2.34%.

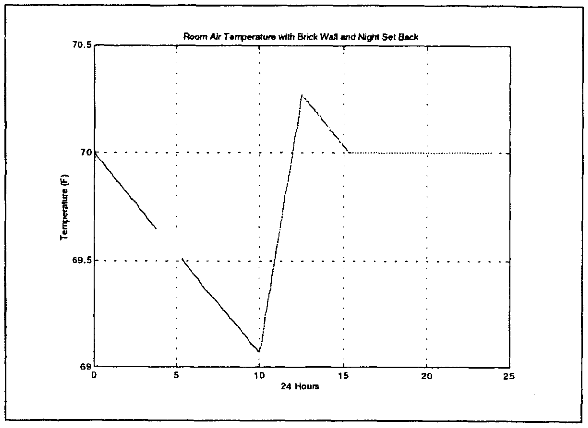
Both model 2 and model 3 show similar results when the brick wall is included in the lumped capacitance equations. Given the enormous mass of the wall, the temperature of the air decreases slightly from 70°F to 69°F over a ten-hour period. During the reheat phase, a certain percentage of the savings gained at night is reduced even further from the slight increase in air temperature. As a result, the overall saving is negligible amount of 0.5%.

Models 2 and 3 also show similar results for a house with a radiant floor. Over a ten-hour period, the room air temperature decreases from 70°F to 68°F. A minimal percentage of the savings gained at night is lost during the reheat phase in the morning. The percentage saving is 0.7%.

Model 2 shows brick wall with night set back

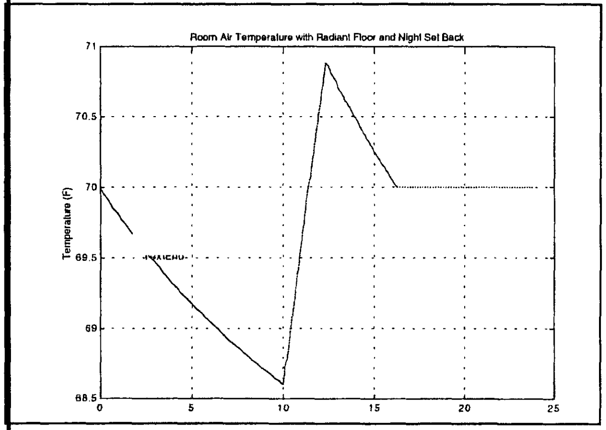
Model 3 shows brick wall with night set back

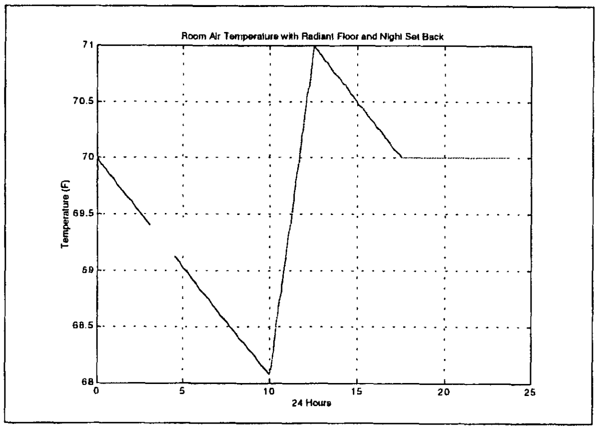




Model 2 shows radiant floor with night set back

Model 3 shows radiant floor with night set back





Time Table

0	5	10	15	20	24
10pm	3am	8am	1pm	6pm	10pm

Figure 4.66

Model 1 demonstrates a saving in the range of 1% to 2% for the radiant wall and floor, respectively. Models 2 and 3 show negligible savings in both cases. In all three models, the increase in mass cuts back on the potential energy savings gained by night set back.

When the mass of the wall is not included in the energy equations, both model 1 and model 2 are reduced to modified model 3 that excludes the mass and specific heat of the radiant wall/floor. The percentage saving is 6% for an older home with 2 ACH per hour. If the house has .2 ACH, then the savings is smaller at 3%.

Model3 (Room Air Temperature without Brick Wall and Night Set Back)

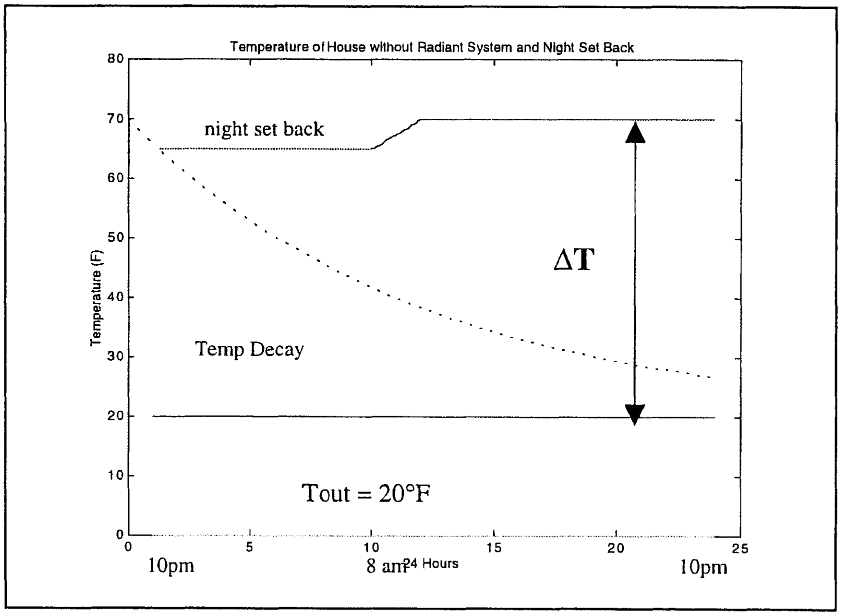


Figure 4.67

Given the enormous mass of the house, a considerable amount of energy is needed to reheat the objects and the air. Lighter frame houses have a faster response to night setback and reheat phase of the building operational dynamics, and can therefore obtain a greater energy saving from night set back.

Economics of Night Set back Versus Radiant Heating systems

The cost of installation is based on a sample home in Rhode Island (from Advanced Comfort Systems Inc). A system with the following specifications may receive the following quote from a contractor.

Table: 4.27

Total Area	4,911 ft^2	Number of floor Loops	33
Min Heat Load	50,198 Btu/Hr	Number of ceiling Loops	0
Fluid Type	100% Water	Total Number of Loops	33
Pump Requirements	10.6 gpm	Number of Zones	11
Total Quote Price			**$15,981.92**

One can assume that the quote would cost the same or greater for the Cambridge House for Sustainability. If residents maintain their thermostat at a constant temperature of 68 degrees Fahrenheit, they would obtain an energy saving around 13% when compared to the conventional forced air system. This would result in approximately $113.36 annual savings per year. A quick analysis demonstrates that although night set back is less efficient than a radiant system, it is still more cost-effective over a twenty year span.

Table: 4.28

			NPV -Capital		
	Capital($)	Annual savings($)	4%	8%	10%
Radiant system	15,981.92	113.36	-14,441.36	-14,868.95	15,016.89
Night Set Back	0.00	44.53	605.163	437.20	379.085

4.6.4 Conclusion: Radiant Heating Systems

Radiant systems can provide energy savings because residents can feel comfortable within a space at a lower thermostat setting. At a set thermostat setting of 68 degrees Fahrenheit, a 13% energy saving is attainable during a heating season. This translates to approximately $113.36 per year. Night set back, on the other hand, might provide an energy saving in the range of 3% to 6%, depending on the energy losses due to infiltration. This amount translates to an amount of approximately of $44.53 dollars per year. An comparison between the radiant system and night set back demonstrates that night set back is more cost-effective over a twenty year span because the capital cost is equivalent to zero.

Clearly, night set back is not possible when a radiant system is installed in a home.

Chapter 5 Rating System for Retrofit Measures and Optimal Analysis

5.0 Energy Savings of Retrofit Measures

The previous chapter was an analysis of the performance and cost-effectiveness of the various retrofit measures applicable to homes in the New England. This chapter rates each upgraded feature in the Cambridge House for Sustainability according to the net savings over the capital cost. Two base case models; one for Cambridge Code, and the other a 1920s home, demonstrate the varying priorities for a homeowner, interested in performing renovations with energy efficiency in mind. The most affordable measures are then added to attain a sum total of the net savings over the sum of the capital cost.

The following table compares the features of a 1920s house, a Cambridge Code house and the Cambridge House for Sustainability.

Table 5.1

	1920s House	**Cambridge Code**	**Camsus**
Building Envelope	R-Value($ft^2h°F/Btu$)	R-Value($ft^2h°F/Btu$)	R-Value($ft^2h°F/Btu$)
Vaulted Ceiling	4	30	30
Frame Walls	3	11	29
Masonry Walls	3	11	19
Below Grade Walls	0	11	13
Doors	3	3	5
Windows	1	2	3
Slab Floors	0	0	5
Infiltration (ACH)	2	.5	.2
Heating System	65% furnace	80% Furnace	GSHP
Cooling System	electric/AC	electric/AC	GSHP
Renewable Energy System	none	none	Photovoltaic
	none	none	Solar Thermal
Distribution System	radiator	radiator	radiant floor/wall
	baseboard units	baseboard units	radiant ceiling
			fan coil units

Based on the energy features above, one can assess the energy savings of each measure relative to the base case models built according to Cambridge Code and one built according to a 1920s standard.

The following two graphs show the annual energy saving of each feature. The graphs are based on the assumption that a homeowner would hire technical professionals to caulk the windows. Therefore, the cost for caulking is at an hourly rate of $100 per hour. In the 1920s base case model, it is assumed that the windows have 2 ACH per hour as opposed to .8 ACH, and the solar thermal panels provide a savings based on the medium limit (Ti = 95°F). In addition, all of the energy collected is used for both space heating and domestic hot water consumption.

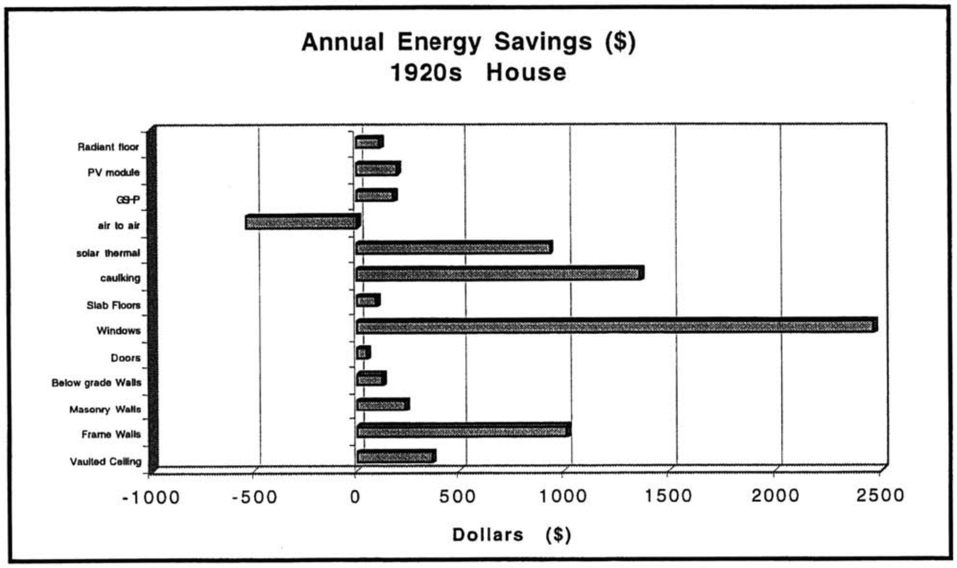


Figure 5.1

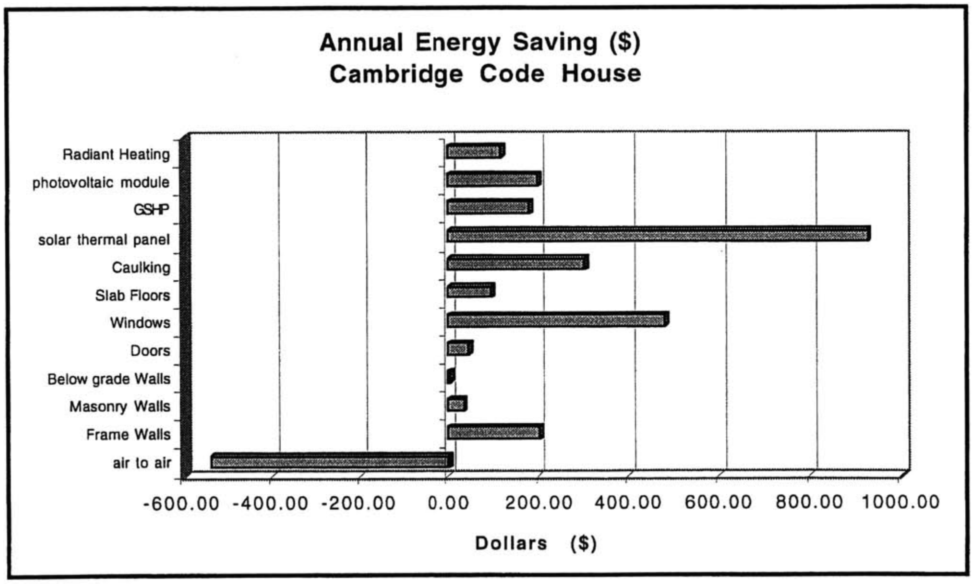


Figure 5.2

The graphs indicate that a proprietor achieves energy savings for all of the measures in the house. The largest savings come from window replacement, caulking, and the solar thermal systems. Air to Air heat pumps yield a negative annual energy savings. These systems were included in this analysis although it was not installed in the Cambridge House for Sustainability.

5.1 Rating System Analysis

An analysis of the net savings over the capital cost,(**R**), over a twenty year span can determine the cost-effectiveness of each energy feature. The following criterion is used to assess which investment yields the highest return for each dollar invested.

Rating	Commentary
$\mathbf{R} < 0$	Poor
$0 < \mathbf{R} < 1$	Modest
$1 < \mathbf{R} < 5$	Good
$5 < \mathbf{R} < 10$	Very good
$10 < \mathbf{R}$	Excellent

A poor rating indicates that a proprietor has lost on his investment. A rating between 0 and 1 indicates that he/she obtains a meager profit or breaks even over twenty years. A (**R**) of 10 or greater indicates that the homeowner obtains a net savings that is ten times greater for every dollar invested. The following tables rate each feature according to the three interest rates (4%, 8%, and 10%) for the two base case models. In addition, the tables take into to account two cases for the solar thermal system. In one case, all of the energy collected is used for both domestic hot water and space heating. In the other, the solar thermal system is used for only domestic hot water. The net present value analysis is also based on two initial costs for the ground source heat pump: the capital cost with inside ductwork, and the other without ductwork.

Retrofit Measures at Present Energy Costs for Base Case 1(Cambridge Code)

Table 5.2: 4% Interest Rate

Hierarchy	Rating (R)	Comments
Doors, R-5	11.50	excellent
Caulking	3.04	Good
Solar Thermal	1.09	Good
Masonry walls, R-19	.98	Modest
Frame walls, R-29	.28	Modest
Slab Floor, R-5	.17	Modest
Solar Thermal (DHW)*	.03	Modest
Below grade Walls, R-13	-.28	Poor
PV Module	-.72	Poor
Windows replacement	-.73	Poor
GSHP (no duct work)	-.84	Poor
Radiant floor	-.90	Poor
GSHP (duct work)	-.93	Poor
air to air	-1.26	Poor

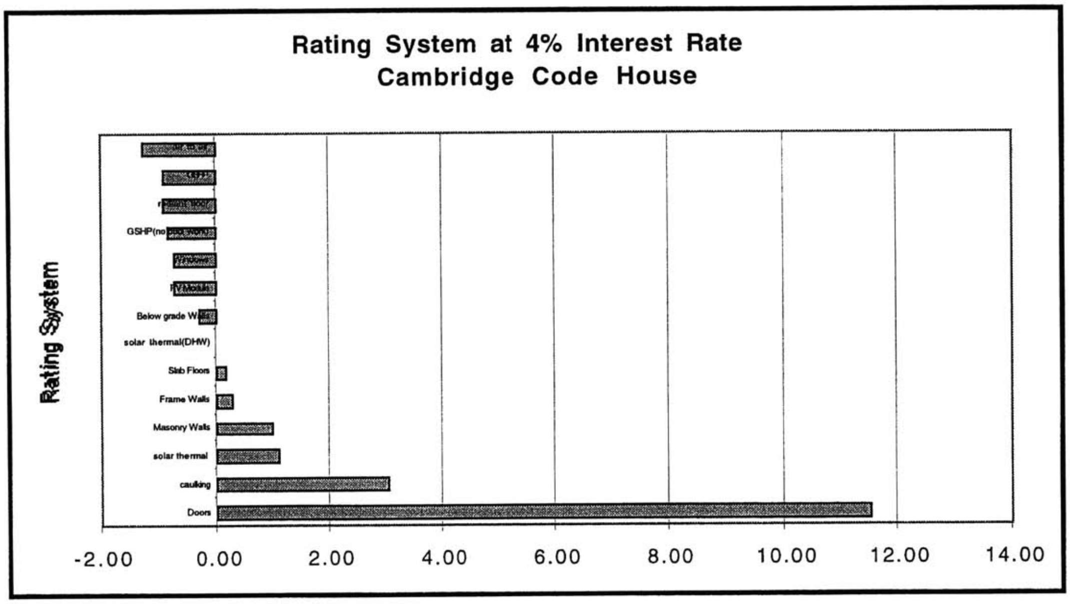


Figure 5.3

At a 4% rate, the most cost-effective measures for retrofitting is the insulation of the doors. Given the small initial cost, the net present value of the saving results in a huge profit margin. The second most cost-effective measure is the investment in the reduction of infiltration, caulking. Solar thermal systems for domestic hot water and space heating are also cost-effective with good savings. The solar domestic hot water system is the least of all profitable of all of the measures that rate above zero.

Among the measures that rate below zero, the insulation of the below grade walls was more cost-effective than window replacement. In addition, the investment in the photovolatic system was more affordable than the ground source heat with or without ductwork.

Retrofit Measures at Present Energy Costs for Base Case 1(Cambridge Code)

Table 5.3: 8% Interest Rate

Hierarchy	Rating (R)	Comments
Doors , R-5	8.03	Very good
Caulking	1.92	Good
Solar Thermal	.51	Modest
Masonry walls, R-19	.43	Modest
Frame walls, R-29	-.08	Poor
Slab Floor, R-5	-.15	Poor
Solar Thermal (DHW)*	-.26	Poor
Below grade Walls, R-13	-.48	Poor
PV Module	-.80	Poor
Windows replacement	-.81	Poor
GSHP (no duct work)	-.88	Poor
Radiant floor	-.93	Poor
GSHP (duct work)	-.95	Poor
air to air	-1.18	Poor

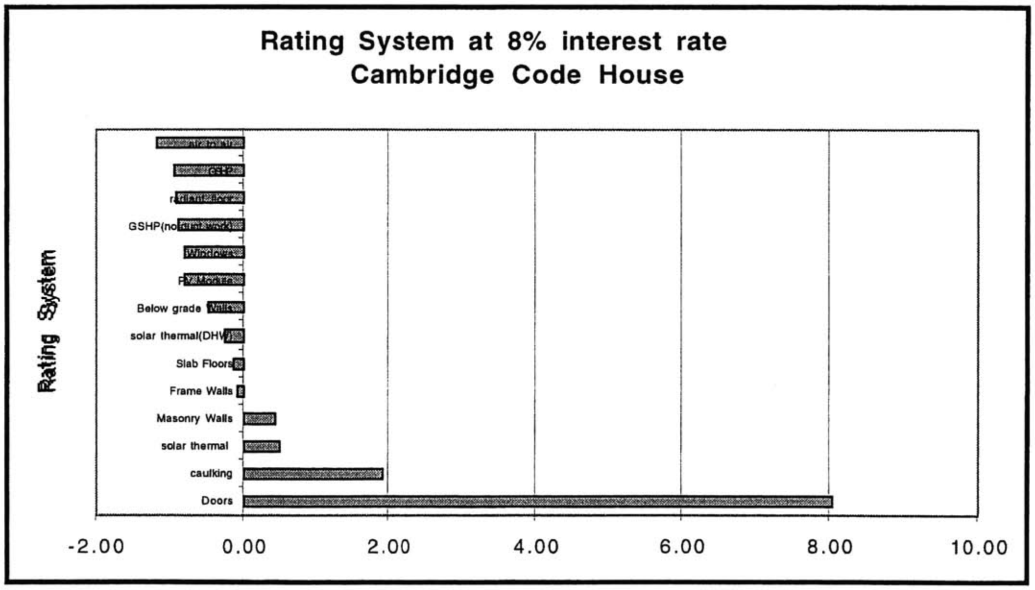


Figure 5.4

At an 8% interest rate, the only measures that rate above zero are the doors, the caulking of windows, the solar thermal system for both space heating and domestic hot water use, and the masonry walls. Clearly, at higher interest rates, the modest measures at a 4% interest are no longer cost-effective at higher interest rates. Interestingly, a homeowner of a Cambridge code house stands to gain the most from caulking windows and insulating doors than the insulation of the walls.

Retrofit Measures at Present Energy Costs for Base Case 1(Cambridge Code)

Table 5.4: 10% Interest Rate

Hierarchy	Rating (R)	Comments
Doors , R-5	6.83	Very good
Caulking	1.53	Good
Solar Thermal	.31	Modest
Masonry walls, R-19	.24	Modest
Frame walls, R-29	-.20	Poor
Slab Floor, R-5	-.27	Poor
Solar Thermal (DHW)*	-.36	Poor
Below grade Walls, R-13	-.55	Poor
PV Module	-.82	Poor
Windows replacement	-.83	Poor
GSHP (no duct work)	-.90	Poor
Radiant floor	-.94	Poor
GSHP (duct work)	-.96	Poor
air to air	-1.16	Poor

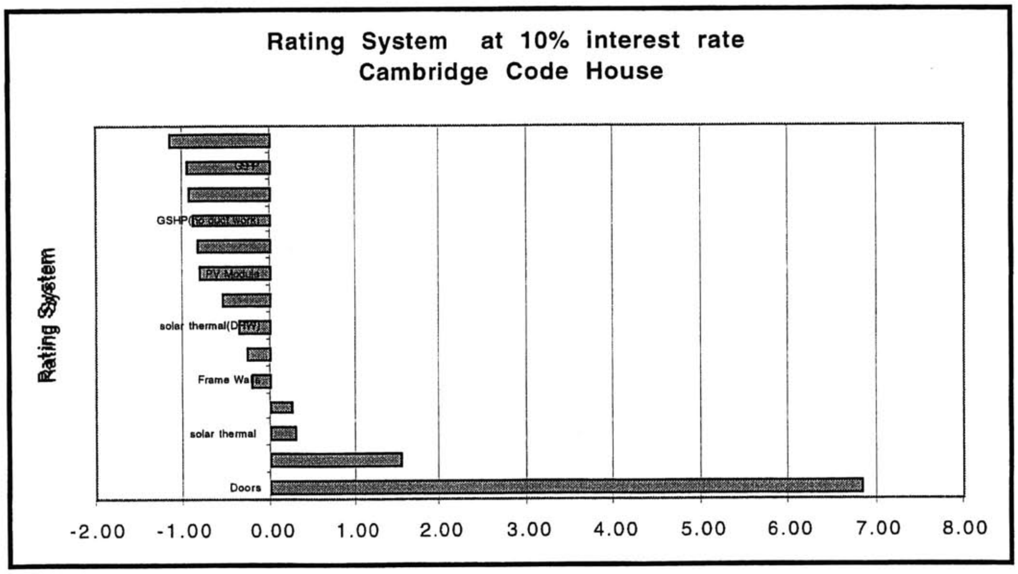


Figure 5.5

At a 10% interest rate, the only measures that rate above zero are the insulation of doors, the caulking of windows, the installation of a solar thermal system, and the insulation of the masonry walls. Clearly, these measures are the most affordable at all three interest rates.

Retrofit Measures at Present Energy Costs for Base Case 2(1920s)

Table 5.5: 4% Interest Rate

Hierarchy	Rating (R)	Comments
Caulking	17.34	Excellent
Doors, R-5	11.50	Excellent
Masonry Walls, R-19	5.91	Very Good
Frame Walls, R-29	3.46	Good
Vaulted Ceiling, R-30	2.32	Good
Below Grade Walls, R-13	1.61	Good
Solar Thermal	1.09	Good
Window replacement	.39	Modest
Slab Floors, R-5	.17	Modest
Solar Thermal (DHW)	.03	Modest
PV Module	-.72	Poor
GSHP (no duct work)	-.84	Poor
Radiant Floor	-.90	Poor
GSHP	-.93	Poor
Air to Air	-1.26	Poor

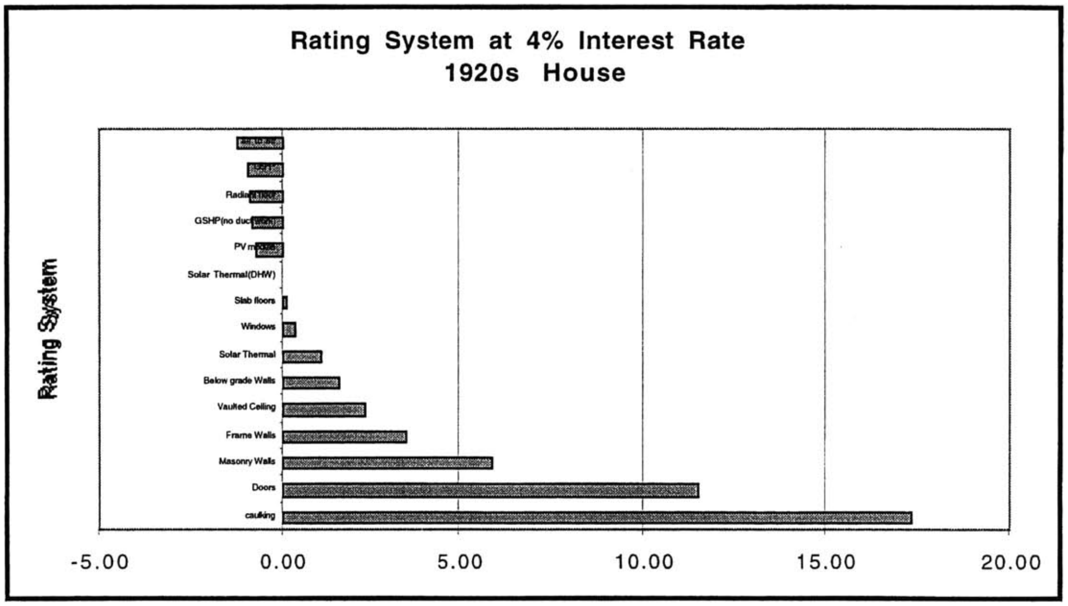


Figure 5.6

In a 1920s home (at a 4% interest rate), a proprietor gains the most by caulking windows, insulating doors, masonry walls, frame walls, vaulted ceiling, below grade walls and slab floors. The installation of a solar thermal system for space heating and domestic hot water yields a good profit over twenty years. Interestingly, the replacement of windows has a modest rating equivalent to 0.39. This would correspond to the upgrade of a single glazed window with 2ACH to double glazed (low-e) window. Of all the measures that rate above zero, the solar system for only domestic hot water, and the insulation of the slab floors is the least cost-effective.

Retrofit Measures at Present Energy Costs for Base Case 2(1920s)

Table 5.6: 8% Interest Rate

Hierarchy	Rating (R)	Comments
Caulking	12.25	Excellent
Doors, R-5	8.03	Very Good
Masonry Walls, R-19	4.00	Good
Frame Walls, R-29	2.24	Good
Vaulted Ceiling, R-30	1.40	Good
Below Grade Walls, R-13	.88	Modest
Solar Thermal	.51	Modest
Window replacement	0.00	Poor/Modest
Slab Floors, R-5	-.15	Poor
Solar Thermal (DHW)	-.26	Poor
PV Module	-.80	Poor
GSHP (no duct work)	-.88	Poor
Radiant Floor	-.93	Poor
GSHP	-.96	Poor
Air to Air	-1.18	Poor

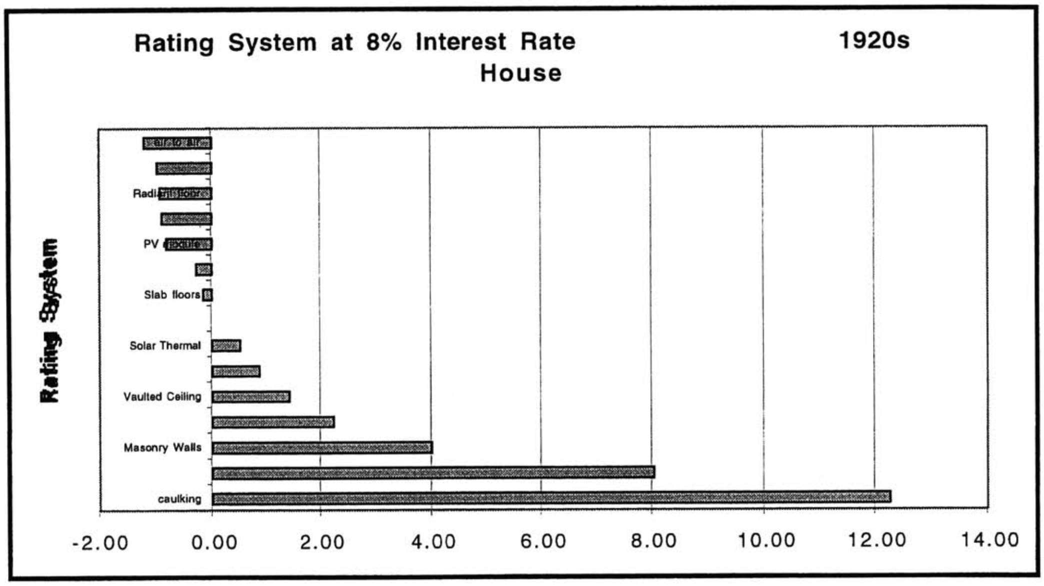


Figure 5.7

At an 8% interest rate, the profitable measures are the caulking of windows, insulating doors, masonry walls, frame walls, vaulted ceiling, below grade walls and the installation of the solar thermal system for both domestic hot water and space heating. Replacement of windows yields a rating equivalent to zero. This indicates that a homeowner breaks even on his/her investment over a twenty-year span. The insulation of the slab floors is not longer cost-effective at higher interest rates. Apparently the energy savings is not enough for the measure to be economical. The slab floor comprised only 6% of the overall annual energy bill and the insulation of R-5 yielded only a 6% reduction in the annual energy cost. (Chapter 4).

Retrofit Measures at Present Energy Costs for Base Case 2(1920s)

Table 5.7: 10% Interest Rate

Hierarchy	Rating (R)	Comments
Caulking	10.49	Excellent
Doors, R-5	6.83	Very Good
Masonry Walls, R-19	3.33	Good
Frame Walls, R-29	1.81	Good
Vaulted Ceiling, R-30	1.08	Good
Below Grade Walls, R-13	.63	Modest
Solar Thermal	.31	Modest
Window replacement	-.13	Poor
Slab Floors, R-5	-.27	Poor
Solar Thermal (DHW)	-.36	Poor
PV Module	-.82	Poor
GSHP (no duct work)	-.90	Poor
Radiant Floor	-.94	Poor
GSHP	-.96	Poor
Air to Air	-1.16	Poor

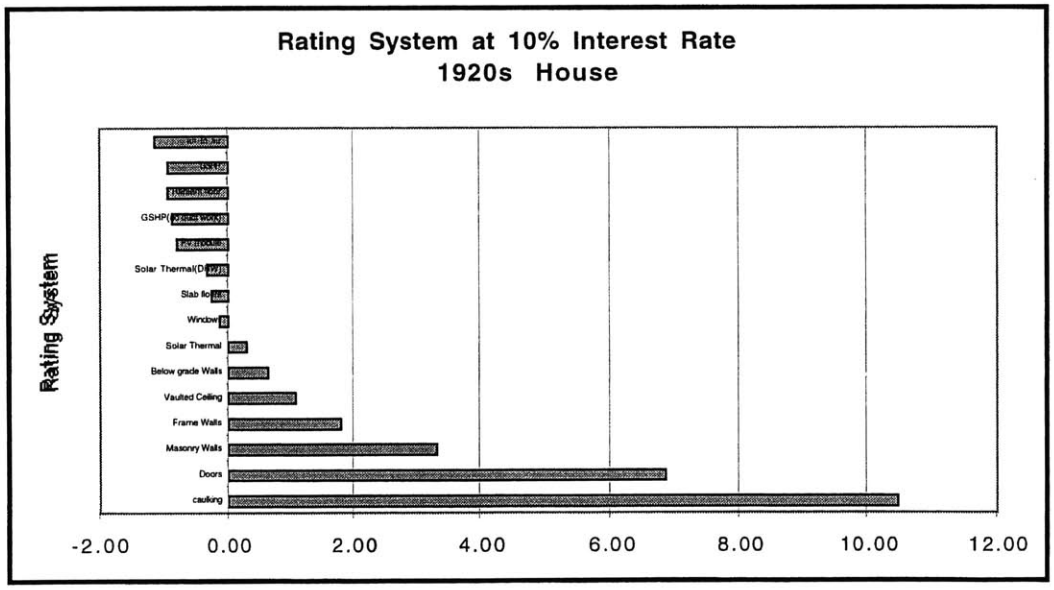


Figure 5.8

Apparently, the most cost-effective measures at all three interest rates are the following: caulking of windows, insulation of doors, masonry walls, frame walls, vaulted ceiling, below grade walls and the installation of the solar thermal system both space heating and hot water.

The measures that rate below zero are the following: the replacement of windows, the insulation of the slab floor, the solar thermal system for domestic hot water, the photovoltaic system, the ground source heat pumps with or without ductwork, the radiant heating system and the air to air heat pumps.

5.2 Rating System at 8% Interest Rate vs. %Savings

The following section compares the rating of each upgraded feature of the building envelope at a fixed interest rate to the relative percentage reduction of the energy bill for space heating and cooling. The Y axis on figure 5.9 shows the percentage savings from each retrofit measure relative to the Cambridge Code standard. The X axis shows the rating system of each upgraded measure at an 8% interest rate. For example, based on the analysis in Chapter 4, the insulation of the frame walls (Cambridge Code) from an r-value of 11 to an r-value of 29 yielded a 10% reduction in the annual heating and cooling cost. Based on the rating system at 8%, the (R) rating was equivalent to -0.08. The most beneficial retrofit measures have a high rating and percentage reduction in energy costs. Therefore, they are located in the upper right region of the graph.

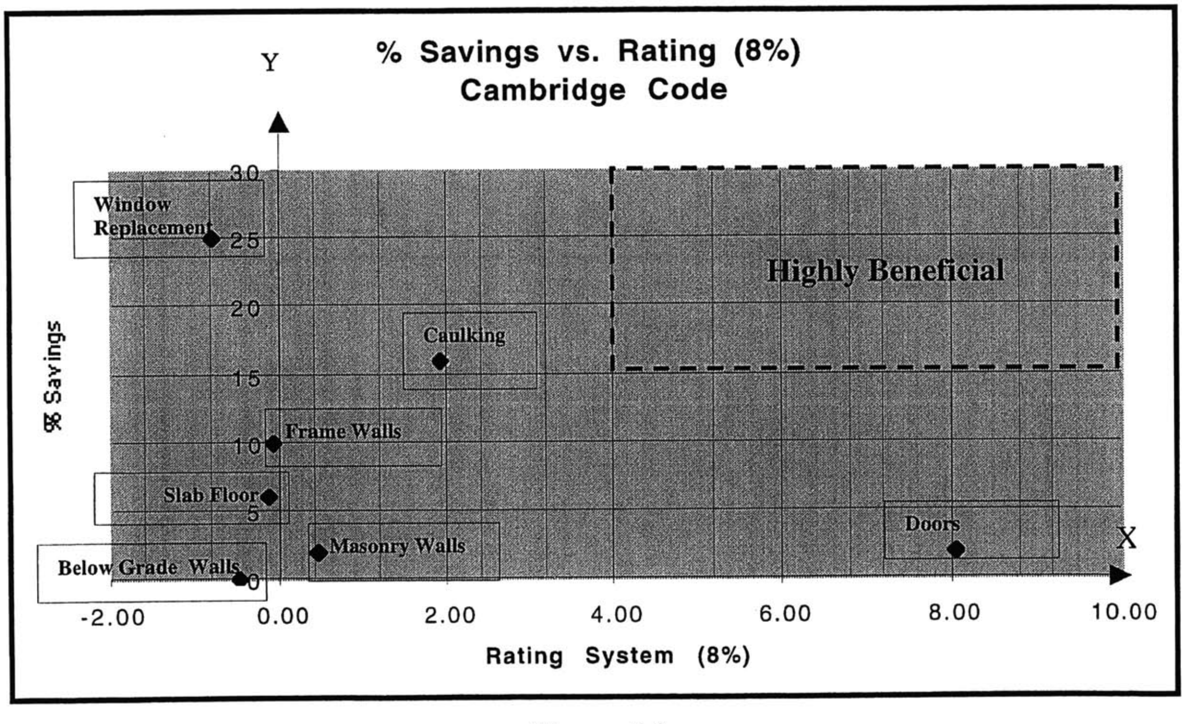


Figure 5.9

Based on Figure 5.9, the insulation of doors reduces the annual heating and cooling costs by only 2%. On the other hand, it yields the highest rating (R) rating of all of the retrofit measures of 8.03. This indicates that insulation of doors is a cost-effective measure, but does not significantly reduce the energy bill. Infiltration through the windows accounts for approximately 26% of the energy bill. When the windows are caulked or weather-stripped, it can reduce the energy bill by 16% and achieve a "good" rating of 1.92. Therefore, it is a very reasonable investment for a homeowner. The replacement of windows reduces the total energy bill by 25%. However, it has a rating (R) of -0.81, indicating that a "poor" retrofit measure.

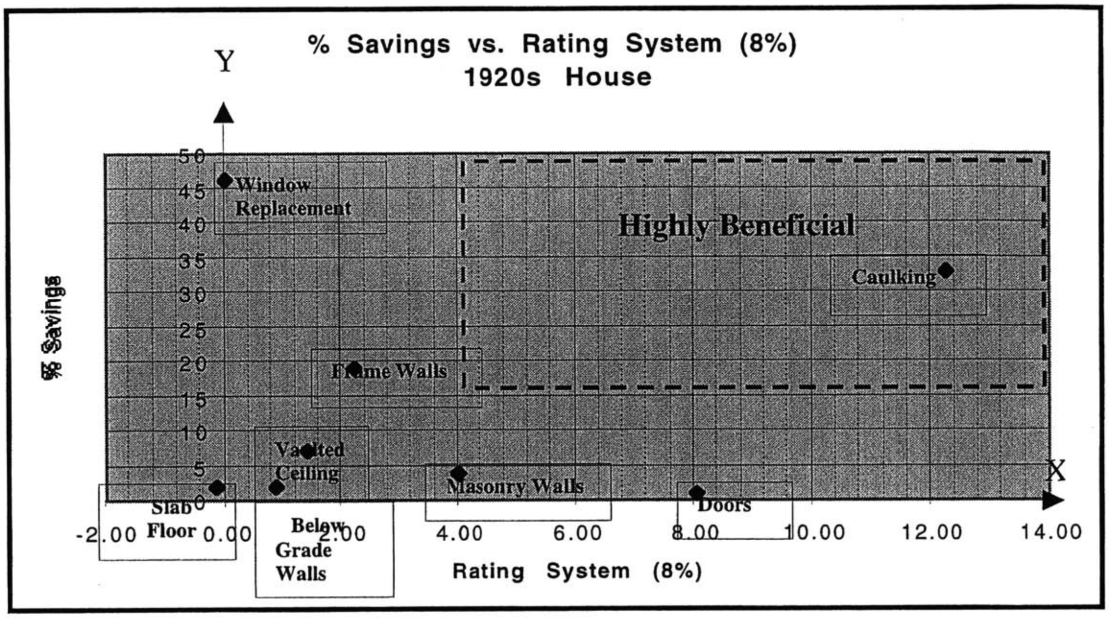


Figure 5.10

The same analysis is applicable to a 1920s home. Infiltration through windows accounts for approximately 37% (2 ACH) of the total energy bill for heating and cooling. When the windows are caulked or weather-stripped, it can reduce the annual energy cost by 33%. In addition, caulking yields an excellent rating of 12.25. Clearly, caulking is highly beneficial retrofit measure. Although the insulation of the doors yields a high rating of 8.03, it yields a 1% reduction in the energy bill for heating/cooling. The insulation of frame walls reduces the annual energy bill by 19% and yields a positive rating of 2.24. Therefore, it is a good retrofit measure for a 1920s home.

Although window replacement can reduce the energy bill by 46%, the rating at 8% interest is equivalent to zero, indicating that a homeowner breaks even on his investment. He/she obtains a modest rating at a 4% interest and will have negative net savings at a 10% interest rate.

5.3 Affordable Retrofit Measures

The most affordable retrofit measure for a base case 1 model (Cambridge Code home) has the following hierarchical order. Affordable is defined as any (**R**) rating that exceeds zero

Base Case 1 Cambridge Code

Table 5.8: Affordable Retrofit Measure Base Case 1

4%	8%	10%
Doors, R-5	Doors, R-5	Doors, R-5
Caulking	Caulking	Caulking
Solar thermal	Solar Thermal	Solar Thermal
Masonry Walls, R-19	Masonry Walls, R-19	Masonry Walls, R-19
Frame Walls, R-29		
Slab Floors, R-5		
Solar Thermal (DHW)		

Base Case 2 1920s

Table 5.9: Affordable Retrofit Measure Base Case 2

4%	8%	10%
Caulking	Caulking	Caulking
Doors, R-5	Doors, R-5	Doors
Masonry Walls, R-19	Masonry Walls, R-19	Masonry Walls, R-19
Frame Walls, R-29	Frame Walls, R-29	Frame Walls, R-29
Vaulted Ceiling, R-30	Vaulted Ceiling, R-30	Vaulted Ceiling, R-30
Below grade walls, R-13	Below grade walls, R-13	Below grade walls, R-13
Solar Thermal	Solar Thermal	Solar Thermal
Window Replacement	Window replacement	
Slab Floors, R-5		
Solar Thermal (DHW)		

When the sum of net savings of the affordable retrofit measures is divided by the sum total of the cost, one can obtain the total net savings over a twenty year span for every dollar investment at the three different interest rates. The capital cost at each interest rate varies with the net savings. In addition, the varying costs for the 1920s house are different from the costs of the Cambridge Code house.

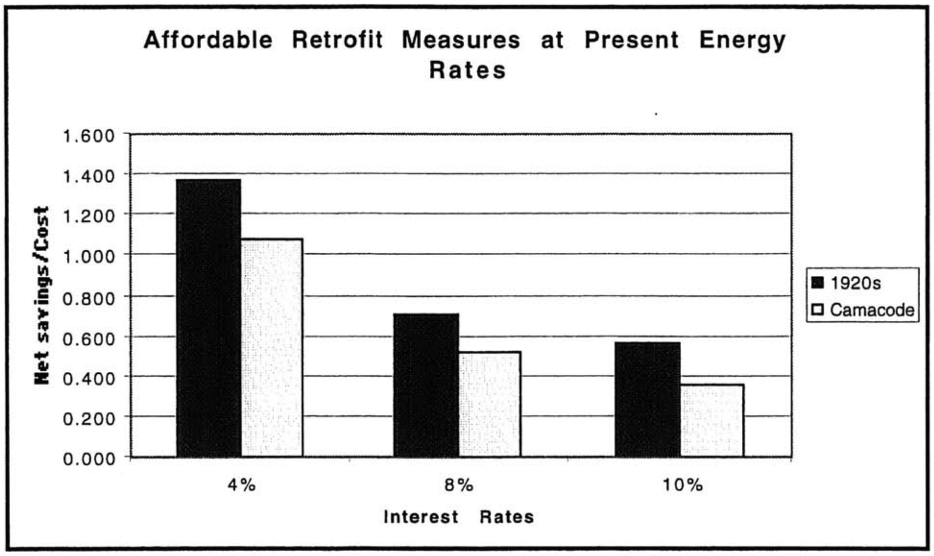


Figure 5.11

The 1920s windows are only marginally affordable at 4% and 8% interest rate; however they comprise almost half of the capital cost. At a 10% interest rate, the capital cost is decreased significantly because the windows are no long cost-effective.

In both cases, the investments in caulking and the insulation of doors yielded the highest return all interest rates. In addition, the solar thermal system (for both domestic hot water and space heating), the insulation of the masonry walls were also the most cost-effective at all three interest rates for both base case models. In the Cambridge code house, many of the cost-effective measures at a 4% interest rate such as the insulation of the frame walls, slab floor and the solar thermal system for domestic hot water only were not affordable at an 8% and 10% interest rate. This indicates that the energy savings are not large enough for these upgrade measures to be affordable. Therefore, a homeowner of a Cambridge Code home that already has frame walls with an insulation level of R-11 may withhold from upgrading to R-29 until there is an increase in the energy rates.

A 1920s homeowner has the most to gain by retrofitting a home, and can obtain a higher net savings overall when compared with the Cambridge Code owner. (Figure 5.11) Most of the improvements to the building envelope were cost-effective at all three interest rates such as the caulking of windows, the insulation of door, masonry walls, frame walls, vaulted ceiling, below grade walls, and the solar thermal system. All of these measures are cost effective at the present energy rates.

Clearly, there are more retrofit options for a 1920s home in comparison to a Cambridge Code home. A Cambridge code homeowner can afford to wait and have a more conservative approach toward his investments because his returns are not as great.

Sum Total of all Retrofit Measures/ Sum Total of Cost

Apparently, the summation of the retrofit measures performed on the building envelope of the Cambridge Code house is not affordable at current energy rates. When the net saving of every energy feature in the house is divided by the sum total of the capital cost, it shows a substantial loss overall. Many of the gains were negated by the losses to yield a negative saving for the sum total of the retrofit measures. The solar thermal system was the only measure that yielded a rating above zero.

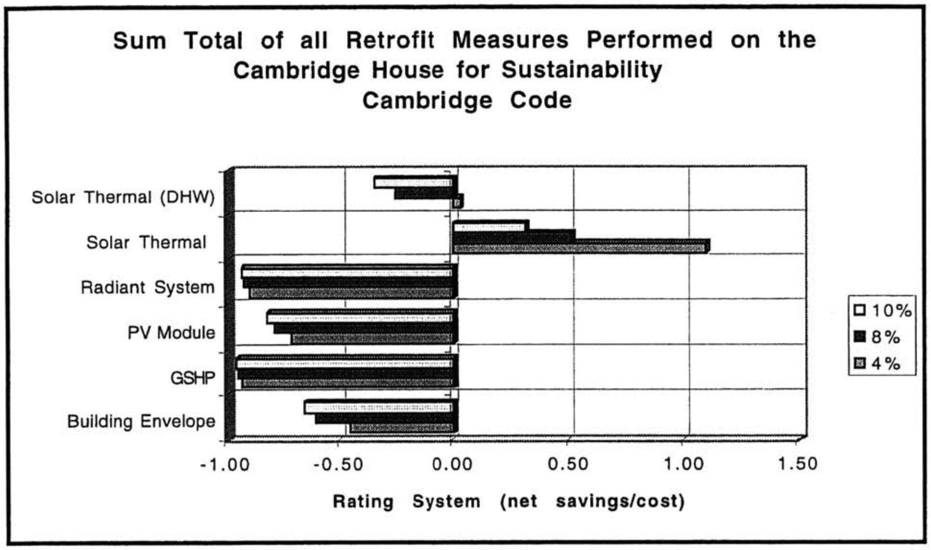


Figure 5.12

The following table gives an estimate on the energy savings gained from all of the retrofit measures performed on a house built according to Cambridge Code.

Table 5.10: Energy Costs

	Cambridge Code	Cambridge(Sus)	(%) Savings
Heating	1641.55	749.34	54%
Cooling	313.62	131.12	58%
Water Heating	455.66	<117.74*	74% or more
Electrical Load	1485.76	1292.61	13%
Total	3896.59	2291.01	**41%**

When all of the retrofit measures are performed on the house (building upgrade, installation of solar thermal system, radiant heating system, ground source heat pump and photovoltaic module system), the total annual saving is 41% when compared to the Cambridge code base case model. The medium to upper limits of performance of solar thermal system demonstrate that it could potentially meet the entire hot water demands; thus decreasing the water heating bill to $ 0 . However, the calculations in chapter 4 were based on average solar radiation data. Given the unpredictability of weather data, it assumed in this table that these panels produce a minimum of 12 KBtus per panel per day, for the entire year. If in fact, the solar system did meet the entire load, then the overall saving would increase to 44% annually. In addition, calculations in table 5.10 assume that the solar system is used only for domestic hot water heating. There is a possibility that the excess solar energy produced during certain times of the year can reduce space heating by 11 % to 21%. These calculations do not take into account a possible percentage savings from the radiant heating system.

In the 1920s base case model, the retrofit measures performed in the Cambridge House for Sustainability fare better.

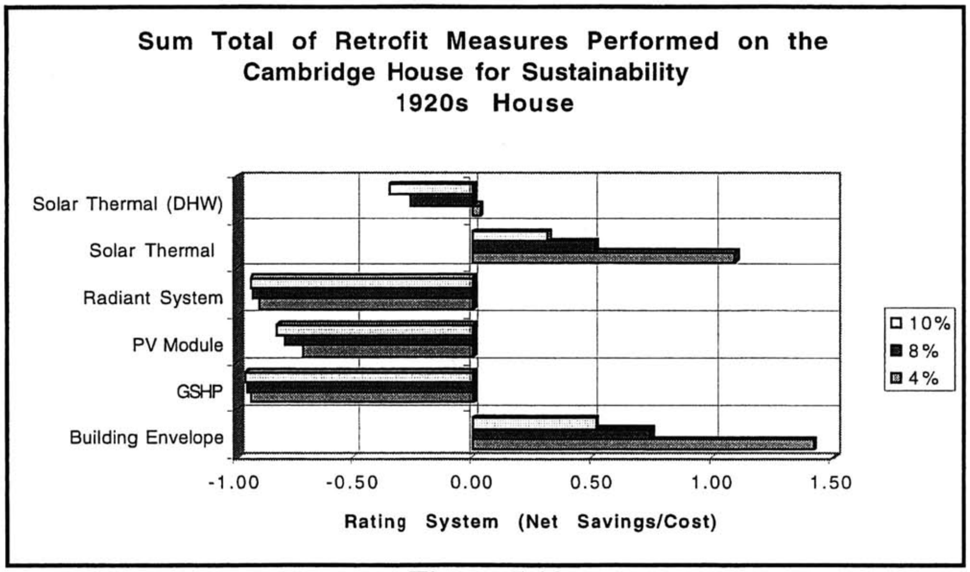


Figure 5.13

Table 5.11: Energy Costs

	1920s House	Cambridge(Sus)	(%) Savings
Heating	3709.41	749.34	80%
Cooling	615.53	131.12	79%
Water Heating	455.66	<117.74	74% or more
Electrical Load	1485.76	1292.61	13%
Total	6266.36	2291.01	**63%**

The overall energy savings of a 1920s home upgraded to the level of the Cambridge House for Sustainability yields an overall energy cost saving of 63%. Unlike the Cambridge Code house, the insulation investments in the building envelope yielded a profitable margin at all three interest rates. Although not all of the individual upgraded features are cost-effective, the profitable measures are greater than the non cost-effective measures. When the sum total of the net savings was added and then divided by the capital cost, it yielded a rating greater than zero at the varying interest rates. The largest profit margin came from the reduction of infiltration and the insulation of frame walls, which were greater than the financial loss from the window replacement. The other energy features such as the ground source heat pump, photovoltaic module system, and the radiant system were not cost-effective.

5.4 Optimal Levels of Investment at Present Energy Rates

At present energy rates, the following upgrade measures are the most optimal:

Optimal Base Case 1 Cambridge Code House

Table 5.12: Optimal

4%	8%	10%
Caulking	Caulking	Caulking
Doors, R-13	Doors, R-11	Doors, R-9
Slab Floors, R-14	Slab Floor, R-14	Slab Floor, R-14
Frame Walls, R-20	Frame Walls, R-17	Frame Walls, R-16
Masonry Wall, R-20	Masonry Walls, R-17	Masonry Walls, R-16
Solar Thermal, tilt angle 53°	Solar Thermal , 53°	Solar Thermal, 53°
Solar Thermal, (DHW)		
Furnace replacement, 65% to 96%		

The optimal analysis takes into consideration the most affordable measures that yield the largest net savings. An optimal insulation level is defined as the maximum net present value of the annual savings minus the capital cost over a twenty year span. Based on the ranking system analysis, it is clear that ground source heat pumps, radiant heating systems, and photovoltaic modules are not economical at present energy rates. Therefore, they are not included in this analysis. The solar thermal system with a tilt angle of 53° maximizes the winter solar radiation and minimizes the summer radiation. A tilt angle of 53° optimizes the performance of the solar thermal domestic hot water system such that it fares slightly better a 4% rate in comparison to system with a tilt angle of 29.7°.

If the most optimal improvements were performed on the building envelope of the Cambridge House for Sustainability (Cambridge Code base case model), it would reduce the heating and cooling load in the range of 40% to 43% depending on the interest rates. The following graph shows rating of the sum total of the improvements on the building envelope in comparison to the solar thermal systems, and furnace replacement. At optimal levels, building envelope investments yields a positive rating indicating that a homeowner has a net gain over a twenty year span.

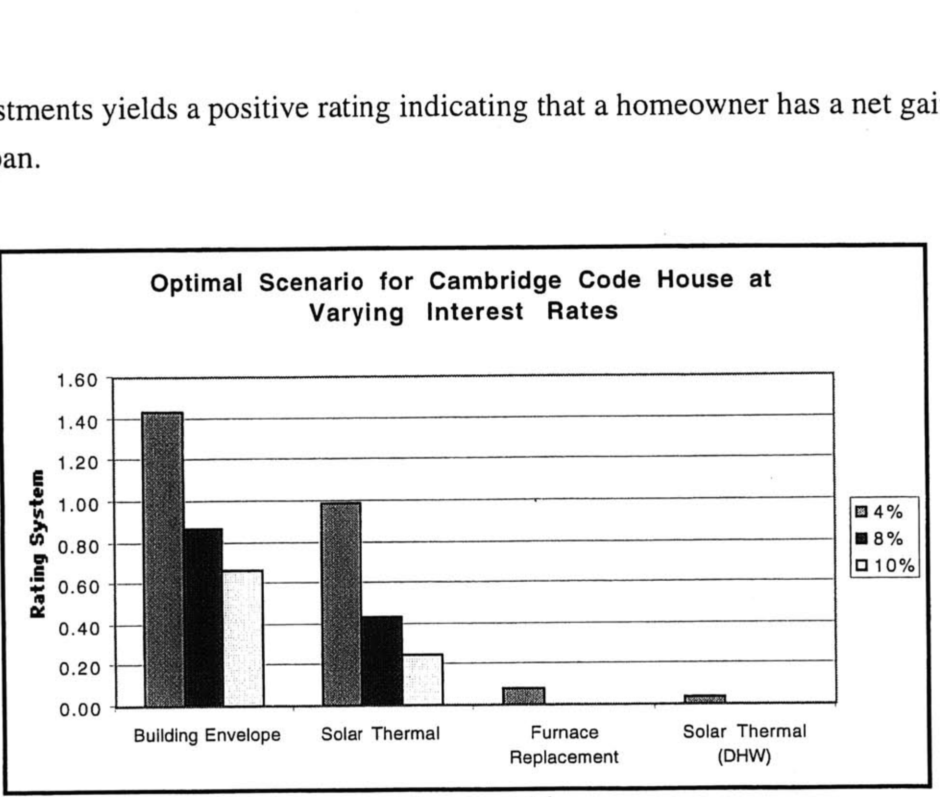


Figure 5.14

The following table estimates the annual percentage savings for the entire house if all of the optimal improvements were made to the building envelope and a solar domestic hot water system was installed in the house. The overall saving is 30%. The analysis is based on the assumption that a homeowner can obtain a 43% saving (at 4% interest) on the heating and cooling load of the house. The solar domestic hot water system at a tilt angle of 53° can potentially meet the entire domestic hot water demand. However, this calculation assumes the panels have a minimal performance of 12KBtus per panel per day. If in fact, the solar domestic hot water system did meet the entire load, then the overall savings would increase to 33%.

Table 5.13: Optimal Improvement of Cambridge code House

	Cambridge Code	**Optimal**	**(%) Savings**
Heating/cooling load	1955.17	1114.45	43%
Water Heating	455.66	<117.74*	74% or more
Electrical Load	1485.76	1485.76	0%
Total	3896.59	2776.59	**30.2%**

Optimal Base Case 2 : 1920s House

Table 5.14: Optimal 1920s

4%	8%	10%
Caulking	Caulking	Caulking
Vaulted Ceiling, R-20	Vaulted Ceiling, R-17	Vaulted Ceiling, R-16
Frame walls, R-20	Frame Walls, R-17	Frame Walls, R-16
Masonry walls, R-20	Masonry Walls, R-17	Masonry Wall, R-16
Doors, R-13	Doors, R-11	Doors, R-9
Slab Floors, R-14	Slab Floors, R-14	Slab Floors, R-14
Below grade walls, R-13	Below grade walls, R-13	Below grade walls, R-5
Solar Thermal	Solar Thermal	Solar Thermal
Solar Thermal (DHW)		
Furnace replacement, 65% to 96%		

If the optimal improvements were made to the building envelope, then a homeowner would achieve a 59% to 61% reduction in the heating and cooling load. If the furnace was replaced and downsized to meet the load reduction in the building envelope, he/she would obtain an additional percentage reduction in the annual heating and cooling bill. The following graph shows the optimal scenario for the Cambridge house based on the 1920s base case standard with 2 ACH air changes per hour.

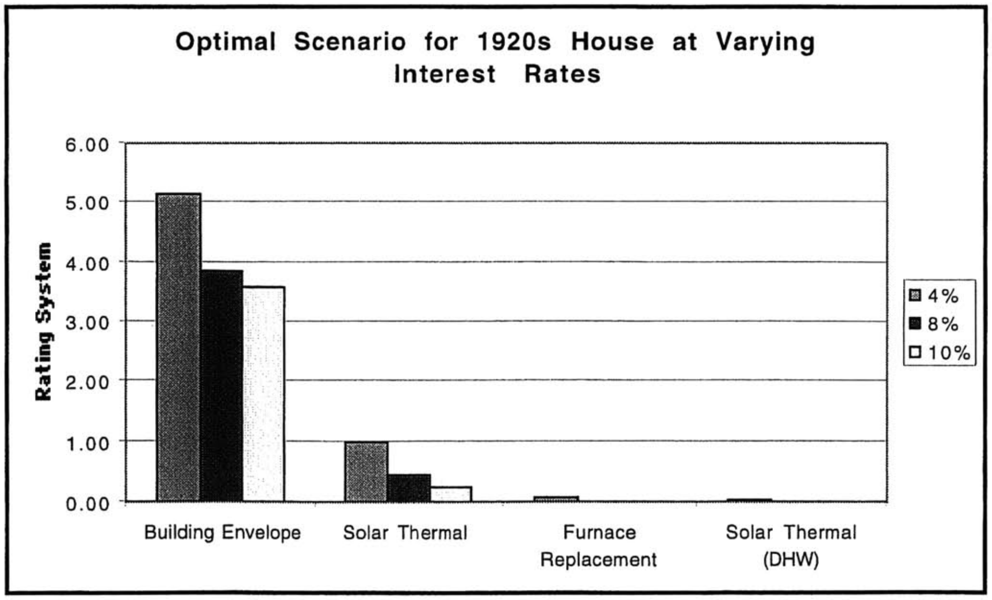


Figure 5.15

Table 5.15: Optimal Analysis for 1920s House

	1920s House	Optimal	(%) Savings
Heating/Cooling	4324.94	1282.28	70%
Water Heating	455.66	<117.74	74% or more
Electrical Load	1485.76	1485.76	0%
Total	6266.36	2885.78	**54%**

At a 4% interest rate, a proprietor would achieve a 61% reduction in the heating and cooling load bill. The replacement of the furnace would add an additional 9% reduction; thus, the sum total is 70%. The insulation improvement combined with the performance of the solar thermal system would reduce the annual energy bill by 54%.

5.5 Affordable Measures at Higher Energy Prices

At current energy rates, photovotaic systems and ground source heat pumps are not economical in New England. Based on the analysis in Chapter 4, both systems require a fuel increase for the net present value of the saving to equal the capital cost. Prices are based on the lower bound estimates.

Table 5.16: Fuel Increase Required for Net Present Value to Equal Cost

	\$/kWh(4%)	\$/kWh(8%)	\$/kWh(10%)
Photovoltaic System	.43	.59	.69
GSHP	.73	1.01	1.17

The following graph estimates the number years for the net present value of the savings to equal the capital cost at varying percentage increases in electricity price if the interest rate is fixed at 8%.

Table 5.17: Increase in Electricity Price over a # of Years

	5% increase in Annual electricity Price, # of years	10% increase in Annual electricity Price, # of years	15% increase in Annual electricity Price, # of years
Photovotaic System	79	40	26
GSHP	148	74	49

The following graphs show some projections on electricity prices and natural gas in New England from 1999 to 2020. The data was taken from a report issued by the Department of Energy and the Energy Information Admistration.[1]

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[1] DOE/EIA, "Annual Energy Outlook 2001", December 22, 2000. report # DOE/EIA 0383(2001)

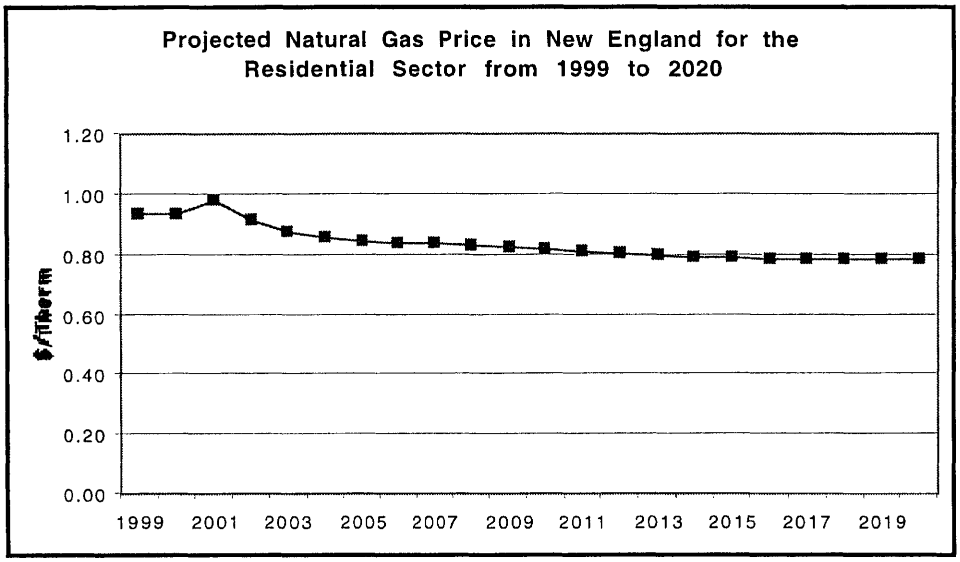

Figure 5.16

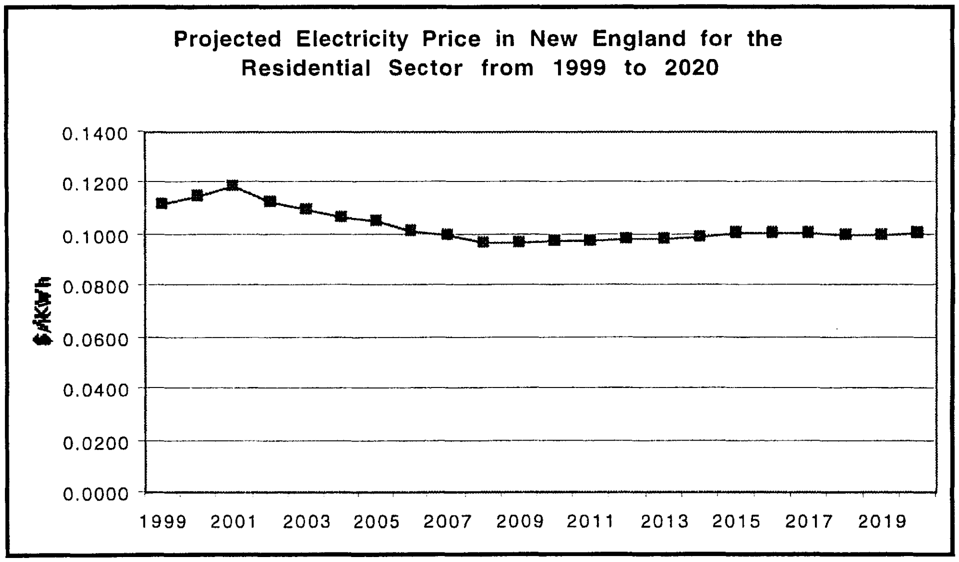

Figure 5.17

Based on the projections from the annual report, it appears as if the both electricity and the natural gas prices will increase at first then gradually stabilize. However, if there is an energy crisis, prices may triple or double in a matter of months. Such a situation would occur if the demand exceeded the supply. The following analysis will consider two scenarios with a price increase in electricity and gas.

Price Increase Electricity = .48 kWh , Natural Gas = $4.4/Therm

If the price of electricity or gas was multiplied by a factor of 4, then certain retrofit measure become affordable.

Affordable Measures

- ☐ Photovolatic System at 4% interest rate
- ☐ Furnace replacement (65% to 80%, 80% to 96%) at three interest rates
- ☐ Solar Thermal (DHW only)
- ☐ Window Replacement*

*S(L)NW replaced by S(A)NW at all interest rates
*S(L)NW replaced by T(A)W at all interest rates
*S(A)NW replaced by T(A)W at all interest rates
*S(L)NW replaced by D(A)W at all interest rates
*D(A)NW replaced by T(A)W at a 4% interest rate

Non Affordable

- ☐ Ground Source Heat Pump
- ☐ Radiant Heating System
- ☐ Photovoltaic Modules at 8%, 10% interest rates
- ☐ Window Replacement of D(A)NW by T(A)W at 8%, 10% interest rates

Apparently, the increase in energy made certain non affordable measures (at current prices) affordable such as the furnace and window replacement. Photovoltaic systems are only cost-effective at a 4% interest rate. It appears as if most of these measures would have been applied to a Cambridge Code House. This indicates that at higher energy prices, a homeowner can perform more retrofit measures to a Cambridge Code house than at present energy rates. For example, a

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* S(L)NW= single glazed, loose fit, non weather-stripped, S(A)NW = single glazed, average fit, non weather-stripped, T(A)W = double glazed with low-e, average fit, weather-stripped, D(A)W = double glazed, average fit, weather-stripped, D(A)NW = double glazed, average fit, weather-stripped

homeowner with an 80% efficient furnace can afford to upgrade to one with 96% efficiency. In addition, a home that already has double-glazed, average fit, non weather-stripped (D(A)NW) windows can afford to replace them to double-glazed, low-e, weather-stripped (T(A)W) at a 4% interest rate. Solar thermal systems for domestic hot water heating are also cost-effective at all interest rates when energy prices are higher.

Ground Source Heat pumps and Radiant heating system are not affordable.

Price Increase Electricity = .96 kWh , Natural Gas = $8.8/Therm

If the price of electricity or gas was multiplied by a factor of 8, then the following retrofit measures become affordable:

Affordable Measures

☐ Photovolatic System at all interest rates
☐ Solar Thermal (DHW only)
☐ Window replacement
    *S(L)NW replaced by S(A)NW at all interest rates
    *S(L)NW replaced by T(A)W at all interest rates
    *S(A)NW replaced by T(A)W at all interest rates
    *S(L)NW replaced by D(A)W at all interest rates
    *D(A)NW replaced by T(A)W at all interest rate

☐ Furnace replacement (65% to 80%, 80% to 96%)
☐ Ground Source Heat Pump at 4% interest rate

Non Affordable Measures

☐ Ground Source Heat Pump at 8%, 10% interest rate
☐ Radiant Heating System

At higher energy prices, a homeowner can afford to replace all window types, install a photovoltaic system, either replace a fairly efficient furnace or install a ground source heat pump. However, the heat pump is only affordable at a 4% interest rate. At higher interest rates, it is no longer cost-effective. Radiant Heating systems are also not affordable indicating that they are not the most appropriate retrofit measure for New England.

5.6 Alternative Design for Cambridge House for Sustainability

The current design of the Cambridge House for Sustainability has a ground source heat pump, radiant heating system, photovoltaic system, and solar thermal system. Based on the previous analysis, most of this technology is not affordable at the present energy rates. Therefore, once a homeowner in Cambridge has upgraded the thermal envelope of a house built according to Cambridge code or the 1920s, he may consider redesigning the heating system. The first most economical measure is to downsize the furnace to satisfy the reduced heating load requirements and increase efficiency.

A typical single family home in New England will have either a warm air furnace or a hot water/steam boiler that is oil or gas-fired. The furnace may have an optional central air conditioner that services the building via a duct system. The boiler, on the other hand, will provide heating with baseboards or radiators. Given the weather conditions New England during the summer (warm temperatures during the day, and cooler ones at night), the cooling load in the area is minimal. Therefore, many homes will not have air conditioning. In older building with an all water system with steam/hot water heating, cooling and fresh air is provided to the building from open windows or the installation of room air conditioning units. These homes will also have a 30 to 50 gallon domestic hot water tank that is heated with gas or electricity.

The following diagrams outline some design schemes applicable to building with either a warm air furnace or oil-fired burner. Design 1 shows the current design of the house with all of the sustainable technology. Designs 2 and 3 show an upgraded warm air furnace with solar system and a heat recovery ventilator. Design 4 and 5 show an upgraded boiler design with a solar system for both space heating and domestic hot water. Both schemes are based on the assumption that the necessary improvements have been made to the building envelope and both the furnace and the boiler have been replaced and downsized.

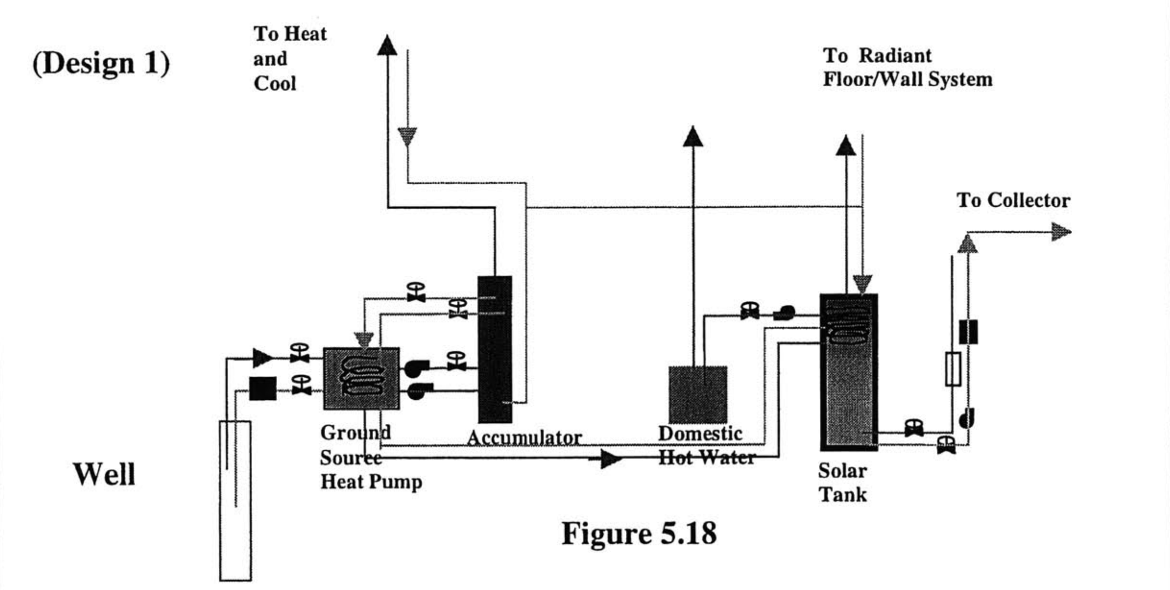


Figure 5.18

**Heating System for a Typical Single Family House in New England
with Warm Air Furnace
(Design 2)**

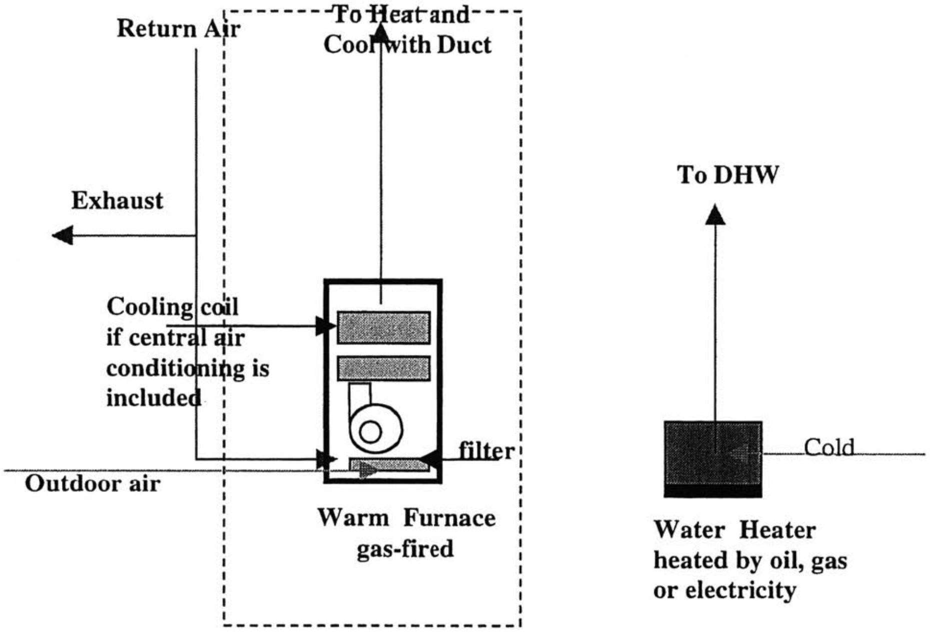


Figure 5.19

**Optimal Design for Single Family House in New England
with a Warm Air Furnace and Heat Recovery Ventilator and
Solar Thermal System (DHW)
(Design 3)**

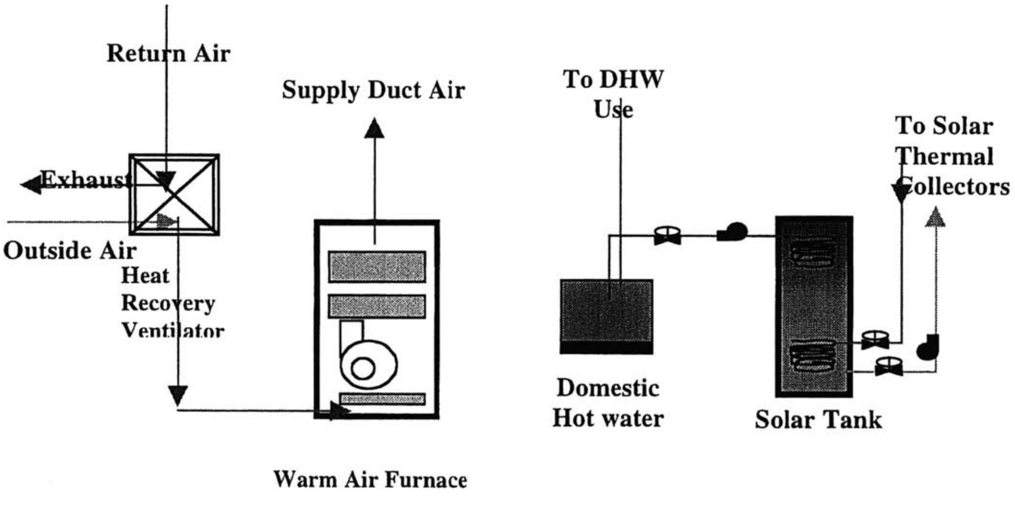


Figure 5.20

Heating System for a Typical Single Family House in New England with Oil-Fired Boiler
(Design 4)

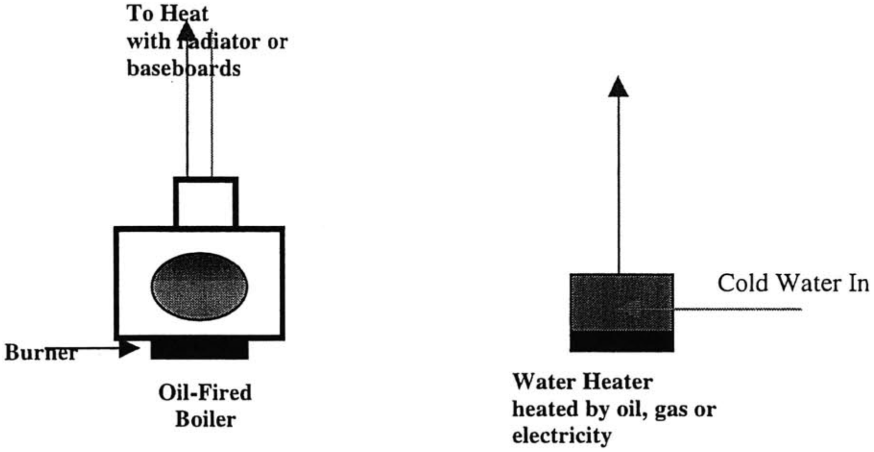


Figure 5.21

Optional Design for Single Family Home with Solar Thermal System
(Space Heating and Domestic Hot Water)
(Affordable at Present Energy Rates)
(Design 5)

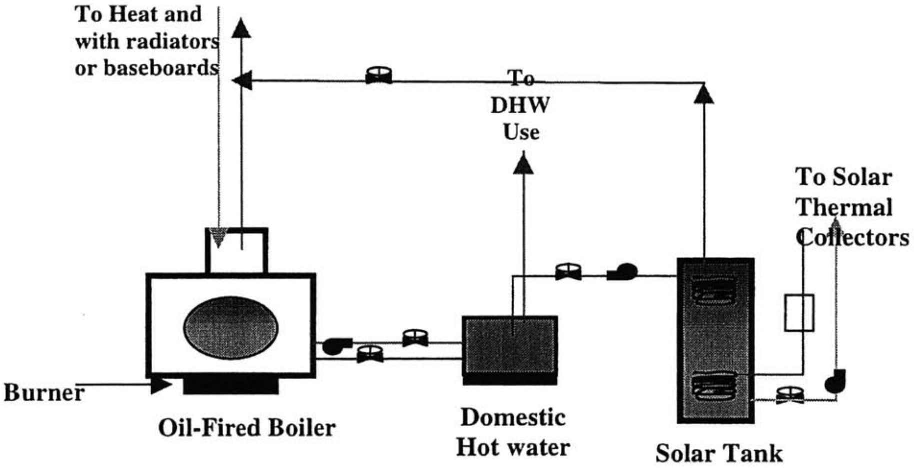


Figure 5.22

5.7 Conclusions

All of the energy features in the Cambridge House for Sustainability yielded a 41% and 63% energy cost savings relative to the Cambridge Code and 1920s house, respectively. The sum total of retrofit measures performed on the building envelope is most cost-effective relative to a 1920s base case model. The sum total of retrofit measures performed on the building envelope relative to a Cambridge Code model was not cost-effective. In both cases, the investment in the ground source heat pump, photovoltaic modules and the radiant heating system yielded an overall loss over a twenty-year span. On the other hand, the solar thermal system for both space heating and domestic hot water yielded positive net savings in both models.

Based on the rating system analysis, the reduction of infiltration yielded a large rating for both base case models. Therefore, the investment in infiltration reduction is a very cost-effective retrofit measure at present energy rates.

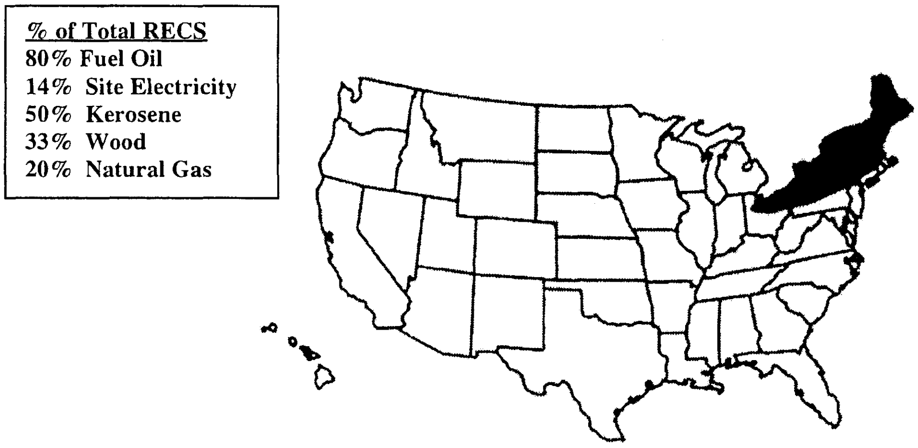
At higher energy rates (without subsidies or rebates), the least affordable technology will become cost-effective. With an electricity price increase to $.96/kWh and an increase of natural gas to $8.8/Therm, photovoltaics and window replacement are affordable at an 4%, 8% and 10% interest rate. The ground source heat pumps are only affordable at a 4% interest rate. Based on the projected performance data, it appears that radiant heating systems are the least affordable retrofit measure.

It must be noted that although ground source heat pumps are not cost-effective, they do significantly reduce energy consumption (Btu). A ground source heat pump reduces the annual energy consumption by 70%. A radiant heating system reduces the energy consumption for only space heating by 13%.

Chapter 6: Conclusions: Forecasts and Role of Conservation

6.0 Energy consumption of Cambridge House for Sustainability

The reduction in consumption reduces the overall demand in the region for fuel oil, electricity and natural gas. New England alone consumes 25% of the heating oil used in the entire country although residents comprise only 5% of the total population[1]. The entire Northeast region is responsible for 80% of the total residential energy consumption of fuel oil[2].



% of Total RECS
80% Fuel Oil
14% Site Electricity
50% Kerosene
33% Wood
20% Natural Gas

6.1 Northeast Region

The application of retrofit measures to the Cambridge House for Sustainability significantly reduced the energy needed for lighting, appliances, water heating, electric/AC and space heating. When compared to the two base case models (Cambridge Code and 1920s), the total percentage reduction was in the range of 71% to 85%, respectively. The largest reduction was from the energy used for space heating, electric air conditioning and water heating. Clearly, most of the improvements came from the building insulation investments, the installation of the ground source heat pump and the solar thermal system. The photovoltaic panel system reduced lighting and appliance use by 13%. In addition to the PV panels, the house has energy efficient lighting and appliances that further reduces electrical consumption. This analysis does not take the percentage reduction of efficient lighting/appliances into account.

If one were to assume that the house was heated by fuel oil during the winter months, then one can approximate the annual consumption in terms of the number of barrels of oil

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[1] Earth Star "Energy Efficiency: A Warming Trend", April, 2001

[2] 1997 Residential Energy Consumption Survey

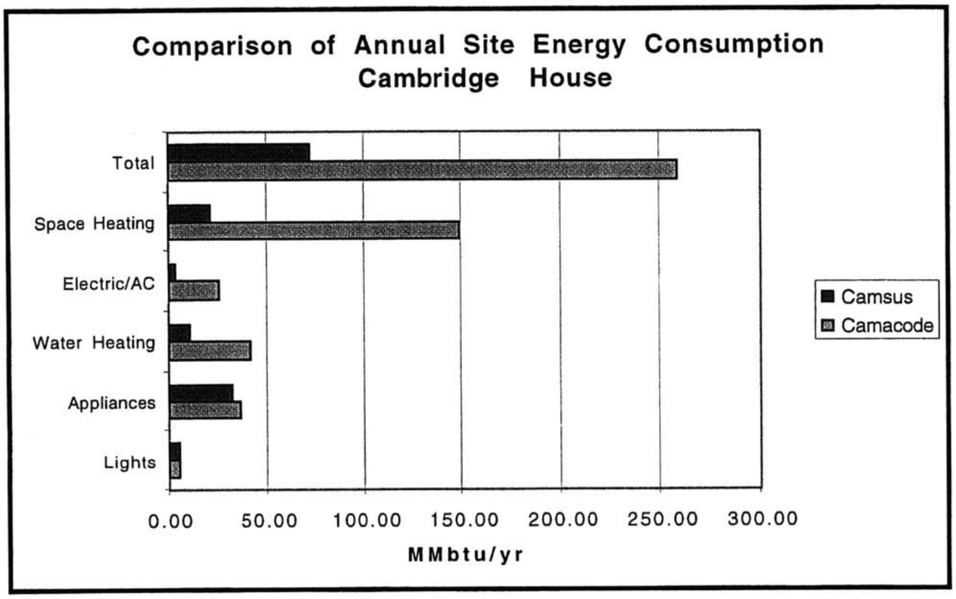

Figure 6.2

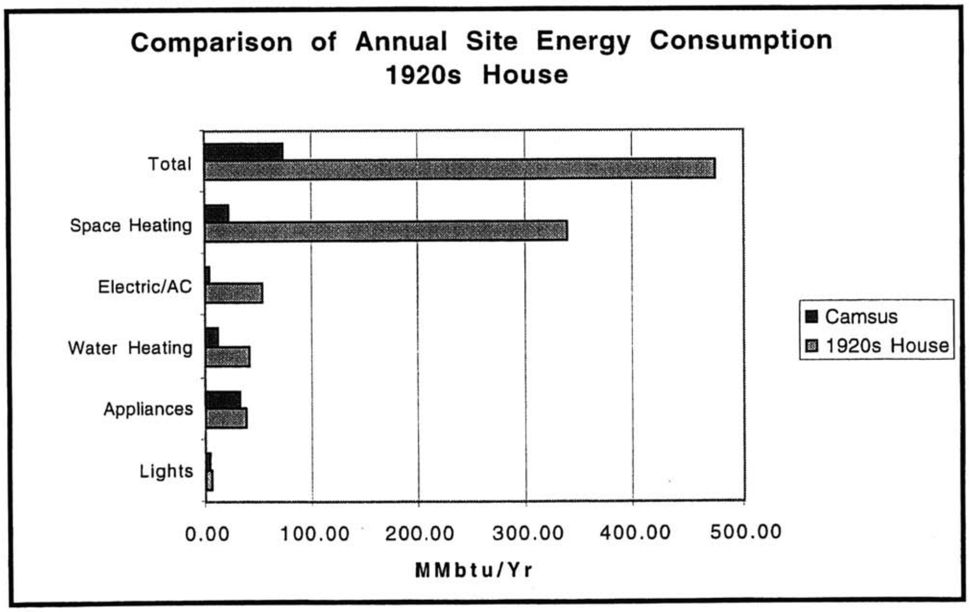

Figure 6.3

(Calculations are based on the loads for space heating). The approximate heat content of fuel oil is 5.825 million Btu per barrel.

One can also approximate the amount of gas in terms of cubic feet if gas were used for both space and water heating. The approximate content of gas is 1026 btu/ft[3].

Table 6.1: Consumption of Heating Oil/Gas

	Consumption of Oil for Space Heating # of Barrels	Consumption of Gas for water /space heating thousand cubic feet
Cambridge House for Sustainability	4	32
Cambridge Code House	26	186
1920s House	68	369

A house built in to the 1920s might us approximately 68 barrels of heating oil per year. A house built according to Cambridge code would use less than half that amount. On the other hand, the Cambridge House for Sustainability uses roughly 1/7 the amount of oil in the Cambridge code house and 1/17 the amount of oil the 1920s home. There is also a sizable reduction the total number of cubic feet needed for gas. Clearly, retrofitting significantly reduces demand.

6.1 Forecast of rising energy prices nationwide: Is there a future energy crisis in Northeast?

Today the state of California faces an energy crisis, and the prospect of rolling blackouts during the summer. This is due to the fact that the overall demand for energy in the region has exceeded the supply. The increase in demand is from high tech industries, consumers and the commercial/residential sectors. Currently there is a lack of electric generating capacity and resources such as gas supply. As a result, energy prices have risen. In March, the Southern California Edison and Pacific Gas & Electric approved the biggest rate increase by 46% for consumers[3].

Politicians have encouraged residents in the state of California to perform several measures such as raising the thermostats in air conditioners and turning off excess lights. As a partial remedy to the problem, the state will develop a two-fold tactic of increasing supply by way of increasing the production of power plants and decreasing demand by encouraging consumers to cut back on use. Several utility companies across the state have rebate programs

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[3] Associated Press, "Californians fear High Electric Bills", May, 10, 2001

that encourage consumers to use renewable energy. The President has also ordered that Federal Buildings in California reduce consumption by 10%.

The current predicament in California may forecast an impending national problem if drastic measures are not taken across the nation. In a bipartisan investigation, two senators, Charles Schumer and Susan Collins recently released a report detailing potential price spikes in oil and natural gas. The analysis predicts that the overall demand for oil, natural gas and electricity will increase by 21% in the next decade[4]. In addition, a new policy by the Organization of Petroleum Exporting Countries (OPEC) will restrict world oil supply far below demand forcing the increase in the price of crude oil. According to the report, this may force energy prices to rise by as much as 171% and almost triple in the next ten years[4]. Natural gas prices may spike by 271% over the decade[4]. Under their projections, crude oil prices may increase from $27.08 to $60.50 per barrel[4]. Their solution to the problem is the construction of 700 new power plants to meet the power demand.

In a region (Northeast) that consumes 80% of the total residential energy consumption of fuel oil, this increase will directly affect consumers, particularly low-income residents. Based on the analysis in this investigation, there are several cost-effective retrofit measures that can be performed on existing building at present energy rates. These improvements include the upgrade of the building envelope, and the installation of solar thermal systems.

In new construction projects, some of the retrofit measures performed in the Cambridge House for Sustainability are economical when the analysis takes into account rebates and subsidies. For example, ground source heat pumps are only cost-effective with a rebate from the utility companies. In new buildings, the installation of high performance windows is also an economical measure. Photovoltaics are only cost-effective in new construction projects when compared to an unsubsidized energy rate of $.33kWh as opposed to the subsidized rate of $.12kWh.

The Northeast can potentially avoid a situation like California by decreasing the demand. Policies effected by state legislation should lean more in the direction of conservation and less in the direction of supply, specifically, the increase in power plant production which further reduces the earth's oil reserves and contributes to global warming. Strategies should include the performance of cost-effective retrofit measures (at present energy prices) on the buildings that consume the most energy (1920s standard). As energy prices rise, the retrofit measures on newer buildings (Cambridge code) will become more economical. This report recommends a two-tiered approach where several buildings in the region are targeted by year of construction and

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[4] Reuters, "U.S Senators say country on verge of energy crisis", May, 10, 2001

retrofitted to high performance standards. Such measures will reduce demand and serve to prevent a potential energy crisis.

The partnership of all factions of society must work together to make these changes take place. This would involve the following steps[5]:

1. Encouragement of capital investment,
   (financing of renewable energy projects),
2. Implementation of supporting policies,
3. The partnership with utility companies,
3. The change of energy rules (better standards and codes)
4. Creative financing,
5. The education of the public by example.

The Cambridge House for Sustainability addresses the fifth objective. Demonstration projects serve to inform a community on alternatives to conventional systems, dispel myths and encourage us all to effect the power of choice. Our choices as consumers as well as the implementation and involvement can effect the changes for a better environment and a sustainable society.

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[5] Nancy Cole and P.J Skerret, Renewables Are Ready: People Creating Renewable Energy Solutions, Union of concerned Scientists, Chelsea Green Publishing Company, Vermont, 1995

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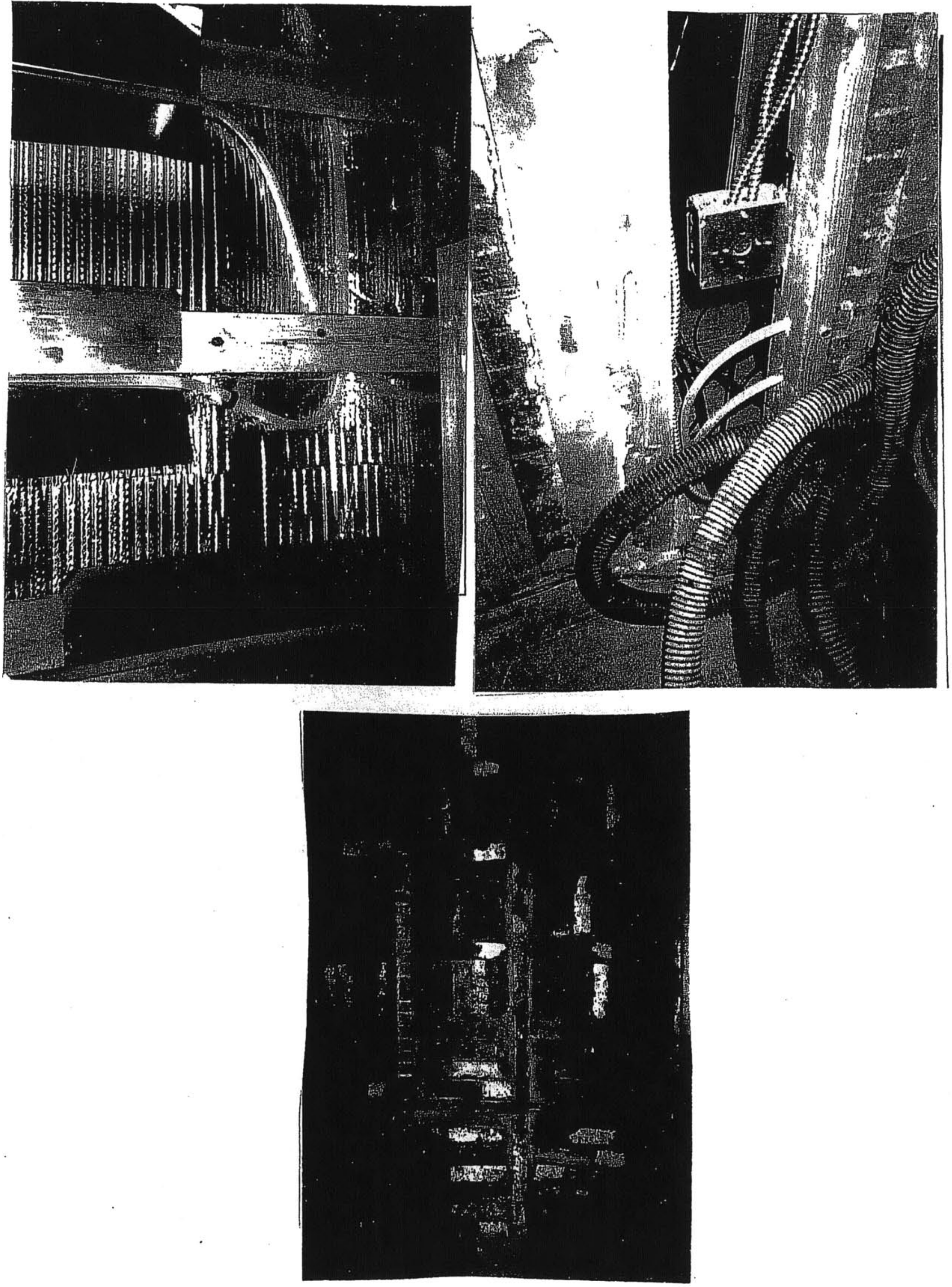
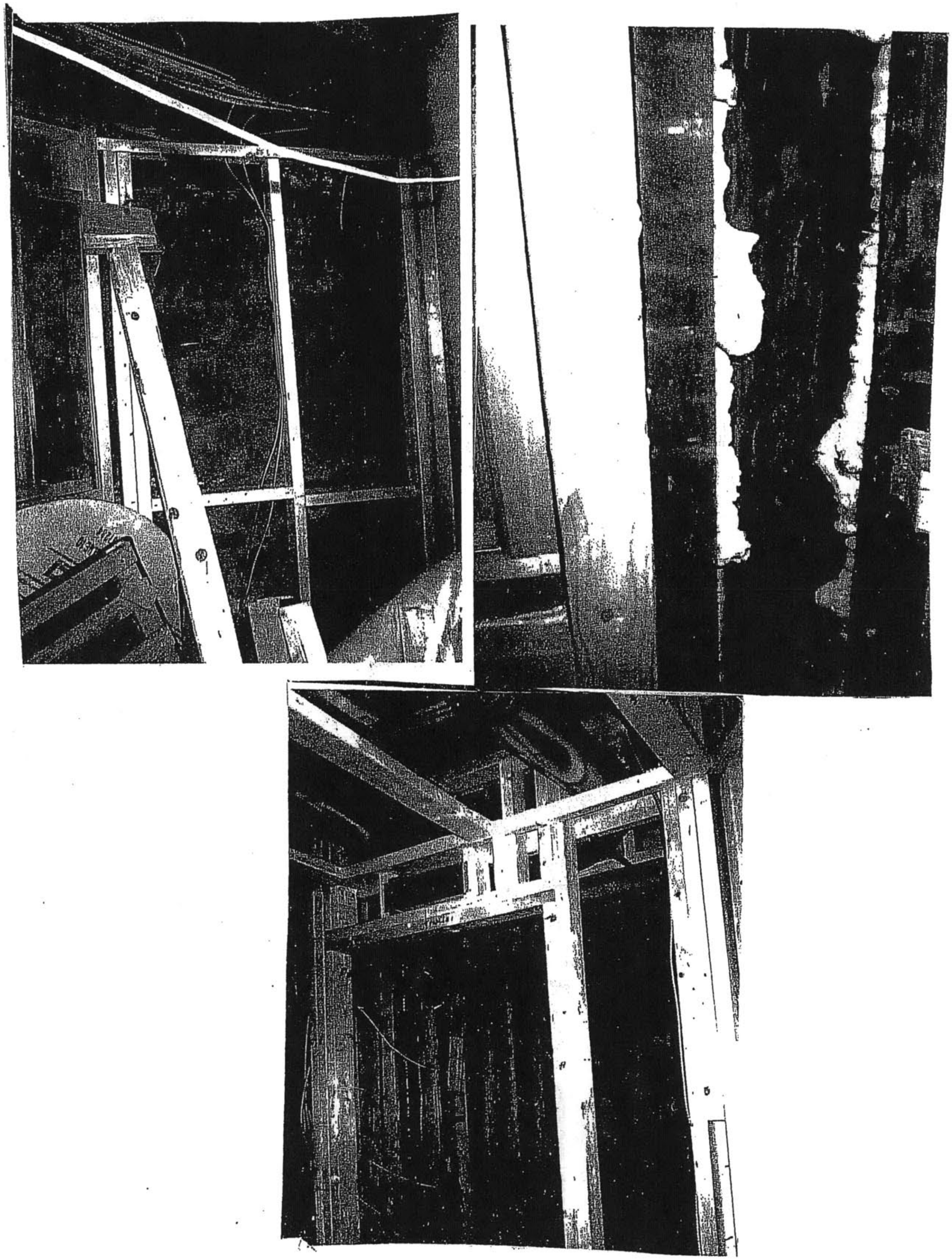
APPENDIX

Cambridge House For Sustainability

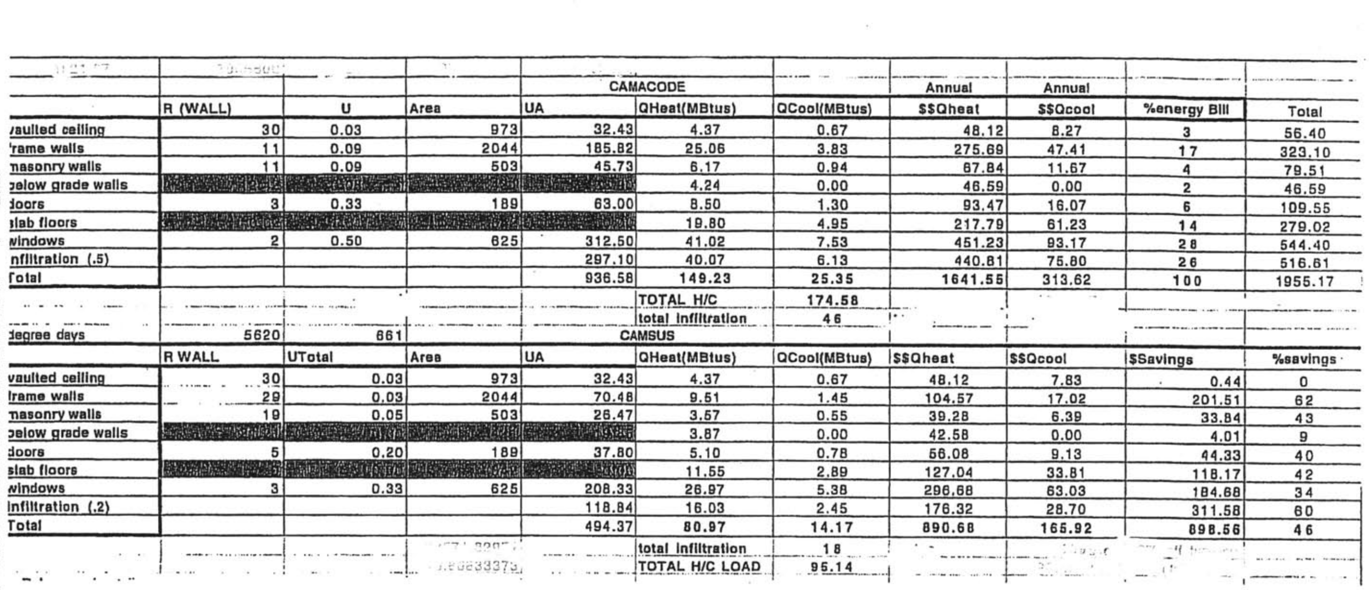


Radiant System Details



Building Envelope Improvements

Sample of Cambridge Code Analysis



camsus/code1

				CAMACODE			Annual	Annual		
	R (WALL)	U	Area	UA	QHeat(MBtus)	QCool(MBtus)	$$Qheat	$$Qcool	%energy Bill	Total
vaulted ceiling	30	0.03	973	32.43	4.37	0.67	48.12	8.27	3	56.40
frame walls	11	0.09	2044	185.82	25.06	3.83	275.69	47.41	17	323.10
masonry walls	11	0.09	503	45.73	6.17	0.94	67.84	11.67	4	79.51
below grade walls	[illegible]	[illegible]	[illegible]	[illegible]	4.24	0.00	46.59	0.00	2	46.59
doors	3	0.33	189	63.00	8.50	1.30	93.47	16.07	6	109.55
slab floors	[illegible]	[illegible]	[illegible]	[illegible]	19.80	4.95	217.79	61.23	14	279.02
windows	2	0.50	625	312.50	41.02	7.53	451.23	93.17	28	544.40
infiltration (.5)				297.10	40.07	6.13	440.81	75.80	26	516.61
Total				936.58	149.23	25.35	1641.55	313.62	100	1955.17
					TOTAL H/C	174.58				
					total infiltration	46				
degree days	5620	661		CAMSUS						
	R WALL	UTotal	Area	UA	QHeat(MBtus)	QCool(MBtus)	$$Qheat	$$Qcool	$Savings	%savings
vaulted ceiling	30	0.03	973	32.43	4.37	0.67	48.12	7.83	0.44	0
frame walls	29	0.03	2044	70.48	9.51	1.45	104.57	17.02	201.51	62
masonry walls	19	0.05	503	26.47	3.57	0.55	39.28	6.39	33.84	43
below grade walls	[illegible]	[illegible]	[illegible]	[illegible]	3.87	0.00	42.58	0.00	4.01	9
doors	5	0.20	189	37.80	5.10	0.78	56.08	9.13	44.33	40
slab floors	[illegible]	[illegible]	[illegible]	[illegible]	11.55	2.89	127.04	33.81	118.17	42
windows	3	0.33	625	208.33	26.97	5.38	296.68	63.03	184.68	34
infiltration (.2)				118.84	16.03	2.45	176.32	28.70	311.58	60
Total				494.37	80.97	14.17	890.68	165.92	898.56	46
					total infiltration	18				
					TOTAL H/C LOAD	95.14				

Sample of 1920s Analysis

1920scamsus/code1

							Annual	Annual		
				CAMACODE						
	R (WALL)	U	Area	UA	QHeat(MBtus)	QCool(MBtus)	$$Qheat	$$Qcool	%energy Bill	Total
vaulted ceiling	4	0.25	973	243.25	32.81	5.02	360.91	58.75	10	419.65
frame walls	3	0.33	2044	681.33	91.90	14.05	1010.88	164.55	27	1175.43
masonry walls	3	0.33	503	167.67	22.61	3.46	248.76	40.49	7	289.26
below grade walls	2.42	[illegible]	421	[illegible]	14.31	0.00	157.43	0.00	4	157.43
doors	3	0.33	189	63.00	8.50	1.30	93.47	15.22	3	108.69
slab floors	0.62	1.61	642	0.00	19.80	4.95	217.79	57.96	6	275.75
windows	1	1.00	625	625.00	83.17	13.98	914.88	163.66	25	1078.55
infiltration (.8)				475.37	64.12	9.80	705.29	114.81	19	820.10
Total				2289.52	337.22	52.56	3709.41	615.43	100	4324.85
					TOTAL H/C	389.77				
					total infiltration	74	MBtus			
				CAMSUS						
	R WALL	UTotal	Area	UA	QHeat(MBtus)	QCool(MBtus)	$$Qheat	$$Qcool	$Savings	%savings
vaulted ceiling	30	0.03	973	32.43	4.37	0.67	48.12	7.83	363.70	0
frame walls	29	0.03	2044	70.48	9.51	1.45	104.57	17.02	1053.83	90
masonry walls	19	0.05	503	26.47	3.57	0.55	39.28	6.39	243.58	84
below grade walls	21.21	[illegible]	421	[illegible]	3.87	0.00	42.58	0.00	114.85	73
doors	5	0.20	189	37.80	5.10	0.78	56.08	9.13	43.47	40
slab floors	0	[illegible]	642	0.00	11.55	2.89	127.04	33.81	114.90	42
windows	3	0.33	625	208.33	26.97	5.38	296.68	63.03	718.83	67
infiltration (.2)				118.84	16.03	2.45	176.32	28.70	615.07	75
Total				514.22	80.97	14.17	890.68	165.92	3268.24	76
					total infiltration	18	MBtus	1056.61		
					TOTAL H/C LOAD	95.14	MBtus			

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