RESEARCH REPORT

Energy & Power Needs and Availability in Housing

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Marbek

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ABSTRACT

This study takes a new look at the complex area of housing energy needs and use. It attempts to estimate the amount and type of energy needed to provide a variety of household services, and estimates the thermodynamic efficiency of the devices that are currently used to meet these needs. The principal findings are that the energy requirements of most household services are extremely low and that thermodynamic efficiency of household devices are often well below 10%. The conclusions are that there is room for significant improvement in household devices through reduction of conversion losses; increased use of on-site heat recovery and ambient energy; better design to match household needs; and better matching of energy source quality to need. Further work needs to be carried out in this area, particularly on the inclusion of embodied energy in the derivation of thermodynamic efficiency, and the simulation of device interaction in advanced housing.

KEY WORDS

Thermodynamic Efficiency, Household Energy, Household Devices, Renewable Energy, Energy Conservation, Energy Efficiency, Household Services

EXECUTIVE SUMMARY

This study attempts to derive the absolute amount and type of energy needed to provide various household services, and estimate the efficiency of components, equipment and other devices currently used to meet these needs. It is a first look at the complex area of housing energy needs and use, to determine whether this is an area where large, or only minor improvements can be made.

The study is part of Canada Mortgage and Housing Corporation's ongoing research on housing design. The work was carried out for CMHC by Marbek Resource Consultants with assistance from Allen and Associates, Sheltair Scientific and Prof. John Timusk.

The study uses the concept of thermodynamic efficiency, comparing the quantity and quality of the energy used by devices to the quantity and quality actually needed - the absolute energy of the service. Absolute energy requirements for the variety of household services were derived, either by estimating the energy required directly (e.g., the amount and intensity of lighting) or by using a "surrogate" estimate of energy need (e.g., the amount of energy delivered by a human carrying out the task). The energy actually used by household devices was estimated either from product specifications and usage rates, or using simulation models.

In addition to the thermodynamic efficiencies of household devices, the amount and quality of ambient energy sources available on a typical housing lot were also estimated. A reference lot and dwelling were used to determine what contribution these ambient "free" sources could make to meeting household energy needs.

The principal findings of the study were as follows:

- the energy requirements of many household services are very low;
- there is more than sufficient energy available on a dwelling lot to meet these energy needs, particularly from solar and soil thermal sources;
- the thermodynamic efficiency of most devices used to meet household energy needs is well under 10% and often less than 1%, mostly due to low conversion efficiencies, mismatch of the device to the task, and poor matching of energy quality; and
- some devices that are currently available however, show significant improvement over conventional equipment, particularly in the maintenance of comfort.

The main conclusion of the study is that significant improvements in the thermodynamic efficiency of household devices are both possible and desirable. These improvements could be achieved through reducing loses in energy conversion; matching the size and design of the device more closely to the need; increasing heat recovery; generally using an energy source where quality more closely matches the need; and utilizing higher proportions of on-site ambient energy.

The findings warrant further work in this area. Future work should introduce the concept of embodied energy[1] into the derivation of thermodynamic efficiency. It should also attempt to improve the simulation of housing devices and strategies so that the complex interactions between devices can be analyzed. Finally, future work should address some of the more complex housing services like air quality in more detail, and attempt to reduce the need to use surrogate absolute energy estimates for some household services.

[1]The energy used in the manufacture of a component or device.

RÉSUMÉ

Cette étude vise à déterminer la quantité absolue et le type d'énergie requise pour fournir divers services domestiques et à estimer le rendement des composants, de l'équipement et d'autres dispositifs actuellement utilisés pour satisfaire ces besoins. Il s'agit d'une première analyse de l'univers complexe des besoins énergétiques et de l'utilisation de l'énergie dans les habitations dont l'objectif est d'établir l'ampleur des améliorations possibles dans ce secteur.

Cette étude se rattache aux efforts de recherche de la Société canadienne d'hypothèques et de logement sur la conception des habitations. Les travaux ont été réalisés pour la SCHL par la firme Marbek Resource Consultants avec la collaboration des sociétés Allen and Associates et Sheltair Scientific ainsi que du professeur John Timusk.

Faisant appel au concept de rendement thermodynamique, les auteurs de l'étude comparent la quantité et la qualité de l'énergie utilisée par les dispositifs à la quantité et à la qualité vraiment requise, c'est-à-dire l'énergie absolue du service. L'énergie absolue nécessaire aux divers services domestiques est obtenue soit en déterminant directement l'énergie requise (p. ex. la quantité et l'intensité de l'éclairage) ou en ayant recours à une estimation «substitut» des besoins énergétiques (p. ex. la quantité d'énergie produite par une personne se chargeant de la tâche). L'énergie réellement utilisée par les dispositifs domestiques est évaluée soit d'après les spécifications et la fréquence d'utilisation du produit, soit par l'entremise de modèles de simulation.

Outre le rendement thermodynamique des dispositifs domestiques, l'étude porte sur l'évaluation de la quantité et de la qualité des sources d'énergie ambiantes accessibles sur un terrain résidentiel type. Un terrain et une habitation de référence servent à déterminer quel rôle pourraient jouer ces sources d'énergie ambiante «gratuites» pour répondre aux besoins énergétiques domestiques.

Voici les principaux résultats de l'étude :

- o les besoins énergétiques de bien des services domestiques sont très faibles;
- o on trouve amplement d'énergie sur un terrain à vocation résidentielle pour répondre à ces besoins énergétiques, en particulier les sources solaires et géothermiques;
- o le rendement thermodynamique de la plupart des appareils utilisés pour satisfaire aux besoins énergétiques domestiques est bien inférieur à 10 p. 100 et se situe souvent à moins de 1 p. 100, surtout à cause de faibles rendements de conversion, d'une mauvaise adaptation des dispositifs à la tâche et d'une mauvaise correspondance de la qualité de l'énergie;
- o certains dispositifs offerts actuellement représentent une nette amélioration par rapport à l'équipement traditionnel, surtout en matière d'entretien et de confort.

Les auteurs concluent qu'il est possible et souhaitable d'apporter d'importantes améliorations au rendement thermodynamique des dispositifs domestiques. Ces améliorations pourraient être réalisées en réduisant les pertes à la conversion énergétique, en adaptant plus adéquatement la taille et le type de dispositif au besoin, en augmentant la récupération de la chaleur, en utilisant généralement une source d'énergie dont la qualité correspond mieux au besoin et en faisant davantage appel aux sources d'énergie ambiante.

Les résultats obtenus justifient la poursuite des travaux dans cette voie. Les recherches ultérieures devraient introduire le concept de l'énergie de production[1] dans la détermination du rendement thermodynamique. Elles devraient aussi viser à améliorer la simulation des dispositifs et des stratégies domestiques de sorte que les interactions complexes qui existent entre eux soient analysées. Enfin, les recherches futures devraient analyser en détail certains services domestiques complexes comme la qualité de l'air et tenter de réduire le recours aux estimations substitut de l'énergie absolue pour les services domestiques.

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1. Énergie utilisée pour la fabrication d'un composant ou d'un dispositif.

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1. INTRODUCTION

1.1 Energy and Housing

Since the early 1970's, there have been considerable advances in the "efficiency" of Canadian housing, to the point where space heating presently requires a fraction of the energy used in earlier designs, and new appliances use less than half what they did in 1979. The question still remains, however, as to how far can we go in minimizing the energy used to build and maintain housing, and minimize its environmental impact -- without compromising comfort, safety, health or convenience. This report attempts to begin to answer these questions, by estimating the actual energy needed to meet typical housing services, comparing this need with the energy used by current technologies, and estimating what contribution can be played by the local sources of energy that are available on a housing lot.

Energy demand in housing is driven by human needs and desires. These needs include light, comfort, food, cleaning, etc. Each need is met through the use of technologies and devices which use energy sources such as electricity, gas, etc. to provide energy "services" such as heat, light, mechanical energy, etc. This report provides a preliminary analysis of the minimum or absolute energy associated with human needs in Canadian housing, and attempts to estimate the efficiencies of devices and technologies that are currently used to meet these needs.

It is not the intent of this study to pass judgement on different levels of comfort or lifestyle. An attempt is made only to estimate the amount of energy actually used in the process of providing a typical set of services, including light, comfort, food, cleaning, etc., and to compare this energy need to the energy used by typical technologies and devices to meet these services.

This work is being carried out as part of CMHC's ongoing research on housing design. The derivation of absolute energy requirements and efficiency of devices provides a better picture of where the largest improvements in energy efficiency could be made. Estimates of absolute energy requirements and energy availability also provide the basis for improved energy end-use analysis, environmental impact assessment, and housing design optimization and simulation studies.

This is a first look into the complex area of energy "needs" and use. It presently ignores embodied energy, an important aspect as we later strive for "optimum" efficiency levels, and only touches on some of the processes needing and deserving analysis.

The goal of this study was to determine whether this is an area where larger, or only minor, improvements could be made. As such, it is quite an eye opener.

1.2 Minimum Energy Requirements to Meet Housing Needs

Types of Energy Services

Gardner and Robinson[2] divide the needs for energy services into two types:

- Energy Intrinsic Services, where the need is for a service in the form of energy itself.

  In housing, energy intrinsic services include: lighting; cooking; drying; sound; etc. The service can be expressed in terms of a minimum amount of energy in a particular form needed per unit activity or unit time.

- Energy Extrinsic Services, where the need is not for energy per se, but where energy in various forms may be used to help provide the service.

  Examples of energy extrinsic services in housing include: maintaining comfort or air quality in a dwelling; security; etc. In these cases, the energy required to meet the need depends on the way in which the need is met. For example, comfort can be maintained by designing a dwelling with sufficient insulation and other features so that no energy is required. However, energy used is still "embodied" in the materials used (see below).

Table 1.1 provides a list of energy intrinsic and extrinsic services in housing. It should be noted that the heating and cooling of air or water is not an energy service per se, but a means of providing space comfort and cleaning. They do not, therefore, appear as actual energy services.

Energy Quantity and Quality

Most energy intrinsic housing needs require energy in a specific form or "quality" such as light, mechanical energy or heat at a given temperature (e.g., for cooking). The term "exergy"[3] is used to define the combination of energy quantity (which is conserved according to the first law of thermodynamics) and energy quality (which is consumed according to the second law of thermodynamics).

Exergy = Energy Quantity x Energy Quality

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[2]Gardner, Douglas T. and John B. Robinson, To What End?: A Conceptual Framework for Energy End-Uses. A paper submitted to Energy Policy. Personal copy provided by John Robinson, Director, Sustainable Development Research Institute, University of British Columbia, B5-2022 Main Mall, Vancouver, B.C. V6T 1Z4.

[3]American Institute of Physics, 1975, p28, Efficient Use of Energy Part I - A Physics Perspective K.W. Ford, G.I. Rochlin, Marc Ross, R.H. Socolar (eds.), New York.

Table 1.1
Energy Services In Housing

Energy Intrinsic Services	Energy Extrinsic Services
Lighting Food Preparation Food Cooling/Freezing Food Thawing Cooking Food Drying Food Refrigeration/Freezing Clothes Washing Clothes Drying Personal Washing Personal Drying Surface Cleaning Snow Clearing Audio/Visual Entertainment Home Repair/Maintenance	Space Comfort Air Quality Security

Mechanical, electrical, and light energy have energy qualities of one (1), therefore exergy = energy quantity. Heat has an energy quality less than one (1), and is a function of its temperature, the lower its temperature the lower its quality. The exergy of heat energy is therefore less than its energy quantity. When an energy intrinsic need such as lighting is met, the light is converted into heat. Energy quantity is conserved, while exergy is reduced.

The measure of energy quality is called the exergy factor or quality factor and is the ratio of exergy to energy. Typical exergy factors are as follows:

Energy Form	Exergy Factor[4]
Electricity	1
Mechanical Energy	1
Fossil Fuels	1
Heat at 250 °C	0.27
Heat at 100 °C	0.12
Heat at 50 °C	0.05

[4]Gyftopoules E.P. and T.F. Widmer "Availability Analysis: The Combined Energy and Entropy Balance" Thermodynamics: Second Law Analysis, R.A. Gaggioli, Ed. American Chemical Society, ACS Symposium Series 122, 1980.

The minimum energy requirements for an energy intrinsic service in housing should therefore be expressed in terms of minimum exergy. Energy extrinsic housing needs, by definition, do not have an explicit energy quality requirement. However, as discussed below, the energy quality of the source of energy used to meet the need is significant in determining how efficiently the need is met.

Energy Intensity and Power Levels

Power is the rate at which energy is used. Energy intensity is energy per unit time and activity.

Power Level = Energy Quantity/Time

Energy Intensity = Power Level/Activity Level

Many housing needs require a minimum power level or minimum energy intensity, as well as a minimum energy quantity and quality. Lighting, for example, requires a minimum light level (lumens per m^2), as well as a minimum quality (light) and a minimum quantity (minimum light levels over a minimum time period each day).

Absolute Energy Requirements

An "Absolute Energy Requirement" can only be defined for an energy intrinsic service, and may be defined as the minimum power level and exergy required to meet a housing need. The absolute energy requirement is independent of the energy source used, the technology or device used to meet the service, and independent of what happens to the energy after it is transformed while meeting the need. Most energy is transformed into heat as it is used.

By definition, there is no absolute energy requirement for an energy extrinsic service.

1.3 Energy Sources Available to Meet Housing Needs

While there are many energy needs in a dwelling unit, there are also many ambient sources of energy available to meet these needs. Ambient sources include: direct and diffuse solar radiation; wind; soil and air heat and moisture content; and mains water pressure. Waste heat results from all processes and transformations taking place within the house. Also, energy may be purchased (brought on to the lot) from external sources.

Table 1.2 provides a list of energy sources available to meet housing needs.

Table 1.2
Energy Sources Available to Meet Housing Needs

Ambient Energy Sources	Internal Energy Sources	External Energy Sources
Solar Energy Wind Energy Soil Thermal Energy Water Supply Heat and Pressure Ambient Air Temperature Ambient Air Moisture Night Sky Radiation Biomass-Derived Heat and Fuel	Ventilation Exhaust Human Heat and Moisture Cooking Heat and Moisture Lighting Heat Heat from Power Cleaning and Other Devices Grey and Black Water Heat Heat and Fuel from Waste Decomposition	Electricity Natural Gas Coal Fuel Oil Wood Propane

Many of these energy sources are not available on a continuous basis. It is therefore important to define the time and duration of their availability, and the power level (intensity) at which they are available. This, along with the amount and energy quality (heat, electromagnetic radiation, mechanical energy) determines how much ambient exergy is available to meet energy service needs.

External sources of energy can be purchased by the dwelling occupant. These sources are usually available at any required power level or intensity. Each external source, however, will be of a specific energy quality, and can be expressed in terms of its exergy. Each energy source also has a "full fuel cycle" efficiency which is a measure of how efficiently a primary resource such as hydro power, coal, oil, natural gas, etc. is delivered to the dwelling lot. Losses between source and lot include mining energy, processing energy, conversion efficiency and transmission losses.

1.4 Devices Used to Meet Energy Needs

Each energy service requirement in a dwelling unit or on a dwelling lot is met using a "device". Devices can include a single piece of equipment such as a refrigerator, or be a combination of materials, equipment and measures such as a building envelope and heating system. Some devices meet more than one need (e.g., a heat recovery ventilator provides air quality control and heat recovery).

Devices both embody energy (in their materials and production) and use energy to meet an energy requirement (i.e., perform its function). Some devices can utilize both ambient and on-site waste heat to meet an energy requirement (e.g., a heat pump or a dynamic wall). Others, such as a battery, embody the required energy and require no ambient or external energy. Most devices, however, use some external energy to meet the housing energy requirement. Some devices are designed to convert an ambient energy source into useful energy by either concentrating it or upgrading its quality (e.g., heat pump or solar photovoltaic generator). Others are designed specifically to meet a household need using combinations of purchased energy, direct ambient energy, converted ambient energy and waste heat from other devices. Some devices, such as a solar water heater, belong to both types.

The ultimate objective of efficient housing design is to develop devices (including the housing envelope) that can utilize the maximum amount of ambient and on-site energy, with the minimum of embodied and external energy.

Appendix A provides a table listing some of the devices that are used to meet energy intrinsic and extrinsic services in housing. For each energy service the various approaches used to provide the service are listed along with the components and usage of these devices.

1.5 Energy Efficiency of Devices

When energy is converted from one form to another, a measure of thermodynamic efficiency is required. Conversion of energy occurs when a technology or device produces useful energy to meet an energy service or need, or when a material or technology is manufactured.

Various measures of efficiency and their applicability in the assessment and analysis of energy use has been extensively reviewed by Gardner and Robinson[5]. Their main conclusion is that a true thermodynamic efficiency can only be defined for energy intrinsic services. For energy extrinsic services, a "Relative Service Efficiency" must be used in which the exergy or energy actually used is compared to the exergy or energy used by the "state-of-the-art" service technology (the service technology that uses the lowest amount of exergy to meet the service need).

As discussed in Section 1.4 above, a technology or device may consist of several components. Each component has an embodied energy, and each may also have the capability of using "free" energy or exergy available from ambient sources such as heat gain through windows, waste heat from other devices, or renewable sources available on the housing lot.

The actual exergy used by a device or technology can therefore be expressed as its embodied exergy, plus the total amount of exergy used from all sources, minus the amount of exergy used

[5]op.cit.

from on site ambient sources. Absolute efficiency for energy intrinsic services can then be expressed as:

$$AbsoluteEfficiency = \frac{Absolute\ Exergy\ Requirement}{Exergy\ Used\ -\ Ambient\ Exergy\ +\ Embodied\ Exergy}$$

It is possible to have an absolute efficiency greater than 100%. For example, the exergy "used" by a device which relies totally on ambient and on-site energy sources will consist only of its embodied energy.

Use of these definitions of efficiency also allows consideration of the penalty of using high quality energy sources for low quality needs. A device which uses waste heat to meet a heating need will have a higher efficiency than one which uses electricity or a fossil fuel.

The total exergy used by a device minus the ambient exergy contribution is of course the amount of external energy used by the device. Since these external sources of energy are delivered to a housing lot in a "processed" form, the thermodynamic efficiency should take the full fuel cycle efficiency of these sources into account. Therefore:

$$Absolute\ Efficiency\ \eta_a = \frac{E_a C_a}{E_e C_e / \eta_e - E_b C_b}$$

where:

	E_a	= *Absolute Energy*
	E_c	= *Exergy of External Fuel Used*
	E_b	= *Embodied Energy*
	η_e	= *Full Fuel Cycle Efficiency*
	C_a	= *Absolute Quality Factor*
	C_e	= *Quality Factor of External Fuel*
	C_b	= *Quality Factor of Embodied Energy*

$$Relative\ Service\ Efficiency\ \eta_r = \frac{E_{eb} C_{eb} / \eta_{eb} - E_{bb} C_{bb}}{E_e C_e / \eta_e - E_b C_b}$$

where $_b$ = Best Technology

It was not possible in this study to analyze and derive thermodynamic efficiencies for all devices now used to meet housing energy processes. The approach taken was to analyze a range of devices, including those most frequently used, but also including the most "efficient" available. Where possible, the technological item which has the greatest promise of improving efficiency was also identified.

The embodied energy of each device was also not considered in the study. It should be taken into account in future work, however, since it will be an even greater proportion of the total energy used in some energy efficient devices, and as will be demonstrated later in this report, is a necessary component in the analysis of the efficiency of any device that requires no operating energy (e.g., a zero energy envelope design or solar system).

1.6 Interactions Between Energy Processes and Devices

There are many interactions between energy processes and devices. As noted above, the waste heat from meeting one energy service can become a source of energy for another. In addition, the design of one device can have a significant effect on the absolute energy efficiency of another. For example, the location, size, and performance of windows affects the energy used to maintain comfort levels, and the energy used to meet lighting needs. It is important, therefore, that all interactions between energy transformations are understood. Only then can a dwelling unit be simulated as the complex system that it is, and progress be made towards designing more efficient buildings. The work carried out in this study will contribute to the greater understanding of these interactions.

2. PROCEDURE

This section outlines the methodology used in this study to derive estimates of absolute energy needs and energy sources, and compare devices in terms of their absolute or relative service efficiencies.

Table 2.1 lists the energy intrinsic and energy extrinsic services addressed in this study. The meeting of some requirements involves both types of service, and it was necessary to sub-divide them. Cold storage, for example, involves i) cooling down food, ii) maintaining it at a reduced temperature, and iii) warming it up to the required temperature for consumption (intrinsic). The first two services are normally carried out by a refrigerator. The first and last processes are energy intrinsic services, the middle one is an energy-extrinsic service.

Table 2.1
Energy Services Addressed in This Study

Energy Extrinsic Services	Space Comfort Air Quality (Oxygen/Carbon Dioxide only)
Energy Intrinsic Services	Lighting Food Preparation Food Preservation (Refrigeration/Freezing) Cooking Personal Cleaning (Washing/Drying) Clothes Cleaning (Washing/Drying) Audio/Visual Entertainment (Radio/TV) Snow Clearing

For the purposes of this study, a residential lot has been defined as a flat area measuring 10m by 35 m (approximately 35 feet by 120 feet), with a total surface area of 350 m^2. The lot is situated in the Ottawa climate zone, and there is assumed to be no shading from outside of the lot boundaries, no streams or other surface water flows, and no major wind obstructions in the vicinity. Details of the Reference house are shown in Appendix B.

2.1 Determining Absolute Energy Requirements for Energy Intrinsic Services

The absolute energy requirements in terms of minimum exergy and power levels was estimated for each energy-intrinsic service for a typical housing unit and family.

In some cases, it was not possible to determine absolute energy requirements, particularly in those cases where the physical transformations occurring are complex and where there was no experimental data. **A surrogate energy requirement was used in these cases.** The best surrogate in many processes was found to be the energy intensity (power level) **delivered** by a human being undertaking the task. For example, a human being can deliver about 20 watts of power when working a hand pump. Power levels of the same order of magnitude would be delivered in scrubbing, sweeping, mixing, etc. All devices (including the human being itself) can therefore be compared with each other on the basis of their respective efficiencies in delivering this energy. It should be noted that using **delivered** human energy as a surrogate energy requirement does not imply that it is either desirable or most efficient for a human to actually carry out the task.

2.2 Estimating the Availability, Size and Quality of Energy Sources

Table 2.2 presents the details of the sources of energy that were identified and assessed. Three types of energy sources were identified as being available on a dwelling lot: i) those from ambient sources on or flowing across the lot, ii) those resulting from activities on the lot, and iii) those purchased from outside the lot. More details on the quality, availability and measure of quantity for each energy source are given in Appendix B.

Many of the energy sources listed in Table 2.2 require some type of conversion device to provide energy in a form or quality that will meet household energy needs. Some sources, however, such as solar energy can be used either directly (e.g., window solar gain) or through a conversion device (e.g., solar collector). Each energy source was briefly reviewed, the intensity and exergy of the energy falling on the typical reference lot was estimated.

Table 2.2
Energy Sources Addressed in This Study

Ambient Services:	Solar Energy Wind Energy Soil Thermal Energy Ethanol from Biomass Wood Fuel from Biomass Water Supply Pressure
Internal Sources:	Blackwater Greywater Municipal Solid Waste
External Sources:	Electricity Natural Gas Fuel Oil Wood

2.3 Estimating the Energy Consumption and Efficiency of Devices Used to Meet Energy Requirements

Tables 2.3 A & B provide a list of the devices that were considered in the study, and the energy intrinsic and extrinsic household services that each of them meet. In some cases, a "package of devices" is needed to meet an energy requirement (a building envelope, for example). In others, one device meets several requirements (a refrigerator cools, freezes, and maintains food at a set temperature). The state-of-the-art or best technology used to judge the relative service efficiency of each device used to meet an energy extrinsic service is also shown in Table 2.3.

The exergy used by each device and the usage that each device makes of ambient on-site energy sources in the standard house, was estimated from product literature and other sources. The thermodynamic efficiency of each device was estimated by comparing the exergy used by the device with the absolute energy requirement.

Table 2.3A
Devices Addressed in the Study
(Energy Extrinsic Services)

Space Comfort	National Building Code Housing Energy Efficient (R2000 type) Housing [6]Advanced Housing with increased thermal mass, and dynamic wall and other features [6]Equipment/Measures for Control of Comfort Parameters Standard and Advanced Space Heating Systems Heat Pumps
Air Quality	Ventilation Systems [6]Photosynthesis

[6]State-of-the-Art as "best" device used to estimate relative service efficiency.

Table 2.3B
Devices Addressed in the Study
(Energy Intrinsic Services)

Lighting	Standard and High Efficiency Lamps/Fixtures Lighting Control and Daylighting
Clothes Washing	Handwash Standard and Advanced Washers Hot/Cold Water Washing Standard and Advanced Water Heaters
Clothes Drying	Clothes Line Standard and Advanced Clothes Dryers
Personal Washing	Shower Bath Sauna Standard and Advanced Water Heaters
Personal Drying	Towelling Hair Dryer
Cooking	Conventional Oven Microwave Oven Crock Pots
Food Drying	Electric and Solar Dryers
Food Preservation	Standard and [6]Advanced Refrigerators/Freezers
Audio/Visual Entertainment	Portable Radio Standard Radio/TV
Outdoor Service	Shovelling Snow Blower Hand and Power Lawn Mower

3. ENERGY AVAILABILITY

This section provides a summary of the availability of each ambient, on-site, and purchased energy source on a typical dwelling lot.

Table 3.1 summarizes the sources of energy available to a residential lot and the maximum or typical quantity of energy that may be extracted using current technology. Note that in the case of ambient sources, this assumes that the entire lot area is dedicated to the collection of energy. For internal sources, this assumes heat energy produced by an average four-person household.

Substantial quantities of electric, thermal and mechanical energy can be derived from ambient energy sources. The two most significant ambient sources are solar energy and soil thermal energy. Compared to these two sources, very little energy (< 1.6 GJ) is available from ethanol or fuelwood production, and mains water supply. The remaining two ambient energy sources are wind (13.4 GJ) and residential solid wastes (11.7 GJ). These two sources are in the same order of magnitude as internal energy sources.

Internal energy sources represent an appreciable amount of heat energy. A typical four-person household could recover up to 6.9 GJ from waste blackwater and 8.9 GJ from waste greywater. Waste heat from household devices varies depending on the efficiency of lighting and other household devices, and occupant activity levels.

External electric and fossil energy sources include electricity, fuel oil, natural gas and wood. Since they are effectively unlimited, the energy available from these sources to a residential lot cannot be quantified in the same terms as used above. Production of each energy source does, however, involve upstream losses. These "fuel cycle" efficiencies for external fuels include extraction, processing, generation and transmission losses, but not energy embodied in the infrastructure built to extract and supply the energy.

A full analysis of each energy source is provided in Appendix B. Fuel cycle efficiencies for several sources of electricity, gas and oil are derived in Appendix C.

Table 3.1
Summary of Energy Sources Available to a Typical Ottawa Dwelling Lot 350 m^2 in Area

Energy Source Origin	Energy Source	Basic Resource Available (GJ/a)	Energy Form	Energy Recoverable (GJ/a)*	Fuel** Cycle Efficiency
Ambient Energy Sources	Solar	1680	As Electricity As Hot Water at 75°C As Process Heat at 250°C As Heat on Dwelling Surface at 30°C	130 390 520 516	
	Wind	510	As Mechanical Energy	7.9	
	Soil Thermal	520	As Heat at 30°C	130	
	Ethanol	-	As Fuel	1.9	
	Fuel Wood	25	As Heat at 250°C	1.7	
	Water Supply		As Mechanical Energy	0.2 - 0.7	
Internal Energy Sources	Blackwater		As Heat at 20°C	6.9	
	Greywater		As Heat at 34°C	8.9	
	Solid Waste		As Heat at 250°C	12	
External Energy Sources	Electricity		Electricity		25-80%
	Fuel Oil		Fossil Fuel		90%
	Natural Gas		Fossil Fuel		84%
	Wood		Biomass Fuel		60%

* Energy available to an average Ottawa dwelling lot (350m^2). For more details see Appendix B.

** Fuel cycle efficiencies are derived in Appendix C.

4. ENERGY SERVICE REQUIREMENTS AND DEVICE EFFICIENCIES

Table 2.3 summarized the household energy requirements and devices addressed in the study. In this section each service is briefly reviewed, and for energy intrinsic services, the absolute energy requirement derived. The devices that are currently used to meet each service are discussed, and the absolute efficiency or relative service efficiency estimated where possible.

For each of the household energy services addressed, the basic objective was to pin down the processes involved, the orders of magnitude (decimal point), and the range of energy requirements and efficiencies. It was not the objective to cover all possible devices and strategies, nor to determine the minimum or optimum solution, nor to make judgements on the necessity of services.

4.1 Comfort Control

4.1.1 Devices and Measures Used to Maintain Comfort

Comfort is normally maintained by control of environmental conditions within a building envelope. The range of environmental conditions in the comfort zone is quite wide and many combinations of air temperature, surface (radiant) temperature, air flow, humidity, clothing level, and air speed may be used to maintain comfort. More information on the definition of comfort and acceptable environmental conditions is given in Appendix D.

The energy used to maintain these conditions will vary with the combination of comfort conditions selected; with the size, structure, materials, etc. in the envelope; and with the conversion efficiency of devices used to convert purchased (off-site) energy into usable heating and cooling, moisture control and air movement.

Devices used to maintain comfort may be divided into two component groups: i) Envelope Components, and ii) Conversion Components. Envelope components determine heating or cooling, humidification or dehumidification, and air movement loads. These devices will also determine the amount of "free"[7] internal heat, solar gain, and natural cooling energy that contributes to the energy requirements. Conversion Components convert external (off-site) energy and ambient (on-lot) energy into useful heating, cooling, humidification, dehumidification, or air movement, sufficient to meet the energy load of an envelope. A conversion device will use a certain degree of on-site free energy (e.g., heat pump or solar photovoltaics or thermal device), and may use several external (off-site) energy sources (e.g., gas for heat, electricity for furnace air).

Each combination of envelope and conversion components will have a different load, internal and free contribution, and ambient contribution. Some envelopes will not require a conversion

[7]Free energy is defined as energy which can be used to meet an energy requirement without conversion and without payment.

device, if all loads are met with free contributions. Sections 4.1.2 and 4.1.4 discuss envelope and conversion devices separately.

4.1.2 Envelope Components and Strategies

Several combinations of envelope components and comfort conditions were analysed and compared against the state-of-the-art or best combination as defined by the study team. Heating and cooling loads for several sets of features were estimated using the ENERPASS simulation model. The assumptions used for each feature are given in Appendix D.

Tables 4.2 and 4.3 show the Gross Heating and Cooling Loads, Purchased Energy, and Free Energy Contribution for some of the features and environmental conditions analysed. Full results for each device as estimated using ENERPASS are given in Appendix D.

The results show that current housing still does not come close to the optimum where all heating and cooling requirements could be met from free sources. Advanced housing techniques recently being utilized, however, show significant promise. Increasing insulation levels; adding seasonal and diurnal heat/cold storage; utilizing modified dynamic walls which collect more of the incident solar energy falling on the house wall; and using natural cooling and 90% heat recovery, appear to be able to provide an envelope which requires no external heat.

Table 4.2
Heating Loads for Various Envelope Strategies

Home Type	Strategy	Window Placement	Gross Heat Load (GJ/a)	Free Heat (GJ/a)	Net Heat Load (GJ/a)
Code Housing	Optimum Temp Normal Clothes Level	Equalized	163.5	47.6	115.9
Code Housing	Min. Acceptable Temp. High Clothes Level	South Optimized	105.9	43.4	62.5
Code Housing with Dynamic Wall	Optimum Temp. High Clothes Level	Equalized	115.2	48.3	66.9
Energy Efficient Housing with 75% Heat Recovery	Min. Acceptable Temp. High Clothes Level	Equalized	58.5	36.5	22.0
Energy Efficient Housing with 10% radiant heat	Min. Acceptable Temp. High Clothes Level	Equalized	62.9	34.2	28.7
Advanced House with Heavy Mass and 90% Heat Recovery	Min. Acceptable Temp. High Clothes Level	Equalized	27.4	27.4	0

Table 4.3
Cooling Loads for Various Envelope Strategies

Home Type	Strategy	Window Placement	Gross Cooling Load (GJ/a)	Free Cooling (GJ/a)	Net Cooling Load (GJ/a)
Code Housing	Optimum Temp. Normal Clothes Level	Equalized	18.3	8.6	9.7
Code Housing	Max. Acceptable Temp. Low Clothes Level Natural Cooling	Equalized	2.2	0.9	1.3
Code Housing	Max. Acceptable Temp. Low Clothes Level Natural Cooling Air Movement Radiant Cooling	Equalized	0.3	0.1	0.2
Advanced House with Heavy Mass	Max. Acceptable Temp. Low Clothes Level Natural Cooling	Equalized	0	0	0

Since the state-of-the-art housing effectively has a heating and cooling load of zero, without including the embodied exergy of each envelope strategy, no relative service efficiency can be estimated.

4.1.3 Moisture Control

In any envelope device, moisture added to the indoor air falls into two categories: that which consumes heat from ambient sources to evaporate, and that which acquires the heat of evaporation from the process that has moisture as its byproducts. For example, it is estimated that some 100 kg of moisture is absorbed by framing lumber during the summer and evaporated during the winter. To evaporate this water, it would take about 0.25 GJ, which would have to be absorbed from the ambient air. On the other hand, a typical family of four would be expected to produce some 1,100 kg of metabolic moisture during a seven-month heating season, at the expense of some 2.6 GJ of metabolic energy.

Two types of moisture sources are found in housing. The first set of sources represents "free" moisture, the second set represents moisture evaporated at the expense of heat from the building interior. These moisture sources are quantified in Table 4.4.

Once the water has appeared in vapour form, no matter what the source, including moisture brought in with the ventilation air, part of this moisture can be recovered by a heat-recovery ventilation (HRV) unit.

The above values suggest that some 6 GJ (70% of 5.5 + 3.1GJ) could be recovered if an HRV can cool the exhaust air to 3°C. For example, a heat pump would exhaust indoor air at 3°C and 100% relative humidity (RH). Here we would be looking at indoor air at about 50% RH. Once the indoor relative humidity approaches 30%, the HRV can no longer condense the vapour in it at the above mentioned performance characteristics. It should also be pointed out that indoor relative humidity during the heating season should not be allowed to go much over 50% in order to guard against the formation of mould and mildew on or in the building fabric.

Table 4.4
Moisture Sources in Housing

Type	Process	kg/month	kg/season	GJ/season
Process Moisture	Metabolic	150	1050	2.6
	Gas Stove	45	315	0.8
	Cooling	30	210	0.5
	Showers	35	245	0.6
	Dishwashing	55	385	1.0
	Total	**315**	**2205**	**5.5**
Moisture Evaporated with Ambient Heat	5 house plants	35	245	0.5
	Floor washing	10	70	0.2
	Framing lumber		100	0.3
	Furnishings[12]		100	0.3
	Gypsum board[8]		100	0.3
	Concrete		600	1.5
	Total	**45**	**1215**	**3.1**

[8]Estimated, other values from NRC Building Science Insight '83: "Humidity, Condensation and Ventilation in Houses".

4.1.4 Conversion Components

The heating and cooling loads determined by the choice of envelope features in housing are met through a variety of heating and cooling systems including electric, gas, oil, wood or biomass furnaces and boilers, electric or gas heat pumps and air conditioners, and electric heating or cooling systems driven by solar energy. All of these components make some use of on-site sources of energy, although some much more than others.

Solar Energy Space Heating System

In Section 3.1, it was shown that the solar energy falling on the residential lot used in this study, amounts to 1680 GJ/yr of electromagnetic radiation, and that a solar collector field could produce 390 to 520 GJ per year of heat and 130 GJ of electricity from this source using current conversion technology. This is not "free" energy because it has to be collected and brought into the home in a useful form. It is sufficient to meet all the heating and cooling needs of each of the houses studied, however, if the energy were "purchased" by installing the collector field. Since there is sufficient solar energy available to meet all heating and cooling needs, the relative service efficiency of a solar system depends on how well the system can match the available energy to the need, ie. what fraction of the heating or cooling load still has to be supplied by external energy sources.

Through the use of sufficient batteries or thermal storage, no external energy contribution is required (100% solar faction). The thermodynamic efficiency is therefore equal to 100%. Including the embodied energy of the technology, however, would reduce the efficiency to less than 100%.

Heat Pumps and Air Conditioners

A similar situation occurs when using heat pumps (or air conditioners) to convert ambient energy sources (ground or air) to useful heating or cooling energy. The heat pump uses electricity (or any high temperature heat source) to upgrade ambient air heat to useful house heat. The thermodynamic efficiency then equals the delivered exergy divided by the embodied exergy of the heat pump and the external exergy consumption of the heat pump. Since in an electric heat pump, the COP is effectively a measure of heat output per unit electricity input (i.e. subtracting the ambient contribution), the thermodynamic efficiency η_t of these typical units, excluding embodied energy, would be as follows:

$$\eta_t = \frac{\eta_e C_o}{COP\ C_e}$$

Table 4.5 shows the thermodynamic efficiency for a variety of heat pump types.

Table 4.5
Thermodynamic Efficiencies of Heat Pumps

Heat Pump	Seasonal COP	Exergy[9] Factor Ratio	Fuel[10] Cycle Efficiency	Thermodynamic Efficiency
Conventional Air/Air	1.7	0.05	0.5	1.5%
Efficient Air/Air[11]	3.0	0.05	0.5	2.6%
Ground Source	4.0	0.05	0.5	3.5%
Practical Best Technology	10.0	0.05	0.5	8.7%

Combustion Heating Systems

A gas or oil furnace has a seasonal combustion efficiency ranging between 75% for a convention unit to 80% for an induced draft furnace, and 92% for a condensing unit. It delivers about 50 GJ/a of energy.

In addition to fuel, a typical furnace fan consumes about 1200 kWh/a of electricity and typically delivers 500 l/s of air for about 1850 hours per year at 75 Pa pressure. For typical forced air systems, blowers deliver at 5 to 15% conversion efficiencies. The efficiency is a function of both the blower (typically 10% to 20%), motor efficiency (50% to 75%), and the design of the distribution system. If air volume flow is twice what it is required for peak thermal delivery (not unusual), matching flow to requirements for the same distribution support and heat exchangers lowers the power requirement 8 times (P is proportional to V^3). Rates may be further modulated to match instantaneous demand, not peak, thus further lowering friction losses (Carrier and Chinook).

The thermodynamic efficiencies for gas and oil furnaces and furnace blowers, are shown in Table 4.6.

[9]Exergy Factor for 50°C heat = 0.05, Exergy Factor for Electricity = 1, Exergy Factor Ratio = 0.05.

[10]Average fuel cycle efficiency for electricity is about 50% (see Appendix B).

[11]With variable speed scroll compressor.

Table 4.6
Thermodynamic Efficiencies of Furnaces & Blowers

Device Component	Seasonal Efficiency	Exergy Factor Ratio	Fuel Cycle Efficiency	Thermodynamic Efficiency
Conventional Gas Furnace	75%	0.05	84%	3.1%
Induced Draft Gas Furnace	80%	0.05	84%	3.3%
Condensing Gas Furnace	92%	0.05	84%	3.9%
Efficient Oil Furnace	85%	0.05	90%	2.5%
Electric Furnace	100%	0.05	50%	2.5%
Air Mover Electric Blower	6%	0.05	50%	3%

Devices To Move Air Over Occupants

Cooling fans are frequently used to move air over occupants. They may be directional for stationary occupancy or whole room. As shown previously, the absolute power requirements are very low due to the low friction and turbulence losses of air in air. A typical 1400 mm diameter ceiling fan draws about 120 watts. It has been estimated that a fan of this size operates at about 3.5 rev/s and will deliver about 5,000 l/s at head height at an average velocity of about 1.6 cm/s[12]. This is equivalent to an efficiency of about 47%. The absolute efficiency, including a fuel cycle efficiency of 50%, would be 24%. This efficiency could be improved through the use of a more efficient fan motor, a more efficient fan design, or the use of photovoltaic electricity to supply the power.

[12]Personal Communication, Allen Associates Ltd., 400 Mount Pleasant Road, Suite 5, Toronto, Ontario M4S 2L6.

4.2 Air Quality

4.2.1 Types of Air Quality Requirements

There are three basic requirements for air quality in a dwelling:

- supply of oxygen for human (and animal) respiration
- removal of carbon dioxide produced by humans and other devices or drawn into the house from external sources
- removal of toxic substances released within the envelope or drawn in from exterior sources

The maintenance of indoor air (IAQ) quality involves many separate tasks, not all of which may be required in every home. Moreover some homes accomplish these tasks using very different systems and technologies, and at varying levels of service for each task. The complexity of the issue requires an approach where each possible IAQ task is addressed separately, without consideration for synergies with other IAQ related energy transformations.

The following air quality control needs have been addressed in this study:

Oxygen supply to occupants:	Life support function
Carbon dioxide removal:	Occupant related pollutant

Because many of the energy requirements are seasonally related, and because the energy values are frequently insignificant over shorter time periods, a one year period is appropriate.

A more detailed discussion of oxygen and carbon dioxide is provided in Appendix E.

The most common "device" used to control air quality is the combination of natural air infiltration and mechanical ventilation. The exchange of fresh air fulfils each of the air quality requirements. It removes toxic substances and carbon dioxide, and brings in sufficient fresh air to maintain oxygen levels. Other "devices" that can be used to remove carbon dioxide and produce oxygen include plants which generate oxygen through photosynthesis. The faster the plant growth, the higher the net oxygen production (photosynthesis minus respiration).

The relative service efficiency of a device such as a mechanical ventilation system used to provide oxygen and remove carbon dioxide is equal to the energy requirement of the most efficient device divided by the external energy used by system, i.e. the energy used to operate the mechanical ventilation system, the energy used to condition the ventilation air (heating or cooling of outside air), and the embodied energy of the system.

The estimated energy used by a typical house for supplying oxygen to the occupants using a mechanical ventilation system is 16,400 MJ/a. When compared with the energy requirement for oxygen supply and carbon dioxide using photosynthesis of 23 MJ/a, the relative service efficiency is equal to 0.14%.

Detailed calculations of the energy used by mechanical ventilation systems to provide oxygen and remove carbon dioxide are provided in Appendix E.

4.3 Lighting

Lighting is a requirement not in itself, but as a means of facilitating other human needs for survival, comfort and enjoyment of life. The need for lighting is also heavily dependent on lifestyle. Before electricity became available, the options for producing artificial light had hardly changed in several thousand years - essentially something had to be burnt to produce light. Now a night shift worker, for example, can live without seeing daylight for extended periods. Similarly, the availability of artificial light has allowed many more tasks to be carried out on a more frequent basis. The "need" for light has therefore greatly expanded. An analysis of household lighting needs is summarised in Table 4.7, and produces a calculated total daily requirement of around 50 kJ or 18 MJ/a. Details on the derivation of these requirements are given in Appendix F.

Lighting can be provided by a variety of means, including: natural daylight, light from combustion of fuels (e.g., kerosene), and electric lamps. The perfect lighting system would translate 100% of energy used into light, and illuminate only those areas needed when light was required. In reality, however, lighting systems do not come close to this. Inefficiencies occur in the lamp itself (as measured by its efficiency), in the fixture (as measured by its coefficient of performance), in its usage (area and deviation), and its frequency distortion. Appendix F provides a table of typical coefficient of performance and lamp efficiencies for a range of standard and high efficiency electric lighting fixtures.

The availability of daylight to meet household lighting requirements is dependent on a vast range of conditions and factors, including geographic latitude, weather patterns, site, time of year, building envelope characteristics (e.g., number, shape, size, location, type of windows and other daylight-transmitting devices/strategies), as well as many aspects of lifestyle (e.g., time spent in the house, daily regime, number of persons present, the various costs of providing artificial illuminance, household "will" to use daylighting, etc).

For this (necessarily) simplified analysis, the amount and intensity of daylight incident on a vertical wall at each cardinal point of the compass was averaged for the Ottawa area. Then estimates were made of the interior lighting requirements which could be met using daylight. These figures total 9.9 MJ/year. More detail is given in Appendix F.

Table 4.7
Residential Daily Activity Lighting Requirements

Activity	IES Class	Intensity (Lumens/m²)	Required Space (m²)	Required Duration (Hrs.)	Required Energy (kJ)
General Lighting	B	75	5	4	7.9
Dining	C	150	4	0.75	2.4
Grooming	D	300	3	2	9.5
Workbench					
Ordinary	D	300	4	0.25	1.6
Difficult	E	750	2	0.25	2.0
Critical	F	1,500	0.5	0.25	1.0
Easel hobbies	E	750	2	0.5	4.0
Ironing	D	300	3	0.5	2.4
Kitchen Counter					
Critical	E	750	0.5	1	2.0
Noncritical	D	300	2	3	9.5
Kitchen Range					
Critical	E	750	0.75	0.25	0.7
Noncritical	D	300	0.75	0.25	0.3
Kitchen Sink					
Critical	E	750	0.5	0.25	0.5
Noncritical	D	300	0.5	0.125	0.1
Laundry	D	300	1	0.125	0.2
Music Study	E	750	1	0.75	3.0
Reading	D	300	0.2	2	0.6
Sewing	E	750	0.5	0.25	0.5
Sleep				8	0.0
House Empty				7.5	0.0

Total Daily Consumption 48 kJ

Total Yearly Consumption 18 MJ

The absolute lighting requirements outlined above were compared against the electricity used by typical lighting "devices". These devices are commonly a combination of windows and electric lighting systems. The electricity consumption of these lighting systems, assuming a certain level of daylighting, were used to produce estimates of absolute efficiency.

Table 4.8 provides estimates of the absolute efficiencies of lighting devices used in a typical house to meet the absolute energy needs shown in Table 4.7, assuming the daylighting contributions shown in Appendix F, and lamp usage found in a typical house, i.e. a mixture of incandescent and fluorescent fixtures designed to illuminate large areas for relatively long periods. The absolute efficiency of the lighting system is equal to the absolute energy requirement divided by electric energy only, i.e. net of natural lighting. Both forms of energy (lighting and electricity) have the same energy quality, therefore there are no exergy effects. The full fuel cycle efficiency of electricity (50%) has to be included, however, in the estimate of efficiency.

More details are provided in Appendix F which shows the fixture efficiencies of the latest advances in lamps and reflectors. If these devices (fixture efficiency of 11%) were matched precisely to the lighting need in terms of time needed and area needed, absolute efficiencies for dwelling lighting could be increased to about 5% (i.e., about 13:1).

4.4 Clothes Washing

Clothes cleaning involves the removal of a wide range of soil materials from clothing, including: water soluble materials (e.g., perspiration), pigments (e.g., oxides, carbonates), fats (e.g., sebum), proteins (e.g., blood, egg), carbohydrates (e.g., starches), and dyes (e.g., tea, fruit). In order to perform these cleaning tasks and others such as whitening and foam regulation, complex detergents have been developed for use in water. Wash performance is highly sensitive to textile properties, soil type, water quality and temperature, washing technique and detergent composition.

Because of the difficulty in defining the actual energy required to remove dirt, a surrogate for absolute energy was used -- the amount of energy used to wash a given quantity of fabric by hand in cold water. This energy requirement was estimated to be about 9 kJ/kg of dry clothing or 31 kJ for a typical wash. More details on how this was estimated are given in Appendix I.

Table 4.8
Actual Electric Lighting Energy Use in a Typical Dwelling

Activity	Duration of Use (hours)	Fixture Type	Bulb Type	Fixture Lighting Efficiency	Area Lit (m^2)	Absolute Lighting Efficiency
General Lighting	4	Ceiling	Incand.	0.7%	20	0.09%
Dining	1	Ceiling	Incand.	0.7%	5	0.16%
Grooming	2	Ceiling	Incand.	0.7%	3	0.37%
Workbench						
Ordinary	0.5	Ceiling	Fluor.	3.4%	4	0.51%
Difficult	0.5	Ceiling	Fluor.	3.4%	2	0.84%
Critical	0.25	Ceiling	Fluor.	3.4%	2	0.42%
Easel hobbies	0.5	Ceiling	Incand.	0.7%	3	0.15%
Ironing	0.5	Ceiling	Incand.	0.7%	3	0.22%
Kitchen Counter						
Critical	1	Ceiling	Incand.	0.7%	2	0.09%
Noncritical	3	Ceiling	Incand.	0.7%	3	0.24%
Kitchen Range						
Critical	1	Hood	Incand.	1.2%	1	0.11%
Noncritical	1	Hood	Incand.	1.2%	1	0.11%
Kitchen Sink						
Critical	1	Ceiling	Incand.	0.7%	0.5	0.09%
Noncritical	1	Ceiling	Incand.	0.7%	0.5	0.05%
Laundry	1	Ceiling	Fluor.	3.4%	10	0.02%
Music Study	1	Lamp	Fluor.	5.3%	4	0.49%
Reading	2	Lamp	Incand.	0.7%	2	0.04%
Sewing	1	Ceiling	Fluor.	3.4%	3	0.07%
Sleep	8					
House Empty	7.5					

Absolute efficiencies for a number of washing devices and cycles and a number of hot water heating devices have been calculated by comparing their measured energy use against the (surrogate) absolute energy requirement - in this case handwashing in cold water - and are given below in Table 4.9.

Efficiency calculations are estimated with and without 50% of the hot water energy input to a wash/rinse cycle being recovered using a "sudsaver" or other heat recovery device. Derivation of the energy used by each washing device is shown in Appendix I. Derivation of the efficiencies of water heating devices, taking into account the different exergies of the various fuels is given in Appendix G.

Table 4.9
Absolute (Surrogate) Efficiencies of Clothes Washing Devices

Clothes Washing Device/Cycle	Absolute (Surrogate) Efficiency
Handwash: cold wash/rinse	100%
Vertical axis hot wash/warm rinse	0.8%
Vertical axis warm wash/cold rinse	1.7%
Vertical axis warm wash/cold rinse with suds saver	3.2%
Horizontal axis: cold wash/rinse	2.4%
Horizontal spraywash: warm wash/cold rinse	5.2%

4.5 Clothes Drying

The energy required to remove moisture from clothes consists of either the mechanical energy needed to physically remove the water or the heat needed to evaporate water. While the mechanical energy needed to remove moisture down to 60% (by dry weight) is relatively small[13], the minimum energy required to remove the last 60% will be by evaporation. This value is estimated to be 1.5 MJ/kg of dry clothes. Details are provided in Appendix I.

Absolute energy efficiency for a number of domestic clothes dryers, including gas dryers and new systems currently under development are shown in Table 4.10. These efficiencies take the exergies of the supply fuel and need into account. More detail is presented in Appendix I.

The energy consumption values shown in Table 4.10 do not include the spin drying energy used by clothes washers (see section 4.4) but do include exhaust blower and tumbler motor energy

[13]Only a fraction of clothes washer energy is consumed by the spin dryer.

as this is included in the power rating. The absolute efficiencies also assume that the dryers take advantage of warm inside air. The efficiencies would be lower if the dryers used colder outside air. The results clearly show the low efficiencies of drying devices, even those which use innovative techniques such as heat-recovery or microwave energy.

Table 4.10
Absolute Efficiencies of Drying Devices

Dryer Type	Total Energy Use/Cycle (MJ)	Exergy Ratio	Absolute Efficiency (%)
1. Clothes Line	0	1	-
2. Conventional Electric Dryer	54.7	0.05	0.3
3. Conventional Dryer with Moisture Sensor	39.9	0.05	0.4
4. Heat Recovery Electric Dryer (with sensor)	29.9	0.05	0.5
5. Heat Pump Dryer (with Sensor)	25.9	0.05	0.6
6. Gas Dryer	20.3	0.05	0.7
7. Microwave Dryer	35.9	0.05	0.4

4.6 Interior Surface Cleaning

Cleaning tasks inside the house include floor and carpet cleaning, and floor waxing/polishing. The absolute energy required to carry out this task will depend on floor surface characteristics, the definition of "cleanliness", and on rates of interior soiling (which depend heavily on lifestyle and other factors).

For the purposes of this analysis, the absolute energy requirement for floor washing and carpet cleaning will be assumed to be the mechanical energy required to clean by hand (brush or a sponge mop) i.e., the energy delivered by a human being. The embodied energy of detergent (and that for heating water) will be disregarded.

A review of the power *delivered* during various hand operated activities, including carpet and floor cleaning are provided in Appendix H. The delivered power for floor cleaning is estimated to be 10 watts. The energy required to clean a floor in 20 minutes is therefore 10.8 kJ or 3 watt.hrs. From Appendix H, the total incremental (i.e. over and above resting rate) metabolic energy used by a human to deliver 10 watts of cleaning power is estimated at 110 watt.hrs (400 kJ) over a 20 minute period. The absolute efficiency of human hand cleaning is therefore 10.8/400 x 100% or 2.7%.

An average sized portable residential vacuum cleaner will draw a current of 4 to 7 amps at 120V, or 500 to 850 watts. If a 700 W machine is used at peak power draw for 5 minutes (equivalent to a 20 minute hand cleaning job), it will use 58 watt.hrs (210 kJ) of electrical energy. The absolute efficiency of the vacuum cleaner is equal to 10.8/210 x 100%, i.e. 5.1%. Since the energy quality of both fuel (electricity) and need (mechanical energy) are the same, there are no exergy effects.

4.7 Personal Washing

Personal washing involves the removal of various dirt and debris from the skin and hair. For comfort and health reasons it is assumed that this is done each day. It is assumed that some hot water will be required for personal washing in order to effectively remove oils, etc., from the body. It is also assumed that some heat is required in order to open the skin's pores for effective cleansing. For the purposes of this study, it was assumed that the minimum energy needed is the amount of energy required to reheat about 6 litres of water to a temperature that is comfortable on the body (say 40°C), and to scrub oneself with a sponge using soap and/or shampoo, then rinse. Other peripheral energy inputs include the embodied energy required to manufacture whatever soap is used and the amount of energy required to pump or otherwise deliver this small amount of water. It is not the intention to imply that using a small quantity of warm water is the recommended or desired level of service, it is only an estimate of the minimum necessary.

The absolute energy requirement is assumed to have two components: i) the energy used to reheat 6 litres of water from the temperature it reaches after washing is finished, (in a perfect situation, the heat lost from the dirty water would be used to reheat clean water) and ii) the energy required to scrub the body by hand. The combination of these two operations is estimated to require 250 kJ/wash. More details are given in Appendix I.

There are numerous ways to clean the body, including immersion of the body in hot water (bath), a hot shower, or use of steam or dry heat. A sauna, for example, can provide effective cleansing using very little water - just enough to wash off sweat and dirt, and this is often cold water, such as a cold shower or rinse. The principle is the same in a Turkish steam bath. Estimates of energy use per cycle (i.e. per "wash") are included below.

The above energy inputs for each washing device/strategy can be compared to the derived absolute energy requirement to produce an estimate of absolute efficiency. More details are given in Appendix I. The resulting absolute efficiencies are shown in Table 4.11. Conversion efficiencies for water heaters are shown in Appendix G.

Table 4.11
Absolute Efficiencies for Personal Washing Strategies

Personal Washing Device	Washing Efficiency
Shower	8%
Bath	1.0%
Sauna, one person use	2.2%
Sauna, four person use	9.4%

Hot water energy can be recovered via a greywater heat exchanger: up to 50% of input energy (See Appendix G). If this energy could be recovered at the point of use, (as in a sudsaver washer or heat recovery dryer), the efficiency would be increased significantly.

4.8 Personal Drying

The removal of water from a person's body can have two energy components: the mechanical energy required to dry the person and the energy required to remove (by evaporation or other means) the water directly from the body or from a towel or cloth. If a Japanese-style drying cloth is used to dry the body, this cloth is wrung out several times during the drying process, meaning that only a fraction of the amount of water originally on the body need be evaporated. A conventional towel is usually air dried so that all the water is evaporated rather than wrung from the towel. The energy required for drying is estimated to be 3.6 kJ/wash. More details are given in Appendix I.

Three personal drying devices/strategies are considered: i) towel dry, ii) towel dry with 2 minutes of hand-held hairdryer (1000 W), iii) 2 minutes of infra-red lamp (500 W) with 1 minute of hand-held hairdryer (1000 W). Absolute efficiencies were calculated by comparing the energy used by each device/strategy with the absolute requirement on a "per person dried" basis. While towel drying will have an efficiency of 100%, use of a hand-held dryer or infra red heater will reduce this to about 3%. More details are provided in Appendix I.

4.9 Food Preparation

Mechanical food preparation, including chopping, mixing, blending, whisking, slicing, etc. is commonly performed in North America using a wide range of mechanical labour-saving devices such as food processors, blenders, electric can openers and carving knives. For the purposes of this study, a surrogate for the absolute energy need was taken as the human effort required to perform these mechanical tasks. This can then be compared to the energy used by various devices to perform those same tasks in order to estimate absolute efficiencies.

The amount of energy used for three common food preparation tasks is as follows:

Chopping:	3.6 kJ
Stirring:	4.3 kJ
Beating:	3.1 kJ

More detail is provided in Appendix J.

The range of labour (and time-) saving devices available for the modern kitchen is wide, and includes everything from electric can openers to coffee grinders. It is assumed that a food processor can be used for each of the above food preparation tasks, having a variable speed electric motor of 400 W size. Absolute efficiencies for each of these tasks can be defined by dividing the respective energy values for human-powered work by the respective energy inputs to the food processor. Absolute efficiency for three tasks are shown in Table 4.12.

Table 4.12
Absolute Efficiencies of Food Preparation Devices

Task	Device	Power (watts)	Time (mins)	Energy Used (MJ)	Efficiency (%)
Chopping	Food Processor	200	5	60	7.5
Stirring	Food Processor	250	10	150	3.5
Beating	Food Processor	400	5	120	1.7

4.10 Cooking

The energy requirement of cooking depends only on the specific and latent heat of the food, and the original (starting) and the final (degree of doneness) temperatures of the food. The power levels required will depend on the cooking time and therefore the original preparation and the device used (see below), i.e. there will be no absolute power level.

The amount of cooking energy which is actually absorbed by food has been estimated by experimentation, by measuring the heat losses and heat absorption of a standard electric oven when it is used for baking. A 1979 study[14] analysed the energy used to bake five food types: sponge cake, Yorkshire pudding, cod fish, pork sausage and potatoes. Results showed that the amount of energy absorbed by each food sample during cooking ranged between 430 and 720 kJ per kilogram of food, over cooking times which varied from 8 to 22 minutes. The author's conclusion was that required cooking energy is directly proportional to the sum of the sensible[15]

[14]R.Collison, *Energy Consumption During Cooking*, Journal of Food Technology (1979) #14, p.173-179.

[15]"Sensible heat" was assumed to include heat of reaction.

and latent heat components i.e. to its water, fat and solid components, and the amount of water it loses during cooking. This implies that the energy required to cook food fully is independent of the time taken to do it; cooking time is therefore a function of the device used, and the degree of preparation of the food.

Cooking devices use various methods to bring the molecules of the food being cooked up to the cooking temperature. The method used determines the cooking time. While cooking time does not affect the energy absorbed by the food, it does effect the amount of energy lost during cooking and of course the power levels required.

Estimates of cooking time, power levels and energy used to cook a casserole in various types of cooking devices are shown in Table 4.13.[16]

Table 4.13
Absolute Efficiencies of Cooking Devices

Appliance	Cooking Time (hrs)	Average Power (watts)	Energy Used (MJ)	Effective Efficiency	Exergy Ratio	Full Fuel Cycle Efficiency	Absolute Efficiency
Gas Oven	1	3280	11.8	5%	0.2	0.84	0.8%
Electric Oven	1	2000	7.2	5%	0.2	0.5	0.5%
Convection Oven	0.75	1853	5.0	33%	0.2	0.5	3.3%
Toaster Oven	0.85	1140	3.4	n/a	n/a	n/a	n/a
Frying Pan/Wok	1	7600	3.2	n/a	n/a	n/a	n/a
Crock Pot	7	100	2.5	67%	0.2	0.5	6.7%
Microwave Oven	0.2	1440	1.3	40%	0.2	0.5	4.0%

The effective cooking efficiencies (including warm-up losses) of various cooking devices have been estimated by a number of food science researchers. The absolute efficiency is equal to the effective cooking efficiency times the exergy ratio[17] between the energy source and need (heat). Typical efficiencies are shown in Table 4.13.

Ambient energy sources such as solar energy must, in most cases, be upgraded in order to effectively perform cooking functions, although some cooking operations are best suited to low grade heat. A solar oven will cook many dishes effectively but slowly, and only when placed in direct sunlight.

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[16] Consumer Guide to Home Energy Savings.

[17] The quality of heat for cooking at 200°C is about 0.2. The quality of electricity or gas is 1.0. The exergy ratio is therefore 0.2.

A more detailed review of cooking energy requirements and devices are given in Appendix J.

4.11 Refrigeration

The energy requirement for refrigeration has two components[18]: firstly the sensible heat energy required to lower the temperature of a food load from the ambient to the refrigeration temperature (normally 4 to 5°C), and secondly the energy required to keep it there within an environment at (for example) 20°C. The first of these energy components is a direct function of the specific heat of the food load, since it does not involve any phase changes. Foods with water contents have high specific heat loads; fat has half the specific heat capacity of water, while solids have one-third.

The second component must be analysed as a rate of heat flow (or power level) rather than as a discrete amount, and therefore a thermal resistance must be defined through which heat flows. This is dependent on the device used for refrigeration.

There is a large quantity of unused or wasted space inside most conventional refrigerators. For example, the absolute volume (i.e. mass/density) of 7.75 kg of food is just 8.2 litres, which, even if doubled to allow for the bulking of spherical fruit and vegetables, amounts to an actual volume of 15 litres. This represents just 3% of the volume of a standard 18 cu.ft. (509 litre) refrigerator. The energy required to cool down and maintain this volume of food is estimated to be only 122 kJ/day (see Appendix J).

The performance of five different refrigeration devices is shown in Table 4.14. These range in size from a standard 18 cubic foot refrigerator to a high efficiency 7 cubic foot unit manufactured in Denmark (the LER200, made by Gram) which is still adequate in size to store the reference load. The other models are intermediate between these two types: two relatively energy-efficient 18 cu. ft. models, one with a consumption of 700 kWh/yr, and one at 275 kWh/yr (the Sunfrost refrigerator, manufactured in California).

Some devices are now being developed which utilize through-the-wall heat pipes connected to outside fans. The heat pipes use outside air to cool the refrigerator when ambient temperatures are below freezing. An estimate of the performance of a heat-pipe adaption of the Sunfrost refrigerator is shown in Table 4.14.

A refrigerator designed with sections which could be activated as required, so that the refrigerated area matched the actual volume of food, and with all of the high efficiency techniques used in the Sunfrost with heat pipe adaptations would use far less electricity.

[18] Strictly speaking the energy required to warm food back up to ambient temperature should also be taken into account here, but since this energy is normally supplied by another device (ambient air, the house heating system or a cooking device), it has been disregarded here.

Table 4.14
Absolute Efficiencies of Refrigerators

Refrigerator Type	Size (cuft)	Size (litres)	Load	Est. Elec. Use (kWh/year)	Est. Elec. Use (kWh/day)	Est. Elec. Use (kJ/day)	Absolute Efficiency (%)***
1. Standard	18	509	7.75 kg mixed	1200	2.5	8877	0.7
2. Small High Efficiency	7	198	7.75 kg mixed	89	0.2	878	6.9
3. Improved Standard	18	509	7.75 kg mixed	700	1.9	6904	0.9
4. High Efficiency	18	509	7.75 kg mixed	275	0.8	2712	2.2
5. Heat Pipe Adaptation	18	509	7.75 kg mixed	200	0.6	1980	3.1

*** Absolute efficiency for a refrigerator is assumed to be the absolute energy requirement (averaged out over a full week for the given thermal load of food) divided by the daily electrical demand of the machine, allowing 50% full fuel cycle efficiency.

The absolute efficiency of a refrigerator is defined as the measured or rated electricity use per unit time (i.e., excluding any ambient contributions) of a refrigerator divided into the rated electricity use of the best technology. Since all units are electric, no allowance for differences in energy quality need to be made. Table 4.14 shows the calculated absolute efficiencies for the refrigerators analysed in this study. The figures range from 0.7% (for the conventional standard 18 cu.ft. unit) to 3.1% for the heat pipe unit, and to 6.9% for the small high efficiency refrigerator.

More details on refrigeration and refrigerators are given in Appendix J.

4.12 Freezing

Freezing food at a temperature of around -18°C effectively kills many microbiological organisms, and prevents the growth of all others. Since the texture and quality of many foods is not adversely affected by freezing, this method is a fast, effective way of food preservation. Energy for freezing was defined in the same way as for refrigeration, with the difference being that latent heat of freezing which is also taken into account.

The energy requirement for freezing therefore has three components: sensible heat, latent heat, and the steady state heat energy required to sustain a temperature difference of 38°C. The energy required for a typical freezer load is estimated to be 430 kJ/day (See Appendix J).

Four freezers are examined here. Each has a volume of approximately 13 cubic feet (368 litres) and each is assumed to be loaded each month with the food load outlined above.

Absolute efficiencies were calculated for each freezer model as device energy use per day divided into the energy used per day to maintain the freezer load at the required temperature.

These calculated values are shown in Table 4.15, and vary from 2.1% for the standard freezer, to 6.8% for the evacuated panel model. More details are provided in Appendix J.

Table 4.15
Absolute Efficiencies of Freezers

Freezer Type	Size (cuft)	Size (litres)	Load	Est. Elec. Use (kWh/year)	Est. Elec. Use (kWh/day)	Est. Elec. Use (kJ/day)	Absolute Efficiency (%)***
1. Standard	13	368	24 kg mixed	1400	2.9	10356	2.1
2. Standard+	13	368	24 kg mixed	680	1.9	6707	3.2
3. High Efficiency	13	368	24 kg mixed	380	1.0	3748	5.7
4. Evac. Panels	13	368	24 kg mixed	320	0.9	3156	6.8

*** Absolute efficiency for a freezer is assumed to be the absolute energy requirement (averaged out over a full month for the given thermal load of food) divided by the daily electrical demand of the machine, assuming 50% full fuel cycle efficiency.

4.13 Food Drying

Drying or desiccation is a food preservation option for many foods which have high water contents. Drying reduces or eliminates the susceptibility of fresh food to microbial attack, and if it is done properly, the nutritional content of the food remains unchanged, although rehydration is usually necessary.

The estimated absolute energy requirement for several foods ranging from beef strips to blueberries is between 1.1 and 1.6 MJ/kg.

Two types of devices are commonly used to dry food, an electric air dryer and a solar air dryer. Taking into account the differences in energy quality between the energy source used (electricity) and the need (heat), the absolute efficiency of an electric dryer is estimated to be about 10%. Since a solar dryer effectively uses no external energy, its absolute efficiency ignoring its embodied energy will be infinite (see Appendix J).

4.14 Audio Entertainment

Sound is a variation in pressure, stress, particle displacement and velocity in a medium (i.e. air). The absolute energy requirement for any entertainment medium which uses sound can be defined theoretically at least, as the energy required to actually oscillate the eardrums of persons listening to it. This is a minute amount of energy, a power level of 10^{-8} W. See Appendix K for more details.

Any number of different devices are available on the retail market to provide audio entertainment, and range in size and power output from the Walkman-type personal stereos to large and powerful speaker systems.

An estimate of the absolute efficiency of a given audio entertainment device can be found by dividing the absolute power requirement by the rated input of the system, both of which are expressed in watts. Some examples are shown in Table 4.16 below.

Table 4.16
Estimated Absolute Efficiencies for Audio Devices

Device	Power Input (watts)	Absolute Efficiency* (%)
Walkman Stereo	4.2	10^{-6}
Speakerphone	3	10^{-6}
Clock Radio	5	10^{-6}
Stereo System	100	10^{-8}

* assuming a comfortable hearing level of 10^{-8} W.

4.15 Visual Entertainment

The absolute energy requirement for a moving visual image is difficult to define. The amount of light and resolution required by a viewer is very small, but is also dependent on the image resolution expected, the distance of the viewer from the "screen", and other factors. A minimum power requirement of 1 watt is (approximately) the power required to operate a colour LCD laptop computer screen with no "built-in" backlighting[19]. This is used as a **surrogate** absolute energy requirement.

Estimates of average TV use in North America vary widely; Lawrence Berkeley Labs has used an estimate of approximately 4 hours/day as a basis for comparison. At a power output of 1 W this corresponds to an absolute energy requirement of 5.3 MJ per year.

The range of audio-visual devices available to the consumer grows yearly. Table 4.14 compares the energy requirements of six devices with that of the 1 W laptop screen.

[19]Competitek: Personal communication with Mr.Bristol Spickney, Sept.'92; LCD screens typically draw from 5 watts (monochrome) to 15 W (colour). However, most of this draw (i.e. more than 90%) is due to backlighting. A Swiss reference quotes the actual LCD input at between 0.00002 and 0.0002 W/cm^2; for a screen sized at 450 cm^2 this represents a power draw of 0.009 and 0.09 watts. Some minor backlighting is therefore assumed for our 1 watt screen power estimate.

Conventional television sets use energy for a number of purposes: to amplify the signal, to heat the filament, and to accelerate and control the electron beam used to excite phosphors on the screen. Electronic tuning also adds to demand, and most TVs also use standby power (1.5 to 8 W) even when the set is turned off, in order to ensure "instant readiness"[20]. Colour sets use an average of 3 times the power of black and white sets.

Energy use by TVs is weakly correlated with screen size, but wide variations exist within each size class. The devices listed in Table 4.17 range in size from a small colour TV (13 inch screen) to a large screen, projector model. One of the devices is also assumed to be used at all times with a VCR, for comparison.

Table 4.17
Absolute (Surrogate) Efficiency for TV Models

TV Model	Est. Power Input (watts)	Est. Avg. Energy Use[21] (MJ/a)	Absolute (Surrogate) Efficiency (%)
LCD display	1	5	100
13" Colour	55	290	1.7
20" Colour	80	410	1.2
20" Colour with VCR	110	560	0.9
26" Colour	110	560	0.9
"Projection" TV 50" screen	310	1600	0.3

4.16 Outdoor Services

A large number of outdoor activities are undertaken in a residential dwelling, from snow removal to gardening. Time and human energy saving devices can be obtained to perform many of these services. This section compares typical energy inputs to some of these devices against the human energy required to do the job using unpowered mechanical devices. The surrogate absolute energy requirement is assumed to be the energy delivered by a human when undertaking outdoor services without the use of powered equipment.

[20]Competitek: *The State of the Art - Appliances*, Rocky Mountain Institute, 1989.

[21]These figures assume an average TV use of 4 hours per day.

Absolute energy estimated on this basis for several outdoor services is shown in Appendix K. Snow removal, for example, requires about 20 watts, equivalent to tossing 5 kg of snow 2 meters every 5 seconds.

Four outdoor services were examined using a powered device, namely a snowblower, electric lawnmower, hedge/edge trimmer and leaf blower (in place of snow shovel, push-mower, shears and rake).

Estimates of the amount of time taken to do various outdoor tasks are as follows, both using power tools and "by hand" are shown in Table 4.18. Also shown are the estimated surrogate absolute energies (by hand energy delivered), the estimated energy used by the power tools, and the subsequent absolute efficiencies. See Appendix K for more details.

Table 4.18
Outdoor Services Absolute (Surrogate) Efficiencies

Task	Assumed Time Taken "by hand"	Estimated Human Power Expended	Assumed Time Taken w/Power Tool	Power Tool Rating	Est. Elec. Power Used	Absolute (Surrogate) Efficiency
	(mins)	(kJ)	(mins)	(watts)	(kJ)	(%)
Snowblowing	30	36	20	3000	3600	1
Grass Cutting	30	27	15	1000	700	4
Hedge Cutting	60	22	45	300	700	3
Leaf Blowing	45	32	30	1200	1800	2

5. CONCLUSIONS

5.1 Absolute Energy

This study showed that the absolute amounts of energy actually needed to carry out common household tasks are usually low. Where the service met is itself a form of energy (cooking, lighting, cleaning, etc.), the amount and quality of energy needed is significantly lower than the amount and quality of energy actually consumed by devices used to meet the need. This leads to very low thermodynamic or absolute efficiencies for these devices. Where the household service is not itself a form of energy (e.g., comfort, air quality, etc.), state-of-the-art devices come close to being able to meet these needs without consuming energy (except for embodied energy), but devices in common use today use significantly more energy.

Absolute energy can be defined as the minimum energy necessary to provide a service. The energy need is often subjective to the occupant's desired level of service, however. For example, the minimum energy necessary for personal washing would be the energy provided in a small amount of warm water plus some mechanical scrubbing action. Most people would not consider this acceptable. The degree of "doneness" of meat is also very subjective, and will also affect the energy required for cooking.

Although absolute energy was often not easily derived in its strictest sense for a given service, it was found that "surrogates" could be used in many cases. One surrogate used was the energy delivered when a task is done by-hand by the building occupants (e.g., snow shovelling, clothes washing). In other cases it was the energy used by the most efficient process (e.g., liquid crystal TV display). The use of surrogates does not imply a recommendation that this is the way a need should be met. The energy delivered by a human doing a task is a measure of the energy needed, not the desirability that the human carry out the task by hand.

It was found that absolute energy also needs to be expressed in terms of the required power level and energy quality. Lighting for example requires a minimum light level for each task as well as a length of lighting time. It also requires a high quality energy form - light. Energy quality is particularly important when the energy need is for a low quality energy form - e.g., warm water or heat. The concept of exergy was found to be a useful measure of quality and illustrated the low thermodynamic efficiencies of many housing devices (see below).

In general it was found that the absolute energy requirements for most intrinsic energy services were quite low. This has real implications as to the possible efficiency improvements to devices which meet those needs (see below).

5.2 Energy Availability

There are many sources of energy available to meet household energy demands. Sources of energy available to a typical residential dwelling lot, can be divided into ambient, internal and external sources. Ambient sources are defined as energy sources available directly to the lot. Internal energy sources are defined as energy resulting from the activities of dwelling occupants and the devices they use in the dwelling which are a source of heat. Finally, external energy sources are defined as energy sources which can be brought on to the residential lot from outside.

It was found that the amount of solar energy, wind energy and soil thermal energy available on a residential building lot are significantly greater than the relatively small needs of intrinsic energy services, or the amounts of energy used to meet energy extrinsic services such as comfort maintenance and air quality. The energy quality of two of these sources, solar and wind, also match many of the energy quality needs of intrinsic services.

The "collection" of this ambient energy into a useful form, however, requires the use of conversion and storage devices. In the case of soil thermal energy, an external source (usually electricity) is also needed to upgrade the quality of the source to a useful quality level. The conversion and storage devices also have embodied energy which will reduce the amount of energy effectively "available" from the source in the thermodynamic sense.

Full fuel cycle efficiencies also reduce the "availability" of external energy sources. One (1) MJ of electricity energy delivered to a housing lot requires an average of 2 MJ of primary energy to generate it and transmit it to the dwelling. Similarly, energy is required to mine, extract, process and deliver fossil fuels to the lot. This full fuel cycle efficiency has a significant effect on device absolute efficiencies (see below).

5.3 Thermodynamic Efficiencies

The thermodynamic efficiencies of household devices used to meet energy requirements were, with a few exceptions, found to be extremely low. Some of the results are summarized in Table 5.1. Many have efficiencies that are lower than 1% even for the most "efficient" device on the market, and most have efficiencies less than 20%.

There is, however, significant room for improvement in the thermodynamic efficiency of household devices. While there are already indications that some innovative work is underway, a great deal can still be done. Some of the areas for improvement are as follows:

- **Improve Conversion Efficiencies** - Many devices do not convert electrical or fossil fuel energy efficiently into the energy actually required. Most of the losses are in the form of heat, either because of inefficient electricity transformation or because of simple heat losses.

- **Matching Device to the Need** - Many devices are far larger than necessary (e.g., a refrigerator) -- usually so that they can be sold to meet a large number of requirements. They also tend to provide a constant output even though the energy need fluctuates (e.g., lighting and refrigerators). Introducing control systems to match output to need and designing the device to meet a variety of loads (e.g., compartmental refrigerator) would improve efficiency.

Table 5.1
Energy Uses and Absolute Efficiencies for Mechanical Devices

Household Energy Requirement		Absolute Efficiency Low - High
Heating:	Heat Pump	1.5 - 8.7%
	Fossil Fuel Furnace	3.1 - 3.9%
	Electric Heat	2.5%
	Electric Blower	3%
Air Movement:	Ceiling Fan	24%
Lighting:		0.02 - 0.8%
Household Cleaning:	Clothes Washing	0.8 - 5.2%
	Clothes Drying	0.3 - 0.7%
	Interior Surface Cleaning	5%
Personal Cleaning:	Personal Washing	1.0 - 9.4%
	Personal Drying	3.0%
Food Preparation:	Chopping	7.5%
	Stirring	3.5%
	Beating	1.7%
	Cooking	0.5 - 6.7%
Food Preservation:	Refrigeration	0.7 - 3.1%
	Freezing	2.1 - 6.8%
	Food Drying	10%
Audio/Visual Entertainment:	Audio Entertainment	10^{-8} - 10^{-6}%
	Audio-Visual Entertainment	0.3 - 1.7%
Outdoor Services:	Snow Removal	1%
	Grass Cutting	4%
	Hedge Cutting	3%
	Leaf Blowing	2%

- **Match Energy Quality Through Choice of Fuel** - Many devices use a high quality energy source (electricity or fossil fuel) to meet a low quality energy need (heat). This results in exergy ratios of less than 0.1, which significantly reduces efficiency. The low generation efficiency (as low as 29% for nuclear generated electricity) coupled with resource extraction and transmission losses, means that fuel cycle efficiencies of purchased energy sources also significantly reduce efficiencies. Using more waste heat and energy sources with high fuel cycle efficiencies would greatly improve exergy ratios and efficiencies.

- **Increased Use of Ambient Energy Sources** - Significant amounts of energy are available from ambient sources on the dwelling lot or within the dwelling (e.g., solar gain), or as waste heat from other devices. Devices should take advantage of these free sources. The solar energy falling on a dwelling lot, the wind energy available, and the heat retained in the ground are sufficient, with the appropriate conversion device to meet significant portions of a dwellings' energy needs. Some devices are designed to utilize on-site energy sources (e.g., photovoltaic generator, wind generator, ground source heat pumps), but most are not.

In the case of the dwelling envelope, the study compared the net energy loads associated with various envelopes and environmental conditions. This allowed each heating and cooling strategy to be judged against how close it came to the "ideal" house where all energy needs are supplied from ambient sources. Although embodied energy was not included, it was shown through computer simulation that net heating and cooling loads of zero were possible through the use of the appropriate mix of environmental conditions, clothing levels, envelope insulation, heat recovery, natural cooling, solar gain, and heat and cold storage.

5.4 Areas Not Covered

This study attempted to take a comprehensive look at energy needs and availability in housing. It was not possible, however, to cover all household requirements which use energy. In a similar way, a cross-section of devices were analysed with respect to their thermodynamic energy efficiency -- concentrating on those currently available and those with high and low efficiencies.

The embodied energy of devices was not addressed in the estimation of absolute efficiency except in one requirement, air quality. Inclusion of embodied energy would lower absolute efficiencies and the relative service efficiencies of the devices analysed. In some cases, exclusion of embodied energy meant that efficiencies could not be estimated.

A wide variety of energy sources available to a dwelling lot were also reviewed and quantified. Some smaller sources and those that would not be available on all lots were not analysed, however. These include surface water flow, composting, and night sky cooling. External sources not included were propane and coal, and while the full fuel cycle of external energy sources was considered, the energy embodied and environmental impact resulting from extraction, processing and generating infrastructure were not, nor were any non-energy resource impacts.

6. RECOMMENDATIONS FOR FUTURE WORK

The findings of this study show that there are significant improvements that can be made in the efficiencies of household devices, and that this area is worthy of more study. Future work should concentrate on the following areas:

- **Inclusion of Embodied Energy in the Derivation of Absolute Efficiencies of Devices**

Future work should build on the present work already begun on the energy embodied in building envelopes and other devices[22]. Energy quality considerations should be included in all embodied energy research. Inclusion of embodied energy would allow a complete thermodynamic analysis to be carried out on household devices.

- **Improved Simulation of Envelope Heating and Cooling, Including More Appropriate Treatment of Dynamic Walls, Heat and Cold Storage, Moisture Storage/Release, Solar/Internal Gains and Natural Ventilation**

The use of housing models to estimate the heating and cooling loads of the building envelope showed significant limitations in the ability of most models to simulate very low energy envelopes with innovative structural features such as dynamic walls and sunspaces, and high thermal storage. Most models also do not effectively model moisture. Further work is needed to improve current models. Use of ex-mainframe models such as DOE2 should be investigated for further use for residential building simulation.

- **More Detailed Analysis of Specific Energy Requirements where Surrogates had to be Used, Including Mechanical Tasks such as Food Stirring and Cleaning**

More research is needed on the estimating of the actual amount of energy transferred when an energy intrinsic service is met. This would minimize the requirement to use surrogates in the estimation of absolute energy.

- **Analysis of Other Air Quality Requirements such as Toxic Substance Removal**

Air quality is a difficult service to analyze. It is energy extrinsic and involves the removal of toxic materials from air and surfaces. More research is needed, particularly on toxic substances removal.

[22] Optimize , A Method for Estimating the Lifecycle Energy and Environmental Impact of a House. Canada Mortgage & Housing Corporation, October 1991.

- **Development of Means to Optimize the Use of Envelope and Other Devices to Minimize Energy Use in Housing**

Understanding the interactions between various energy services and the devices used to meet these needs will contribute to the optimization of housing design. One of the follow-up areas of study should be simulation of the reference dwelling in which the absolute energy requirements and the thermodynamic efficiencies of each device are linked together, so that the optimum efficiency of each device can be determined.

APPENDIX A

HOUSING DEVICES

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HOUSING ENERGY DEVICES

Table A.1 presents a summary of energy services, both extrinsic and intrinsic, and the appliances/components used to meet these services.

Table A.1
Devices Used to Meet Housing Energy Services

Energy Service	**Approach Used**	**Appliances/Components Usage**
Energy Extrinsic Services:		
Space Comfort	Heating	Envelope Insulation Solar Gain Control Chemical Mass Air Mover Moisture Control Surface Temperature Control Electric/Gas/Oil/Solar Heating System
	Cooling	Envelope Insulation Solar Gain Control Thermal Mass Moisture Control Air Mover Surface Temperature Control Electric/Gas/Oil/Solar Heating System
	Moisture Control	Dehumidifier Humidifier Moisture Storage Air Mover
Air Quality	Oxygen/Carbon Dioxide Control	Ventilation Systems
	Toxic Substances Removal	Ventilation Systems Filter Systems
Security	Alarms	Electric Alarms

Energy Service	Approach Used	Appliances/Components Usage
Energy Intrinsic Services		
Lighting	Light Fixtures	Incandescent Lamps Fluorescent Lamps Halogen Lamps Reflectors Ballasts Daylight-Enhancement Task Timing Control Systems Kerosine Lamps Candles
Food Preparation	Mixing/Cutting, etc.	Food Mixers/Processors
Food Cooling/Freezing	Heat Removal	Refrigerators Freezers
Food Thawing	Heating Natural Evaporation	Microwave Oven Range
Cooking	Heating	Range Microwave Oven Crock Pot
Food Drying	Heating	Solar/Air Dryer Electric Dryer
Food Preservation	Low Temperature	Refrigerators Freezers
Clothes Washing	Water	Detergents Clothes Washers Electric/Gas/Solar Hot Water Heaters
	Dry Cleaning	Solvents Dry Cleaning Equipment
Clothes Drying	Draining	
	Air Drying Heating	Clothesline Electric/Gas Dryer

Appendix A: Housing Devices

Energy Service	Approach Used	Appliances/Components Usage
Personal Washing	Water	Bath Shower Electric/Gas/Solar Hot Water Heaters
	Perspiration	Sauna
Personal Drying	Towel Drying	
	Air Drying	Hair Dryer
Surface Cleaning	Dirt Removal (Physical)	Vacuum Cleaners Sweeping
Snow Clearing	Snow Removal (Physical)	Snow Blowers Shovelling
Audio/Visual Entertainment	Radio	Personal system Room System
	TV	
Home Repair Maintenance	Nailing/Sawing/Drilling	Hand held tools Power tools

APPENDIX B

ENERGY SOURCES AVAILABLE ON A TYPICAL HOUSING LOT

Marbek

ENERGY SOURCES AVAILABLE ON A TYPICAL HOUSING LOT

B1. Types of Sources Available

Table B.1 presents a summary of the availability, quality and measures of quantity for three types of energy sources available in housing:

- Ambient Energy Sources
- Internal Energy Sources
- External Energy Sources

Table B.1
Availability and Quality of Energy Sources

Source	Quality	Availability	Measure of Quantity
AMBIENT SOURCES			
Solar Energy	Radiant	Diurnal and Seasonal	Energy falling on vertical and horizontal surfaces and captured by building or collection device
Wind Energy	Mechanical	Variable with season & height	Power level and frequency at various heights above ground and captured with conversion device
Soil Thermal Energy	Thermal	Seasonal swings in temperature	Low grade heat capacity of soil and captured by heat pump
Water Supply	Mechanical Thermal	Seasonal temperature swing and constant pressure	Power at mains pressure and heat capacity for typical temperature swings
Ambient Air Temperature	Thermal	Diurnal and seasonal variation	Degree days above and below several temperatures

Source	Quality	Availability	Measure of Quantity
Ambient Air Moisture/Dryness	Thermal	Diurnal and seasonal variation	Humidity levels above and below comfort range
ENERGY FROM ACTIVITIES			
Ventilation Exhaust Air	Thermal	Depends on ventilation profile	
Human Heat and Moisture	Thermal	Task dependent	
Cooking Heat and Moisture	Thermal	Task and device dependent	
Lighting Heat	Thermal	Task and device dependent	
Heat from Power Cleaning and Other Devices	Thermal	Task and device dependent	
Grey and Black Water Heat	Thermal	Task and device dependent	
Heat and Fuel from Waste Decomposition	Thermal Chemical	Task dependent	
EXTERNAL ENERGY SOURCES			
Electricity	Electromagnetic	Continuous*	Full fuel cycle efficiency from several primary sources
Natural Gas	Chemical	Continuous*	Full fuel cycle efficiency
Coal	Chemical	Continuous	Full fuel cycle efficiency
Oil	Chemical	Continuous	Full fuel cycle efficiency for each grade

Source	Quality	Availability	Measure of Quantity
Wood	Chemical	Continuous	Full fuel cycle efficiency

* Subject to distribution system interruption

B2. Typical Housing Lot Used As A Reference Dwelling

The basic Ottawa house which is used in the study as a reference lot has the following characteristics and dimensions:

- Detached, 2-storey with basement, unshaded
- 4 walls, oriented to cardinal compass points
- Floor area = 133 m^2; Gross ceiling area = 67 m^2
- Basement 1.6 m below grade, Floor area 67 m^2
- Areas as follows:

Orientation	Wall Area (m^2)	Window Area (m^2)	Door Area (m^2)
East	36.0	5.75	1.8
South	54.0	5.75	
North	36.0	5.75	
West	54.0	5.75	
Total	**180.0**	**23.0**	**1.8**

B3. Solar Energy

Basic Resource

Solar energy approaches the earth as electromagnetic radiation extending from X-rays that are 0.1μm in wavelength to radio waves that are 100m in wavelength. The earth maintains a thermal equilibrium between the annual input of shortwave (0.3 to 2.0 μm) radiation from the sun and the outward flux of longwave radiation (3.0 to 30 μm). About 99% of the sun's radiant energy is contained between 0.28 and 4.96 μm.

Table B.2 lists the average monthly solar radiation falling on a horizontal surface in Ottawa, and also that falling on a plane inclined at 45° to the horizontal facing south.

Table B.2
Mean Daily Global Solar Radiation on Horizontal and Inclined Surfaces, Ottawa (assuming south-facing inclined surface)

	Average Daily Radiation on Horizontal (MJ/m^2)	Total per Month on Horizontal Surface (MJ/m^2)	Average Daily Radiation on Inclined Surface @ 45° Facing South (MJ/m^2)	Total per Month @ 45° (MJ/m^2)
July	21.3	660	18.1	561
August	18.1	561	18.3	567
September	13.4	402	17.8	534
October	8.6	267	15.7	487
November	4.7	141	11.7	351
December	4.3	133	12.6	391
January	5.7	177	15.3	474
February	9.4	263	19.0	532
March	13.6	422	20.3	629
April	16.8	504	18.6	558
May	19.9	617	17.9	555
June	21.4	642	17.3	519
Total per year		4789		6158

Sources: Canadian Climate Normals, *Solar Radiation 1951-80*, Environment Canada AES, Table 1 p.4
Ratios of Horizontal to Inclined Radiation from *Solar Engineering of Thermal Processes*, J. Duffie and W. Beckman, John Wiley 1980, Table D4

The annual solar energy falling on the reference lot is therefore equal to 4789 MJ/m^2 x 350 m^2 or 1680 GJ.

This is more than sufficient to meet all the energy needs of a house, including heating, cooling, lighting and other requirements. The proportion of this energy that can be collected, however, depends on the form or quality needed (heat, electricity, etc.) and the efficiency of the conversion device. A larger proportion of energy can be converted by tilting the conversion device towards the sun. The house itself is also a potential collector, with free energy being available through windows, and additional energy falling on the walls and roof.

Solar energy can therefore be made available to a dwelling in three ways:

i) as electricity through photovoltaic conversion on the dwelling lot, and transferred to the dwelling
ii) as heat through thermal conversion on the lot, transferred to dwelling, and
iii) as direct solar energy falling on the dwelling itself.

Solar Energy Available on Lot Through PV Conversion

An estimate of the maximum amount of PV energy which can be collected on an average lot can be calculated if we assume collection efficiency and tilt and orientation. However this calculation is complex, since the sun's altitude varies daily, and an optimum solution has to be found for the vertical dimensions of PV panels, their horizontal spacing across the lot and their angle of tilt. A rigorous analysis of the optimal dimensions of these variables is beyond the scope of this summary.

The total amount of solar radiation incident annually on a range of PV panels sited uniformly across a 10m x 35m Ottawa residential lot, assuming a tilt angle of 45°, a spacing between rows of 2.42m, and a panel height of 1.0m can be estimated as follows:

Number of collector rows = 35/2.42 = 14
Total solar panel area = 14 * 1.0 * 10 = 140 m^2
Total incident solar radiation on panels = 140 x 6158 = 860 GJ

Assuming a PV collector efficiency of 15%, the total amount of electricity generated by this array is therefore (0.15 * 860) = **130 GJ/a.** The maximum possible collection efficiency for photovoltaics is agreed to be about 30%. This technology would provide 260 GJ/a.

Note: the amount of direct sunlight received by the PV array will be slightly less than this amount due to the spacing of the rows, which permits clear sunlight to shine on them at any angle greater than or equal to 24.6°; at the winter solstice, the sun's maximum elevation is 22° in Ottawa, meaning that a part of the PV array will be shaded for a short time at midwinter.

Solar Heat Available on Lot Through Thermal Conversion

An estimate of the average amount of solar energy available for thermal conversion, on the same Ottawa residential lot described alone, for two different types of collectors, is as follows.

Assuming the same collector area as above, the total incident solar radiation on the collectors is 860 GJ. For a typical glazed flat-plate collector supplied with a selective surface absorber and operating with a fluid inlet temperature of 40°C, the average efficiency is about 45%. Therefore, the amount of thermal energy available is:

45% x 860 GJ = **390 GJ/a**

The maximum temperature at which this energy can be delivered at this efficiency is about 75°C.

For a typical cylindrical parabolic concentrator operating with a fluid inlet temperature of 200°C, the average efficiency is about 60%. Therefore, the amount of thermal energy available is:

60% x 860 GJ = **520 GJ/a**

Collectors of this type can deliver energy up to as high as 250°C, which is high enough to operate absorption cooling devices and generate electricity.

Solar Heat Available Directly on Building Envelope

The average monthly incident solar radiation on a vertical surface in Ottawa is given in Table B.3. The data is based on measured weather parameters.

Table B.4 is based on the data provided in Table B.2, and shows the amount of incident solar radiation (direct and diffuse) on the unshaded Ottawa reference house with equalized window spacing and wall dimensions given in Section B.2.

Table B.3
Monthly Incident Solar Radiation on Vertical Surfaces (Ottawa) (MJ/m^2)

Month	North	East	South	West
July	184	361	281	351
August	140	332	322	332
September	89	215	296	219
October	65	173	346	172
November	41	88	213	95
December	87	144	319	143
January	109	181	378	181
February	130	186	303	189
March	247	408	525	393
April	198	379	398	331
May	165	339	295	354
June	202	376	289	398

Source: *Solar Heat Gain through Windows in Canada*, S.A.Barakat, NRCC 18674.

Table B.4
Monthly Incident Solar Radiation on Unshaded Reference House (Ottawa)

Month	Window (GJ)	Total Wall (GJ)	Sum (GJ)
July	6.7	43.9	50.7
August	6.4	42.3	48.7
September	4.7	31.6	36.4
October	4.3	30.2	34.6
November	2.5	17.7	20.3
December	3.9	28.2	32.2
January	4.8	34.4	39.3
February	4.5	31.7	36.3
March	7.4	48.3	55.7
April	7.5	50.2	57.7
May	6.6	43.1	49.7
June	7.2	47.1	54.3
Total (GJ/a)	67.1	449	516

B4. Wind Energy

Basic Resource

Wind energy is a manifestation of solar energy, caused by the flow of air across the earth's surface between areas of higher and lower pressure. Wind power is directly proportional to the cube of wind speed, and is also dependent on air density. Wind velocity varies all the time, and for simplification, a standard probability distribution of wind velocity is used to calculate net available energy over extended periods of time.

The flow of wind over the earth is retarded by surface friction and interference with surface features such as trees and hills. All wind energy conversion systems operate within this boundary layer, which is normally between 300m and 500m in depth. Wind speed data is usually collected for a height of 10m above the ground. For Ottawa, in an open area (e.g., airport) the average annual windspeed at 10m is around 4.1 m/s. In a built up or treed area, the windspeed will be lower and about 2.7 m/s in the Ottawa area.

Mechanical Wind Energy Available Annually on Dwelling Lot

Table B.5 shows the average annual wind velocity on an Ottawa residential lot at 10m above ground to be 4.1 m/s, and the average kinetic power in the wind at this height to be 80.6 W/m^2. The total wind energy available to a lot 10 m by 35 m will also depend on the direction of the wind. The minimum energy available, assuming that wind could be collected up to a height of 20m would be equal to 80.6 W/m^2 x 200 m^2 x 8760 hrs or 510 GJ/a.

Usable Energy

A Wind Energy Conversion Device (WECD) is any device which converts kinetic energy from a moving airstream into a more useful form of energy. Both vertical axis and horizontal axis WECDs are common. The theoretical maximum useful energy that can be derived by a wind generator from a given airflow is 0.593 times the total aerokinetic energy. However, any design must perform well over a large range of airspeeds. A typical coefficient of performance (C_p) for a state-of-the-art WECD is 0.3. Table B.6 provides an estimate of usable mechanical energy that could be produced using a WECD with a C_p of 0.3 and a rotor diameter equal to 10 m (the maximum practical size for a dwelling lot 10 m x 35 m), with its shaft at 10m above the ground. This represents the maximum amount of energy that could be retrieved on the lot if it were outside a built-up or treed area.

This mechanical energy may be used directly (e.g. for pumping, etc) or it may be converted into electricity using a generator. The amount of delivered energy will be equal to the usable energy multiplied by the overall efficiency of the mechanical and electrical conversion system, where the usable energy is the theoretical maximum aerokinetic energy which can be extracted.

Table B.5
Average Annual Wind Velocity and Kinetic Wind Power, 10m above Ground

Month	Average Wind Velocity (m/s)	Average Kinetic Power of Wind (W/m²)
January	4.5	106.6
February	4.5	106.6
March	4.6	113.9
April	4.7	121.5
May	4.1	80.6
June	3.7	59.3
July	3.3	42.0
August	3.2	38.3
September	3.6	54.6
October	3.9	69.4
November	4.2	86.7
December	4.3	93.0
Annual Average	**4.1**	**80.6**

Table B.6
Usable Mechanical Energy of a 10m diameter WECD

Month	Usable Energy (GJ)
January	0.88
February	0.85
March	0.94
April	0.97
May	0.66
June	0.47
July	0.34
August	0.32
September	0.43
October	0.57
November	0.69
December	0.77
Annual Total	**7.9 GJ/a**

B5. Soil Thermal Energy

Basic Resource

In most parts of Canada, the depth of frost penetration is between 1.0 and 1.2 metres. Below a depth of around 5m, the temperature is stable at approximately 7 - 9°C year round. The ground beneath any residential lot therefore contains large quantities of low-grade heat which can be extracted to meet user needs.

The temperature profile of soil is affected by three general categories of conditions: meteorological, terrain and subsurface. Meteorological variables include ambient temperature regime; duration and intensity of solar radiation; and type and amount of precipitation. Terrain variables include topography, type and amount of vegetation. Subsurface variables include types and thermal properties of soils and rocks, presence and movement of water.

The ability of soil to store heat energy is defined as its volumetric heat capacity (C_v). This property varies widely for any soil type depending on its water content; higher water content produces higher C_v values and increased rates of heat flow through the soil. In the Ottawa region, where soils are primarily fine-grained, typical C_v values range from 1.80 - 2.50 kJ/kg°K. There is usually a significant time lapse between ground temperatures and surface temperatures; in Ottawa the maximum ground temperature at a depth of 5m is reached 4 to 6 months after the summer air temperature peak.

The total available heat energy in the ground beneath an Ottawa residential lot (350 m^2), assuming C_v = 2.0 KJ/Kg°K, down to a depth of 5m from the surface, has 2 components, sensible heat and latent heat. The sensible heat component has been calculated assuming the drop in temperature of soil over the heating season is 8°C, for the total volume of soil (350 * 5 = 1750 m^3) and is approximately 28 GJ. The latent heat component is much larger in most soils, since water liberates around 334 kJ/kg when it freezes. Assuming a soil dry density of 2400 kg/m^3, and a water content of 35%, the latent heat component for the same soil volume is calculated at 490 GJ. The total energy content is therefore about 520 GJ. Assuming that snow cover prevents any make up of this heat during the heating season, this represents the maximum available per year.

Heat Energy Available from a Residential Lot Using a Ground Source Heat Pump

While it is possible to extract heat from the ground and use it directly, the small temperature gradients and therefore low rates of heat flow require that the quality of the energy be upgraded; normally this means pumping the heat to a higher temperature. This can be accomplished using a ground source heat pump (GSHP). GSHPs may be installed in horizontal trenches in the soil, or in shafts drilled vertically beneath a lot. Horizontal GSHPs are typically placed at the normal frost line in order to utilize the latent heat given off when water freezes in the ground below the frost line.

It has been shown that the most efficient configuration for a GSHP is to use a horizontal spiral heat exchanger laid in a 30 cm diameter ditch[1]. Measured values for heat extraction from a horizontal spiral GSHP installation in Ottawa vary from 140 watts/m in December to 125 W/m in March. The seasonal coefficient of performance of GSHPs are now approaching 4.0. A 10m spiral coil GSHP would therefore extract 1200 to 1400 watts during the winter heating season at a power input of around 400 to 450 watts. At 1000 full load hours per season, this would deliver the equivalent of 6.5 GJ of heat. A 200m spiral (about the maximum that could be used on a 10m x 35m lot), would produce 130 GJ of heat (while consuming 32 GJ of electric power), which is more than enough for any normal dwelling.

B6. Ethanol Production from Biomass

Basic Resource

Ethanol can be produced by fermentation of a wide variety of plants. Basically, the process involves fermentation by microorganisms (e.g. yeasts) of simple sugars to ethanol and carbon dioxide. Feedstocks can be selected from among many plants which produce either simple sugars or starch and cellulose. If starch and cellulose-producing plants are used, then these products must be reduced from their complex form to basic glucose. Typical feedstock crops are sugar beet and various grains, such as wheat and barley. If grains are used, then the breakdown of starch products must involve milling or grinding, and the preparation of a slurry which can be heated to temperatures high enough to break the cell walls of the starch (around 60°C), producing complex sugars which can be further reduced by enzymes to the desired sugar product.

Fermentation (using yeast) of the simple sugar solution produces ethanol and CO_2, a process carried out between 27 - 35°C. For each kilogram of ethanol produced, the fermentation process liberates 0.957 kg of CO_2. The yield of ethanol is around 0.5 kg ethanol for each kilogram of sugar. Ethanol boils at around 77°C so it can easily be removed from the resulting solution by distillation. While fermentation of cereal grains to produce ethanol uses most of the carbohydrates, almost all of the protein can be recovered in the stillage coproduct, and this stillage can be fed to animals as a high-protein source.

[1]Otto Svek, 1990/91, National Research Council

Chemical Energy Available on a Residential Lot from Ethanol Production

Typical ethanol yields from various domestic feedstocks are as follows[2]:

Cereal grains - 11.4 litres/bushel
Potatoes - 6.4 litres/cwt
Sugar beet - 83 litres/tonne

Assuming a yield of 65 bushels of corn/acre = 161 bushels/ha; ethanol production is 1832 litres/ha. For an area the size of our residential lot (350 m^2), ethanol production from cereal grain can therefore be estimated at (350/10000)*1832 = 64 litres.

Assuming an energy value of 30 MJ/litre for ethanol, energy production for an area 289 m^2 in size is (30 * 64) = 1.9 GJ/year. To put this figure in perspective, this energy is equivalent to the average amount of solar energy falling on a 10m x 4m south facing wall in Ottawa during 3.3 days in January.

B7. Fuelwood Production

Basic Resource

To within a few percent, all woods have the same energy content when compared on an oven-dry, unit weight basis, 19.8 MJ/m^3. The major differences which exist between wood types primarily concern density and moisture content; for example, green Chestnut heartwood has an average moisture content (on a dry basis) of 120%, while for green pine or cedar the moisture content is close to 30%.

The energy content of a cord therefore depends on the wood type and dryness. One full cord contains an estimated volume of 80 cubic feet of solid wood (2.27 m^3), in a stacked volume of 128 cu.ft. (3.4 m^3). If a cord is assumed to be 50% hardwood (r.d. = 0.75) and 50% softwood (r.d. = 0.35), then its heat value is estimated at 24.8 GJ (assuming oven dry wood).

Chemical (Fuel) Energy Available on a Residential Lot through Fuelwood Production

The Woodburner's Encyclopedia[3] reports that a sustainable annual fuelwood yield from a mixed (i.e. hardwood and softwood) 5 acre (2.02 ha) woodlot is around 3 full cords. Therefore the size

[2]Source: Fuel from Farms - A Small Scale Guide to Ethanol Production, SERI, U.S. DoE, 1980.

[3]by J. Shelton and A. Shapiro, pub. Vermont Crossfields Press, 1976, p.7

of woodlot required to produce a single cord on a sustainable basis is approximately 0.67 ha (6700 m^2), or 1.7 acres.

For an area of size 350 m^2 = 0.035 hectares, maximum sustainable wood production is therefore in the order of (0.035 * 2.02) = 0.07 full cords, with a heating value when dried of (0.07 * 24.8) = 1.7 GJ.

B8. Water Supply Pressure and Heat

Basic Resource

When pressurized water is brought across the lot line, it represents a potential source of mechanical energy. This summary looks only at the energy available per unit mass once the water is brought to the lot, not at the efficiency of the greater municipal delivery and pumping system.

In built-up or suburban areas, water is generally delivered from a street mains pipe at a typical pressure of 60 psi (413.7 kPa).

Since pressure = $p = \rho gh$ = 1000 kg/m^3 * 9.81 m/s^2 * h; solving for h at 60 psi yields a head of 42.2m. The velocity of efflux of an ideal fluid from a small orifice under a static head varies with the square root of the head, or: $v = (2gh)^{0.5}$; solving, v = 28.8 m/s. This represents the maximum velocity of water from a half-inch pipe at 60 psi.

Household water supply is also a source of heat. The temperature of the water varies over the year, and along the mains distribution system. It is possible for the water temperature to gain as much as 8°C in the winter months and lose 2°C in the summer months, between the water purification plant and the residential lot (depending on flow rate, distance, ambient group, etc.). A typical profile of mains water temperature at both an Ottawa water purification plant and an Ottawa lot are listed in Table B.7.

Table B.7
Typical Ottawa Mains Water Temperature

Month	Mean Water Temp. of Purification Plant (°C)	Average Water Temp. at Residential Lot (°C)
January	0.1	6.0
February	0.2	6.2
March	0.6	7.8
April	4.1	8.1
May	13.4	17.8
June	21.0	21.4
July	23.4	22.6
August	23.0	21.2
September	19.1	19.3
October	11.7	15.9
November	5.9	9.1
December	0.9	4.8

Mechanical Energy Available to a Dwelling from Residential Water Supply

Assuming that 0.5 inch plumbing pipe is used within the house, the cross sectional area A of the pipe = 1.27×10^{-4} m^2; the rate of water flow Q = $28.8 * 1.27 \times 10^{-4}$
= 3.65 litres/s = 3.65 kg/s.

The kinetic energy of the moving body of water is given by $E = 0.5mv^2$. Therefore assuming the maximum flow rate through half-inch pipes, the kinetic energy delivered is:

$$E = 0.5\ (3.65)\ (28.8)^2 = 1513 \text{ J/s} = 1.51 \text{ kJ/s}$$

The amount of kinetic energy which is delivered to a household annually via the mains water supply is therefore dependent on the volume of water used. Table B.8 estimates these amounts for various levels of water use.

Table B.8
Kinetic Energy Delivered in Household Water Supply

Volume of Water Use (litres/Household.day)	Total Kinetic Energy Delivered (MJ) per year @ 60 psi
100	15
500	75
1000	151
2000	302
3000	453
5000	755

If this mechanical energy were converted to electricity, using a turbine generator, the amount of electricity would be equal to kinetic energy times generator efficiency.

Putting this into perspective, a small appliance has an annual electricity consumption of around 150 MJ/a; this is the electrical energy supplied by about 1000 l/day of water when delivered at 60 psi through a half inch pipe at 100% conversion efficiency. The City of Ottawa Water Supply Dept. reports an average daily rate of water use of approximately 1000 litres/day, for a four person family.

This calculation represents delivered "free" energy on site; it should be remembered that energy is used at the pumping station to pressurize the water.

B9. Residential Solid Waste

Basic Resource

Estimates of the amount of solid waste produced by an average Canadian family vary considerably, and have been the subject of numerous studies as part of efforts by municipalities to cope with the waste stream. In Ontario, a recent engineering study undertaken in the town of Fergus on behalf of the Ministry of the Environment[4], found that low income families generated the lowest average daily refuse rate (0.78 kg/person.day), followed by mid income families (0.80 kg/person.day). High income families, at 0.88 kg/person.day had the highest rate of domestic solid waste production. The weighted generation rate for all incomes and dwelling types was found to be 0.804 kg/capita.day

[4]*Residential Waste Composition Study*, Gore and Storrie, and Decima Research, for Waste Management Branch, MOE, January 1991, Appendix A1

The composition of the waste analysed, and the corresponding energy content is shown in Table B.9.

Table B.9
Energy Content of Typical Solid Waste Stream

Waste Type	**Percentage of Waste Stream (%)**	**Energy Content (dry basis) (kJ/kg)**
Paper - various	27.3	17,220
Glass	5.3	-
Ferrous - cans, etc.	3.7	-
Non ferrous cans, etc.	0.9	-
Plastics - all	8.6	44,200
Organic - food waste, etc.	28.8	19,250
Wood	1.4	19,800
Ceramics & Fibreglass	1.8	-
Diapers	4.4	23,500
Textiles, Leather, Rubber	4.2	-
Hazardous - paint, solvents	0.4	-
Dry Cell Batteries	0.07	-
Kitty Litter	3.3	-
Medical Waste	0.07	-
Miscellaneous	0.8	-
Ashes	-	-
Blue Box items	8.6	-

Heat Energy Available through Combustion of Residential Solid Waste

The residential waste stream can be considered a potential source of energy if it is burned to recover heat. The average heat energy equivalent produced per week from combustible solid waste by a family of 4 is shown in Table B.10, based on a total waste production of (4 * 7 * 0.804 kg) = 22.5 kg.

Table B.10
Solid Waste Production from Typical Household

Combustible Waste Type	Amount Produced (kg/week)	Energy Available (MJ/week)
Paper - various	6.2	106.7
Plastics - all	1.9	83.9
Organic - food waste, etc.	6.5	125.1
Wood	0.3	5.9
Diapers	1.0	23.5
Total per Household	15.9	345.1

Therefore a total of 345 MJ/week is available; if this material is burned in a stove or incinerator with an overall efficiency of 65%, then the heat generated weekly = 224 MJ.

On an annual basis, this represents a total heat availability (at 65% combustion efficiency) of 11.7 GJ. There is also a downstream impact on energy use as combustible waste does not have to be collected and landfilled.

B10. Composting

Composting is a potential source of heat/fuel gas energy since composting is an exothermic process. As long as the composting temperature is maintained, excess heat from composting organic waste (kitchen, garden and human) is available for use on the lot.

B11. Ambient Air

Ambient air is an unlimited source of heating and cooling, and can be used directly when the ambient temperature is above or below the required temperature, or indirectly using a heat pump at any temperature. In general, the amount of energy available is proportional to the degree days above or below the desired temperature over the desired period. See Section 4 for more discussion of outside air source heat pumps.

B12. Waste Water

B12.1 Blackwater Heat

The water flow from toilets can represent a significant source of heat loss in a building during the heating season. According to the Rocky Mountain Institute publication *Water*, published in 1988, most North American toilets use approximately 19 litres per flush (innovative design and engineering can easily reduce this amount, to less than 5 litres per flush).

An average family of four living in Ottawa will use around 1000 litres per day, of which 240 litres are hot water, and a further (estimated) 300 litres are mixed with this hot to produce warm water for various uses. Assuming a further 50 litres per day for drinking, cooking and watering household plants, etc. this leaves (1000 - 590) = 410 litres per day used by house toilets, which translates to 21.5 flushes per day.

If we assume a groundwater temperature of 9°C, and an interior air temperature of 20°C, and if all the toilet water is assumed to reach the air temperature, then the total recoverable daily heat will be (410 kg * 4.18 kJ/kg°C * 11°C) = 18.8 MJ. The annual recoverable heat would be 6.9 GJ.

B12.2 Greywater Heat

The energy recoverable from greywater is inversely proportional to the drop in temperature of hot water from intake to outflow in each hot water use. During a shower, for example, the water temperature of the flow falls by around 7 - 8°C, with this heat being absorbed by the body, ambient and by the bottom of the bathtub or shower stall. The outflow water is therefore at 30 - 32°C, and if a greywater heat exchanger is used, much of this heat can be recovered into the incoming flow.

Average outlet temperature is a function of average inlet temperature, with the mix of cold and hot water assumed as follows:

Inlet:	Shower/Bath:	40°C	Outlet:	Shower/Bath:	30°C
	Dishwash:	55°C		Dishwash:	45°C
	Clothes wash:	50°C		Clothes wash:	35°C

Assuming an overall use pattern as follows, average outlet temperature can be calculated

Shower/Bath, etc.: 60% Dishwash: 14% Clothes wash: 26%
Avg. Outlet Temperature = (0.6(30) + 0.14(45) + 0.26(35)/1.0) = 33.4°C

The average four-person household has an average daily hot water demand of 240 litres. Assuming an average inlet temperature of 9°C and an average greywater outlet temperature of 33.4°C, the total daily recoverable heat will be (240 kg * 4.18 kJ/kg°C * 24.4°C) = 24.5 MJ. The annual recoverable heat would be 8.9 GJ.

APPENDIX C

FUEL CYCLE ANALYSIS

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EXTERNAL ENERGY SOURCES - FUEL CYCLE ANALYSIS

C1. Introduction

A "fuel cycle" efficiency analysis is used to quantify each of the upstream energy losses associated with the delivery of various external energy sources. These upstream losses include those incurred during extraction, processing, transporting, refining and transmitting the various external energy sources which are commonly used in Canadian residences.

This brief analysis summarizes estimates of fuel cycle efficiencies for the following fuels:

Electricity - from Coal
Electricity - from CANDU Nuclear
Electricity - from Hydro power
Fuel Oil
Natural Gas

Ontario Hydro reports an installed system capacity of approximately 32.5 GW for 1993 (based on the operation of the Darlington nuclear station). This generating capacity and overall utilisation is broken down by fuel type in Table C.1.

Table C.1
Ontario Hydro Generating Capacity (projected 1993)

	Capability			Deployment		
Type	Fuelling Unit Energy Cost ¢/kWh	Capacity Factor (%)	Annual Energy (TWh)	Capacity Factor (%)	Energy (TWh)	Demand (%)
Hydraulic	0.1	63	36	63	36	23
Nuclear	0.5	80	99	78	96	62
Fossil-Coal	2.4	80	65	29	23	15
Fossil-Oil	5.6	80	18	0.5	0.1	
Total			218		155.1	100

Source: *Providing the Balance of Power*, Ontario Hydro DSP Report, 1990, 4-6

The following analysis looks at each distinct process in the production and delivery process for each of the major residential fuels. For these processes, a "primary energy efficiency" figure and an "ancillary energy use" figure is given, based on estimates or measurements of the energy required to do that particular task. The primary energy losses concern direct losses to the energy source (e.g. coal spillage during shipping or gas pipeline leaks) while the ancillary energy requirements concern the energy input by various means to the process (e.g. electricity required to drill coal out of the rock, diesel fuel needed to transport it). To estimate the ancillary energy requirements, tertiary energy estimates are multiplied by secondary efficiency coefficients.

The primary efficiency and the ancillary energy estimates are then combined to give an efficiency coefficient for the process as a whole.

C2. Coal-Fired Electrical Systems

Coal Supply

Ontario Hydro's coal is presently supplied by U.S. mines around Morgantown, West Virginia, and Pittsburgh, Pennsylvania. Generally, the coal is mined underground before being processed and transported to Ontario Hydro's power generating facilities. For each stage of the production of electricity, an efficiency coefficient (expressed as a percentage) has been calculated, as shown in the following sections. The overall, or full fuel cycle efficiency is therefore the product of these coefficients, as given in Section 2.6 and summarized in Figure 1.

Extraction: Mining

The U.S. uses two underground mining methods, namely "room and pillar" and "longwall" mining. Energy requirements are supplied by purchases of diesel fuel and electricity required to operate drills, draglines, tractors, trucks, etc. In all cases this ancillary energy is only around 0.4% - 0.6% of the embodied energy of the processed coal[5]. One other mining activity which has minor energy requirements is related to the gathering and transportation of the mined coal to a central collection point and delivery to the mine surface. This amount has not been quantified, but is believed to be insignificant.

i) Mining
- *Primary Efficiency* *100%*
- *Ancillary Energy* *0.5%*

ii) Underground Mining
- *Primary Efficiency* *100%*
- *Ancillary Energy* *0.02%*

Estimated Process Efficiency: 99.5%

[5] *Overall Thermal Efficiency of Residential Space Heating Modes*, U. of Waterloo Research Institute, 1976

Processing

This is usually done near the mine mouth, and consists of the following steps: crushing and screening; cleaning to remove dust and non-coal materials; and drying to prepare coal for shipping.

The cleaning process used is called "dense media" cleaning, which adds moisture to the coal and so reduces its available energy. In order to meet OH specifications the coal is then dried using hot air streams. The breaking and sizing operation has ancillary energy requirements of about 0.2%, with most of this (85%) energy supplied by electricity and the remainder by fuel oil.

For the washing operation the ancillary energy requirement is reported as 0.22 to 0.25%[6], at an efficiency of around 96%.

i) Breaking and Sizing

Primary Efficiency	*100%*
Ancillary Energy	*0.5%*

ii) Washing

Primary Efficiency	*96.4%*
Ancillary Energy	*0.6%*

Estimated Process Efficiency: 95.3%

Transportation

Coal from the U.S. industrial belt reaches Southern Ontario by rail transport to the port at Conneaut on Lake Erie, where it is shipped to the generating stations located on Lake Erie and Lake Ontario.

Primary efficiency losses from the transportation process include the following: wind loss of coal from the rail cars (an estimated 1% of the tonnage shipped), spillage during loading and unloading, the energy required to load and unload and the energy required to transport the coal 800 km by rail and 130 km by ship.

Primary Efficiency	*97.0%*
Ancillary Energy	*1.4%*

Estimated Process Efficiency: 95.6%

[6] Ibid.

Electricity Generation - Coal Fired Station

The efficiency of electrical generation is dependent to some extent on the fuel used, but also on the age of the plant and its use (i.e. for base load, peaking etc). For coal fired electricity generation, this report uses reported efficiencies from Ontario Hydro's plants at Nanticoke and Lambton. These efficiencies are reported to be 37.5% (90% load factor), 36.4% (50% load factor) and 35.2% (5% load factor). In accord with present usage at Nanticoke station, a figure of 36.4% was assumed.

Estimated Process Efficiency: 36.4%

Transmission of Electricity

Losses from transmission of electricity are proportional to line voltage. According to Ontario Hydro the transmission efficiency is calculated at approximately 95% i.e. 5% losses.

Estimated Process Efficiency: 95%

Distribution of Electricity

Distribution losses are those occurring after electricity has been sold by Ontario Hydro to the municipal utilities. Due to the shorter transmission distances involved here, these losses are lower than those outlined above, and are estimated at 3.5%, or an overall efficiency of 96.5%

Estimated Process Efficiency: 96.5%

Overall Efficiency - Coal Fired Electrical Systems

When the above components are multiplied together, an overall efficiency for coal fired electricity delivered to the home of 30.3% is obtained (see Table C.2). While this figure will vary somewhat depending on the type of electrical generating station used, and its use characteristics, it will not vary greatly due to the inherent inefficiencies of electrical production from thermal means. The burning of fossil fuels in an electrical power plant involves three energy conversion steps: chemical to thermal energy; thermal to mechanical energy; mechanical to electrical energy. While there are some losses associated with burning fossil fuel in the first step (typically 10 - 14% stack losses) the greatest source of inefficiency lies in converting heat energy to mechanical energy. A well designed steam turbine system has an efficiency of about 47%, which constrains the whole system to a maximum efficiency of less than this figure.

Table C.2
Coal Fired Electricity Generation - Stages and Estimated Efficiencies

STAGE	EFFICIENCY
EXTRACTION: Mining	99.5%
PROCESSING: Breaking and Sizing, Washing, Drying	95.3%
TRANSPORTATION: 500 Rail Miles, 75 Ship Miles	95.6%
ELECTRICITY GENERATION: Modern Coal-Fired Station	36.4%
TRANSMISSION: Ontario Hydro	95.1%
DISTRIBUTION: Municipal Hydro	96.5%
OVERALL EFFICIENCY	30.3%

C3. Electricity Generation From CANDU Nuclear System

The CANDU Reactor

The CANDU system has been developed and marketed in Canada and overseas by AECL. It differs from reactors used in the U.S. and elsewhere in that it uses natural, un-enriched uranium fuel and a heavy water (D_2O) moderator. Most other nuclear reactor systems require enriched uranium fuel but they can use ordinary water as a moderator and coolant.

Mining and Milling

Most Canadian uranium (around 94%) comes from the Elliot Lake region of Northern Ontario, with the remainder supplied by a deposit in N. Saskatchewan. The Ontario uranium is mined at depths of 2000 - 3000 feet using room-and-pillar methods. Broken ore is scraped from the floor of the room and delivered through chutes onto rail cars. It is then moved through a primary jaw crusher after which it is conveyed to the surface in skips.

After being raised to the surface the ore undergoes further crushing, fine grinding in rod and ball mills and chemical treatment or leaching. Estimates of primary efficiency account for a 5.5% loss of uranium depending on the leaching process, giving an overall figure of 94.5%.

Estimated Process Efficiency: 94.5%

Transportation of Uranium

The high energy density of uranium fuel makes the transportation requirements insignificant on a percentage basis, and have been calculated on the order of 0.0001%.

Estimated Process Efficiency: 100%

Processing of Uranium

This section is taken to include the energy requirements for producing the small amounts of heavy water which have to be replaced annually due to leakage. It does not include the energy required to produce the working quantity of heavy water, since this product is available to other CANDU reactors after decommissioning.

Primary energy losses start with the conversion of U_3O_8 to UO_2, which has a reported conversion loss of 0.5%. During the fabrication of fuel bundles an additional 0.2% loss is incurred. Ancillary energy requirements are estimated at 0.7% of the thermal value of the fuel, and about 80% of this amount is associated with heavy water makeup due to losses.

Primary Efficiency	*99.3%*
Ancillary Energy	*0.7%*
Estimated Process Efficiency:	*98.6%*

Electricity Generation - CANDU Nuclear Station

It is estimated that the Pickering nuclear station operates at a generating efficiency of 29%.

Estimated Process Efficiency: 29%

Transmission and Distribution

The figures reported in section C.2 will also apply to nuclear generated electricity.

Overall Efficiency - CANDU Nuclear Systems

The overall efficiency of nuclear-generated electricity in Ontario is estimated at 24.8%, which is the figure obtained by multiplying the above efficiency coefficients, as set out in Table C.3.

Table C.3
CANDU Nuclear Electric System - Stages and Estimated Efficiencies

STAGE	EFFICIENCY
EXTRACTION: Mining and Milling	94.5%
TRANSPORTATION: Elliot Lake to Port Hope	100.0%
PROCESSING: U_3O_8 to UO_2, Fuel Fabrication, Heavy Water Makeup	98.6%
ELECTRICITY GENERATION: Pickering CANDU Station	29.0%
TRANSMISSION: Ontario Hydro	95.1%
DISTRIBUTION: Toronto Hydro	96.5%
OVERALL EFFICIENCY	24.8%

C4. Electricity Generation From Hydro Power

Hydro Power

Hydroelectric stations are among the most efficient energy producing systems, largely because they do not require any thermal-to-mechanical energy transformations; instead, the potential energy of water (i.e. mechanical energy) can be converted directly to electricity by using it to power a generator.

Estimated Efficiency

Information from Ontario Hydro[7] indicated the following:

- Turbines used in Ontario generating stations are 92% - 93% efficient.
- Measured efficiencies for two of the largest hydro stations are 90% for the Sir Adam Beck- Niagara #2 station, and 88% for the Robert H. Saunders-St.Lawrence station (these 2 stations accounted for 43% of the total OH hydro power output in 1974.
- All newer stations are over 90% efficient.

[7] Ibid.

Based on this information the efficiency of hydroelectric stations in Ontario is taken as 90%.

Overall Efficiency - Hydro-Electric Systems

The overall efficiency of electricity generated by hydro power in Ontario is calculated as 82.6%, as delivered to the average residence in the province. The same transmission and distribution losses are assumed as used for coal and nuclear generated electricity.

C5. Fuel Oil

Oil Supply

Fuel oil, as burned in residential furnaces, is one of many refined hydrocarbon products produced from crude oil. For Southern Ontario, the main source of supply has historically been the western provinces, particularly Alberta.

In addition to crude oil, natural gas is also processed to recover liquid hydrocarbons.

Extraction and Processing

The numerous variations in oil field characteristics makes it almost impossible to define a typical oil well operation. However, the majority employ electricity-driven pumps to extract the oil itself, provide water flooding for enhanced recovery, or both. A certain amount of field processing is usually required to separate the oil from associated natural gas and remove a variety of impurities including water and sand (tar sand extraction, however, is a different process altogether; it is not considered here).

The processing of natural gas to recover liquid hydrocarbons involves a significant energy expenditure, estimated at 4.9% of the resulting hydrocarbon liquids.

Crude Oils and Condensates (82.3%* of supply)

Primary Efficiency	*99.6%*
Ancillary Energy	*0.1%*

Natural Gas Liquids (17.7%* of supply)

Ancillary Energy	*4.9%*

Estimated Process Efficiency: *98.7%* (weighted average for above)

Pipeline Transportation

Crude oil is transported from Western Canada to Southern Ontario via pipelines operated by Interprovincial Pipe Line Ltd (IPL). The crude is processed at refineries in the Sarnia and Port Credit areas. Data from IPL indicates that the ancillary energy requirement associated with bringing western crude oil to Ontario is around 0.8% of the crude moved.

Ancillary Energy *0.8%*

Estimated Process Efficiency: 99.2%

Processing

Primary efficiency statistics of Canadian petroleum refineries are published by Statistics Canada, but it is not possible to define an efficiency specific to one refinery product. For this reason it is simpler to apply the efficiency of the refinery as a whole to the production of heating oil. A number of sources quote internal refinery use at between 6% and 7% of the total refinery output. For these purposes the primary efficiency of oil production is taken at 93%.

Ancillary energy uses in Canadian refineries are also reported by Statistics Canada, and are assumed to be 1.2% of the refinery input.

Primary Efficiency	*93.0%*
Ancillary Energy	*1.2%*

Estimated Process Efficiency: 91.8%

Fuel Oil Distribution

Energy consumed by the furnace oil distribution system is small, mainly due to the proximity of the oil refineries to the bulk of the Southern Ontario market. Although pipelines are used to transport heating fuel oil, the predominant link between the distributor and the residential customer is a tank truck of several thousand gallons capacity. It is estimated that the energy consumed in furnace oil delivery is about 0.1% of the energy delivered.

Overall Efficiency - Fuel Oil

As shown in Table C.4, the overall efficiency of heating fuel oil as delivered to residences in Southern Ontario is estimated at 89.8%.

Table C.4
Residential Fuel Oil - Stages and Estimated Efficiencies

STAGE	EFFICIENCY
EXTRACTION: Canadian Oil Fields	98.7%
TRANSMISSION: Interprovincial PipeLine Ltd.	99.2%
PROCESSING: Canadian Refineries	91.8%
DISTRIBUTION: Tank Trunk	99.9%
OVERALL EFFICIENCY	89.8%

C6. Natural Gas

Gas Sources

Most natural gas used in Ontario originates from wells situated in Alberta. Raw natural gas, besides the predominant methane, also contains varying quantities of ethane, propane, butane and pentanes, and water vapour is a normal constituent. Hydrogen sulphide may be present at some wells in quantities up to 40% by volume.

Extraction

Energy used during extraction comprises three components: gas wasted and flared in the field; field disposition and use; gathering system disposition and use. The first of these may be classified as a primary energy loss, while the gas used in the field is an ancillary loss.
Average primary losses have been reported at 2.1%, and ancillary losses at 1.4% for the extraction stage. These figures were representative of the entire Canadian natural gas industry in 1975.

Primary Efficiency *97.9%*
Ancillary Energy *1.4%*

Estimated Process Efficiency: 96.5%

Processing

Depending on the nature of the local product, a certain amount of field processing occurs to prepare natural gas for pipeline transmission. In addition to the removal of water, sand and sulfur, liquid fractions (pentanes plus condensates) are separated from the gas. Where feasible, elemental sulfur is recovered as a byproduct. In order to improve the recovery of liquid hydrocarbons a certain amount of the processed gas is reinjected back into the well. In addition to field processing, complex processing plants are used to separate the valuable natural gas liquids such as propanes and butanes.

Ancillary Energy *3.2%*

Estimated Process Efficiency: 96.8%

Transmission

Natural gas is transported across the country from Alberta, and enters Ontario near Sarnia, where it is stored underground or transmitted further to the Toronto area via another pipeline. Data published by Statistics Canada, which is based on average figures for the country, indicate that average transportation uses and losses yield a primary efficiency of 99.3%, and gas used for pipeline fuel yields an ancillary energy use of 3.93%. However, since the distance from Ontario to Alberta is considerably greater than that of most Canadian pipelines, a gas transportation efficiency of 90% is considered more accurate[8].

Estimated Process Efficiency: 90.0%

Distribution

Distribution efficiency in Ontario (e.g. by Consumers Gas) has been calculated at 99.3%

Estimated Process Efficiency: 99.3%

Overall Efficiency - Natural Gas

The overall efficiency of natural gas as delivered to residences in Southern Ontario is found to be 83.8% using the coefficients given above. Table C.5 summarizes these figures.

[8]Ibid.

Table C.5
Natural Gas - Stages and Estimated Efficiencies

STAGE	EFFICIENCY
EXTRACTION: Canadian Gas Fields	96.5%
PROCESSING: Natural Gas Plants	96.8%
TRANSMISSION: TransCanada PipeLines	90.4%
DISTRIBUTION: Consumer's Gas Co.	99.3%
OVERALL EFFICIENCY	83.8%

APPENDIX D

MAINTAINING BUILDING COMFORT

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MAINTAINING BUILDING COMFORT

D1. Comfort Levels

Human beings must maintain their body temperature within relatively narrow limits to survive. The body produces heat as by-products of metabolism, respiration and exercise that are dependent on activity level. Heat is lost by conduction, convection, radiation and evaporation (sweating) from the surface of the body. A heat balance is set up in which body heat production equals heat loss at any instant. The environmental variables which affect heat loss include air temperature, mean radiant temperature, relative humidity, clothing, and air movement.[9]

A body is comfortable if the environmental conditions allow a balance to be set up between heat production and loss, sweat rate and skin temperature, at the current activity level. ASHRAE has determined the optimum and acceptable body temperatures for summer and winter conditions.[10]

	Clothing/Air Speed Levels*	Optimum Temp (°C)	Acceptable Temp (°C)
Winter	CLO=0.5 Still Air	24.4	22.8
	CLO=1.2 Still Air	20.0	17.8
Summer (50% RH)**	CLO=0.5 Still Air	24.4	26.1
	CLO=0.05 Still Air	27.2	29.6
	CLO=0.05 Air=1.0 m/s	29.7	31.5

* 1 CLO[11] is a measure of thermal resistance of clothing = 0.155 $m^2.^0K/W$

** RH means relative humidity

[9]Fanger, P.O. Thermal Comfort, McGraw-Hill, NY 1992.

[10]American Society of Heating, Refrigeration, and Air Conditioning Engineers Thermal Environmental Conditions for Human Occupancy, ASHRAE Std. ANSI/ASHRAE 55/1981.

[11]Typical CLO values are as follows:

0.05	light T-shirt and shorts
0.5	long sleeve shirt and pants
1.0	heavy shirt, pants and jacket
1.2	sweater, shirt and heavy pants

These temperatures are equivalent air temperatures at which a person would be comfortable if the mean radiant (surface) temperature of a space were the same as the air temperature. For a mean radiant temperature (T_{rad}) different from the air temperature (T_{air}), the equivalent or "subjective" temperature (T_{sub}) has been shown to be as follows[12]:

$$T_{subjective} = 0.56\ T_{air} + 0.44\ T_{rad}$$

Air temperatures lower than those given above are therefore comfortable if a certain percentage of heating is in radiant form.

There are, therefore, many combinations of air temperature, radiant temperature, air speed, clothing level, and relative humidity which make up lower and upper bounds of the comfort zone for a human body at rest.

D2. Heating and Cooling Loads

The energy used by an envelope to maintain comfort will consist of the energy used on a continuous basis over the life of the envelope, plus the embodied energy of the envelope. The energy used on a continuous basis will in turn be supplied from activities within the envelope (waste heat from devices and occupants), solar gain through the envelope, and purchased energy supplied by conversion devices. The proportion of the energy used that is met by each of these sources will again depend on the structure of the envelope.

The following envelope designs and performance levels were analyzed to determine typical envelope heating and cooling loads.

1. A National Building Code single detached dwelling ("Code Housing")
2. A Super Energy Efficient House (R-2000 type) detached dwelling ("Improved Housing")
3. A "Best" or "Advanced" detached dwelling with high levels of insulation ("Best Housing").
4. A "zero energy" modification of the Advanced house designed with sufficient thermal mass and other features so that all loads are met from internal gains and ambient sources.

The temperature set points associated with each comfort level are shown in Table D.1A. Each dwelling conformed to the reference house described in Appendix B. The assumptions used for each envelope design are shown in Table D.1B.

[12] McIntyre, D.A. Indoor Climate. Applied Science Publishers, London, 1990.

The following variations were analyzed for the first three of the above basic envelope types:

- Equal and south dominant window orientation (heating only)
- At optimum and min/max acceptable subjective temperatures (see attached Table D.1A)
- With low and high clothing levels (see Section 4)
- With and without a heat recovery ventilator with efficiency of 75% (heating only)
- With and without 10% radiant heating (heating only)
- Still and moving air at 1 m/sec (cooling only)
- With and without natural cooling (cooling only)
- With and without a dynamic wall system designed to reduce heat losses by drawing ventilation air in through the wall[13]. (NBC Design only).

The envelope features analysed in the study are summarized in Table D1.C.

The zero energy house modification assumed south dominant windows, max./min. acceptable temperature, optimum clothing levels, 95% heat recovery, 10% radiant cooling, moving air and full natural cooling.

The heating and cooling loads and the contributions of free energy (internal gain, solar gain, and natural cooling) for all envelopes were estimated using the ENERPASS simulation model assuming Ottawa weather data, and two living zones (basement and main floors). Simulation of the dynamic wall used an equivalent wall R value based on experimental data. The thermal characteristics of each housing type and the temperature set points for each variation are those shown in Tables D.1B and D.1A respectively.

Gross heating and cooling loads calculated using ENERPASS are shown in Tables D2 and D3 respectively. Net heating load and free heating contributions are shown in Table D4 and Figures D1 through D8. Net cooling loads are shown in Table D5 and Figures D9 through D14.

The ENERPASS model does not allow effective analysis of the effects of thermal or moisture storage, or the effect of varying humidity levels. Thermal storage is difficult to model, and should be addressed more completely in future work because it can have a large impact on the proportion of free energy that is used to meet energy needs using each envelope device. The simulation of the zero energy house required extending the ENERPASS parameters beyond their normal range. In the ENERPASS simulations, moisture was maintained constant at 40% relative humidity and any shortfall in humidity (due to ventilation with dry outside air) was included in the heat load as a latent heat requirement.

[13] A dynamic wall is also able to utilize a portion of the solar energy falling on the walls of the dwelling. This contribution was not considered in the analysis, however.

The quality of the energy used in each house will vary with the device. In a conventional house, energy for heating is required as heat at between 17 and 24 °C. In a house that uses radiant heating, some energy is required as heat at temperatures of 35 °C, the rest at 17 to 24 °C. Energy for cooling is required as "cold" at 17 to 31 °C.

To reduce the number of variables studied, it was assumed that heat would be available from internal sources at a constant rate and that there would be continuous ventilation according to CSA standard F376. In a house with conventional walls, this ventilation air is drawn in through an air inlet and exhausted through a venting system. A heat recovery ventilator (HRV) may or may not be used to recover heat and pre-heat incoming air. In a house with dynamic walls, ventilation air is drawn in through the envelope and exhausted through a venting system. In this case, the wall itself preheats incoming air (conducted heat from the building interior and solar heat falling on the outside of the wall). A heat pump is often used to recover heat from exhausted air, such that the heat energy recovered can be used for other purposes (e.g., domestic hot water). In the analysis of envelope devices to maintain comfort, this heat pump recovery was not included.

As shown in other sections of the report, the energy from internal sources (except metabolic), and that used for ventilation (air quality), are functions of the energy efficiencies of the devices used to meet these other energy needs. If high efficiency appliances are used and air quality is maintained with air cleaners and oxygen generators, for example, the heating and cooling loads of the house, and the amount of internal energy available, will then both be lower. In the analysis of comfort devices, therefore, it was assumed that energy used for ventilation and contributed by internal sources, would be as per the ENERPASS defaults.

Finally, there are many other envelope devices (besides thermal storage) that were not addressed in order to keep the work within the resources available. These devices are designed to either reduce the total energy used to maintain comfort or increase the proportion of energy that can be obtained from ambient sources (increase absolute efficiency). These devices include attached sunspaces, dynamic windows, high performance and "smart" windows, Trombe wall, water wall, thermal divide walls, night sky radiation, evaporative cooling, earth coupling and use of vegetation.

Tables showing the temperature set points, and annual heating and cooling loads for each of the ENERPASS simulations, and monthly variations in loads in graphical form are attached.

D2. Contributions from Ambient Sources

Figure D15 shows that the amount of energy falling on the house itself (walls and windows) is sufficient (even in December) to meet the heating load of the Code house, and therefore all of the houses analyzed. The contribution of "free" and purchased heating energy utilized by each house towards meeting the heating load and monthly variations in contribution are attached. Free energy includes internal sources and solar gain through the windows. A comparison of ENERPASS simulation results and Figure D15 show that only a small portion of the load is met by these free sources in most designs, when it is possible to meet all the load from these sources.

The envelope devices likely to make the highest use of free sources and approach the ideal case would be diurnal and seasonal thermal storage and dynamic wall type devices which "collect" and store not only solar energy falling on windows but also the walls. This design was used in the zero energy housing simulation runs.

"Free" cooling is available to a house when the ambient temperature is lower than the summer temperature set point of the house, and the house can be cooled by natural ventilation. This contribution is limited by air flow from sources such as wind and natural convection. Each house utilizes a portion of this energy through the use of continuous ventilation. If the house is designed to take greater advantage of natural cooling, then the proportion of purchased energy for air conditioning falls. The contribution of natural cooling and purchased energy for three housing types and monthly variations are shown in the attached tables.

Table D.1A
Air Temperature Setpoints (based on T_{sub} Comfort)
Accounting for Mean Radiant Temperature
(°C)
$T_{sub} = 0.56\ T_a + 0.44\ T_r$

Strategy[1]	Code		Improved		Best	
	ASHRAE	Acceptable	ASHRAE	Acceptable	ASHRAE	Acceptable
Heating						
CLO = 0.5	25.0	23.4	24.8	23.2	24.4	22.8
CLO = 1.2	20.6 *	18.4	20.4	18.2	20.0	17.8
CLO = 1.2						15.3
+10% radiant		15.9		15.7		
Cooling						
CLO = 0.5	25.1	26.1	25.1	26.1	25.1	26.1
CLO = 0.05	27.2	29.0	27.2	29.0	27.2	29.0
CLO = 0.05 +airspeed		31.5		31.5		31.5
CLO = 0.05 +airspeed +10% radiant		32.8		32.8		32.8

Notes:
ASHRAE and Acceptable refer to subjective comfort levels based on temperature setpoints considered optimum and acceptable, respectively, by ASHRAE, and adjusted for wall type and other factors.

CLO refers to the quantity of clothing normally worn by the occupants. A level of 0.5 is average; of 1.2 indicates heavier clothing is normally worn during the heating season; and 0.05 indicates lighter clothing is normally worn during the cooling season.

HRV indicates the presence of heat recovery ventilation.

Radiant surfaces are walls, ceilings or floors designed to carry heat to the living space.

* This set point was also used to model the CODE house with dynamic wall.

Table D.1B
Insulation levels for Walls, Ceiling, Windows, Door and Basement for each Housing Type

	Code	Improved	Best	Zero Energy
Above Grade Insulation (RS1):				
Walls (conventional)	3.50	6.40	9.00	15.00
(dynamic)*	6.00	6.40	9.00	
Windows	0.35	0.60	1.60	3.50
Ceiling	5.50	9.00	15.00	20.00
Door	1.20	1.20	1.20	1.20
Basement Insulation (RSI):				
Wall -- Insulated	2.00	2.00	3.50	10.00
Wall -- Uninsulated	0.20	0.20	0.20	
Window Transparency	0.66	0.61	0.45	0.60

* Equivalent RSI of Dynamic Wall

Table D1.C
Envelope Features Analyzed in the Study

Insulation Levels (Walls/Windows)	National Building Code Energy Efficient (R200 Type) Advanced House[14]
Window Placement	Equally Spaced South Optimized[14]
Subjective Temperature	Optimum (ASHRAE) Minimum/Maximum Acceptable[14]
Clothing Level	Low[14] High[14]
Cooling Strategy	No Natural Cooling Maximum Natural Cooling[14]
Thermal Mass	Zero Thermal Mass High Thermal Mass Very High Thermal Mass[14]
Air Movement	No Air Movement 1 m/s Air Speed[14]
Surface Temperature	No Radiant Heating 10% Radiant Heating[14]
Ventilation Heat Recovery	No Heat Recovery 75% Heat Recovery 90% Heat Recovery[14]
Wall Strategy	Conventional Wall Dynamic Wall[14]

[14]Features equivalent to State-of-the-Art Envelope.

Table D.2
Results of Enerpass modelling
for Heating

Parameters	Code	Gross Heat Load (GJ) Improved	Best
ASHRAE CLO=0.5	163.5	120.1	91.0
ASHRAE CLO=1.2	123.9	89.9	66.8
Acceptable CLO=1.2	105.9	76.6	56.3
ASHRAE CLO=1.2 Dynamic Wall	115.2	–	–
Acceptable CLO=1.2 with 75% HRV	88.4	58.5	37.4
Acceptable CLO=1.2 with 10% radiant	86.9	62.9	45.5
Acceptable CLO=1.2 Heavy Mass 90% HRV	–	–	27.4

Table D.3
Results of Enerpass modelling
for Cooling

Parameters	Window Placement	Gross Cooling Load (GJ) Code	Improved	Best
No natural cooling ASHRAE CLO=0.5	equalized S–optimized	18.3 19.6	19.1 20.3	16.0 16.8
No natural cooling ASHRAE CLO=0.05	equalized S–optimized	9.6 10.7	11.8 12.9	10.7 11.5
Natural cooling ASHRAE CLO=0.05	equalized S–optimized	4.4 5.0	4.8 5.4	3.7 4.1
No natural cooling Acceptable CLO=0.05	equalized S–optimized	6.4 7.3	8.9 9.9	8.2 9.0
Natural cooling Acceptable CLO=0.05	equalized S–optimized	2.2 2.5	2.5 2.9	1.8 2.1
Natural cooling Acceptable CLO=0.05 with airspeed	equalized	0.6	0.8	0.5
Natural cooling Acceptable CLO=0.05 with 10% radiant and airspeed	equalized	0.3	0.3	0.3

Table D.4
Net Heat Load and Free Energy Contributions to Annual Gross Heating Load

Strategy	Window Placement	Code Type Housing					Improved Type Housing					Best Type Housing				
		Heat Load (GJ/y)	Net Heat Load (GJ/y)	Net Heat Load (%)	Free Energy (GJ/y)	Free Energy (%)	Heat Load (GJ/y)	Net Heat Load (GJ/y)	Net Heat Load (%)	Free Energy (GJ/y)	Free Energy (%)	Heat Load (GJ/y)	Net Heat Load (GJ/y)	Net Heat Load (%)	Free Energy (GJ/y)	Free Energy (%)
ASHRAE CLO=0.5	equalized	163.5	115.9	70.9%	47.6	29.1%	120.1	78.4	65.3%	41.7	34.7%	91.0	54.7	60.1%	36.3	39.9%
	S-optimized	163.5	112.0	68.5%	51.5	31.5%	120.1	76.0	63.3%	44.1	36.7%	91.0	53.0	58.3%	38.0	41.7%
ASHRAE CLO=1.2	equalized	123.9	75.9	61.3%	47.9	38.7%	89.9	47.1	52.4%	42.8	47.6%	66.8	30.5	45.6%	36.3	54.4%
	S-optimized	123.9	70.7	57.1%	53.2	42.9%	89.9	43.0	47.8%	46.9	52.2%	66.8	27.0	40.4%	39.8	59.6%
ASHRAE CLO=1.2 Dynamic Wall		115.2	66.9	58.1%	48.3	41.9%	–	–	–	–	–	–	–	–	–	–
Acceptability CLO=1.2	equalized	105.9	67.1	63.4%	38.8	36.6%	76.6	37.7	49.3%	38.8	50.7%	56.3	23.5	41.8%	32.7	58.2%
	S-optimized	105.9	62.5	59.0%	43.4	41.0%	76.6	33.3	43.5%	43.2	56.5%	56.3	20.1	35.7%	36.2	64.3%
Acceptability CLO=1.2 with 75% HRV		88.4	46.4	52.4%	42.0	47.6%	58.5	22.0	37.7%	36.5	62.3%	37.4	8.4	22.4%	29.0	77.6%
Acceptability CLO=1.2 with 10% radiant		86.9	49.0	56.4%	37.9	43.6%	62.9	28.7	45.7%	34.2	54.3%	45.5	17.0	37.4%	28.5	62.6%
Acceptability CLO=1.2 Heavy Mass 90% HRV		–	–	–	–	–	–	–	–	–	–	27.4	0.0	0.0%	27.4	100.0%

Table D.5
Net Heat Load and Free Energy Contributions to Annual Gross Cooling Load

Strategy	Window Placement	Code Housing Type: Cool Load (GJ/y)	Code: Net Cool Load (GJ/y)	Code: Net Cool Load (%)	Code: Free Energy (GJ/y)	Code: Free Energy (%)	Improved Housing Type: Cool Load (GJ/y)	Improved: Net Cool Load (GJ/y)	Improved: Net Cool Load (%)	Improved: Free Energy (GJ/y)	Improved: Free Energy (%)	Best Housing Type: Cool Load (GJ/y)	Best: Net Cool Load (GJ/y)	Best: Net Cool Load (%)	Best: Free Energy (GJ/y)	Best: Free Energy (%)
No natural cooling ASHRAE CLO=0.5	equalized	18.3	9.7	53.0%	8.6	47.0%	19.1	10.1	52.7%	9.1	47.3%	18.0	8.0	50.1%	8.0	49.9%
	S-optimized	19.6	10.4	53.0%	9.2	47.0%	20.3	10.7	52.7%	9.6	47.3%	16.8	8.9	52.6%	8.0	47.4%
No natural cooling ASHRAE CLO=0.05	equalized	9.6	5.2	54.5%	4.3	45.5%	11.8	6.3	53.8%	5.4	46.2%	10.7	5.3	50.0%	5.3	50.0%
	S-optimized	10.7	5.8	54.4%	4.9	45.6%	12.9	6.9	53.6%	6.0	46.4%	11.5	6.1	53.4%	5.3	46.6%
Natural cooling ASHRAE CLO=0.05	equalized	4.4	2.6	58.5%	1.8	41.5%	4.8	2.8	57.8%	2.0	42.2%	3.7	1.9	50.1%	1.9	49.9%
	S-optimized	5.0	2.9	57.9%	2.1	42.1%	5.4	3.1	57.5%	2.3	42.5%	4.1	2.4	58.0%	1.7	42.0%
No natural cooling Acceptability CLO=0.05	equalized	6.4	3.5	55.6%	2.8	44.4%	8.9	4.8	54.5%	4.0	45.5%	8.2	4.1	50.1%	4.1	49.9%
	S-optimized	7.3	4.0	55.0%	3.3	45.0%	9.9	5.4	54.1%	4.5	45.9%	9.0	4.8	53.8%	4.2	46.2%
Natural cooling Acceptability CLO=0.05	equalized	2.2	1.3	61.0%	0.9	39.0%	2.5	1.5	60.3%	1.0	39.7%	1.8	0.9	50.5%	0.9	49.5%
	S-optimized	2.5	1.5	60.2%	1.0	39.8%	2.9	1.7	60.7%	1.1	39.3%	2.1	1.3	61.0%	0.8	39.0%
Natural cooling Acceptability CLO=0.05 with Airspeed	equalized	0.6	0.4	65.5%	0.2	34.5%	0.8	0.5	67.1%	0.3	32.9%	0.5	0.3	50.0%	0.3	50.0%
Natural cooling Acceptability CLO=0.05 with 10% radiant and airspeed	equalized	0.3	0.2	69.2%	0.1	30.8%	0.3	0.2	67.6%	0.1	32.4%	0.3	0.1	48.0%	0.1	52.0%

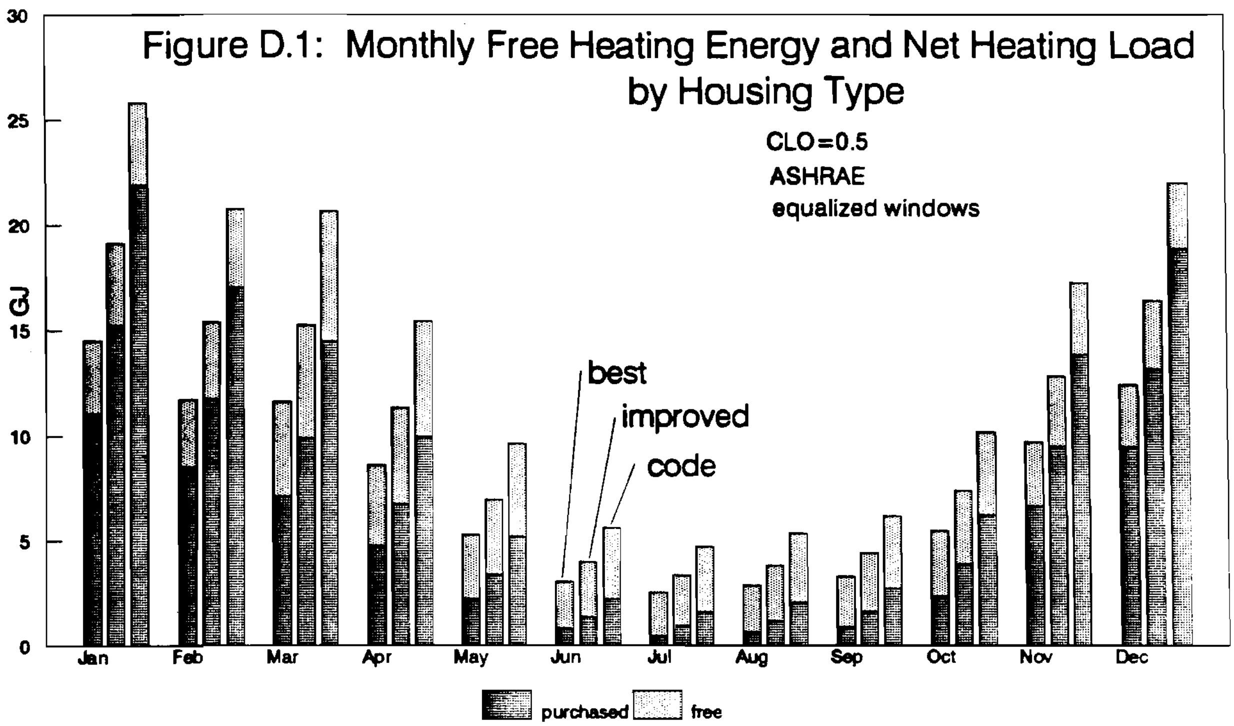
Figure D.1: Monthly Free Heating Energy and Net Heating Load by Housing Type
CLO=0.5
ASHRAE
equalized windows
GJ
30
25
20
15
10
5
0
best
improved
code
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
purchased
free

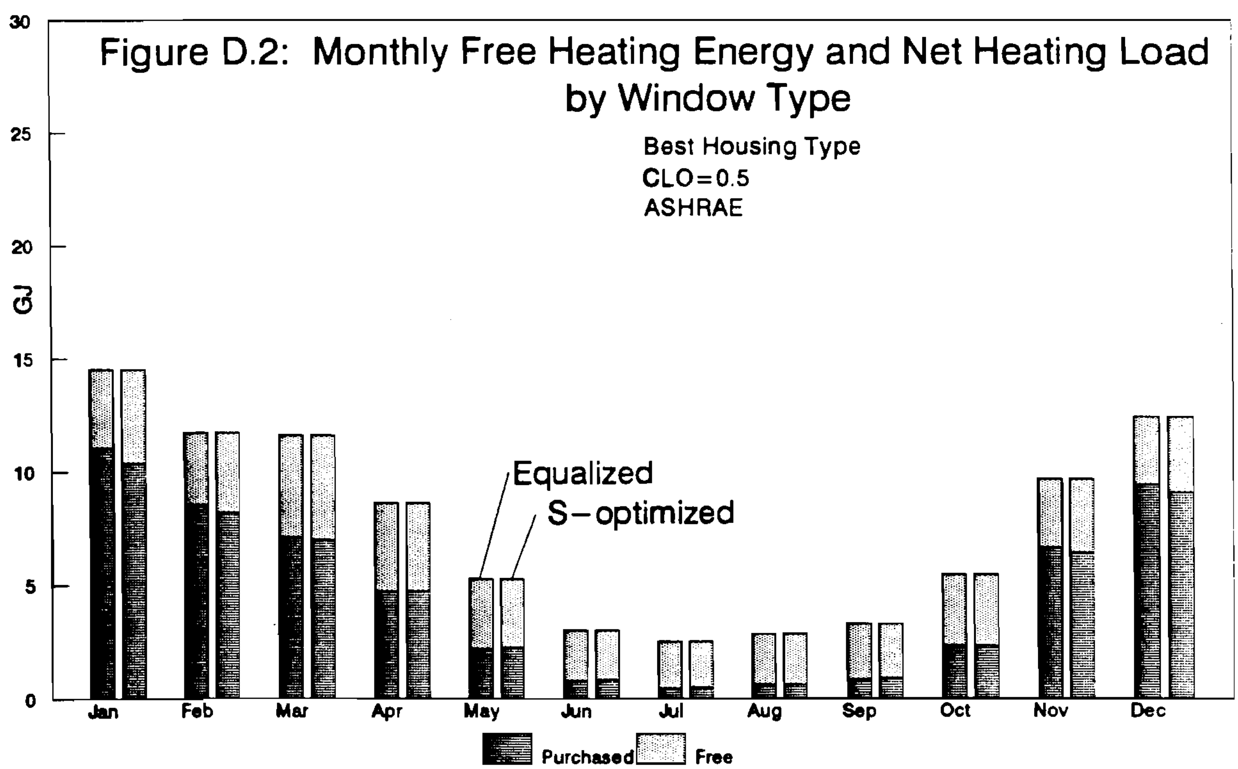
Figure D.2: Monthly Free Heating Energy and Net Heating Load by Window Type
Best Housing Type
CLO=0.5
ASHRAE
GJ
30
25
20
15
10
5
0
Equalized
S-optimized
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Purchased
Free

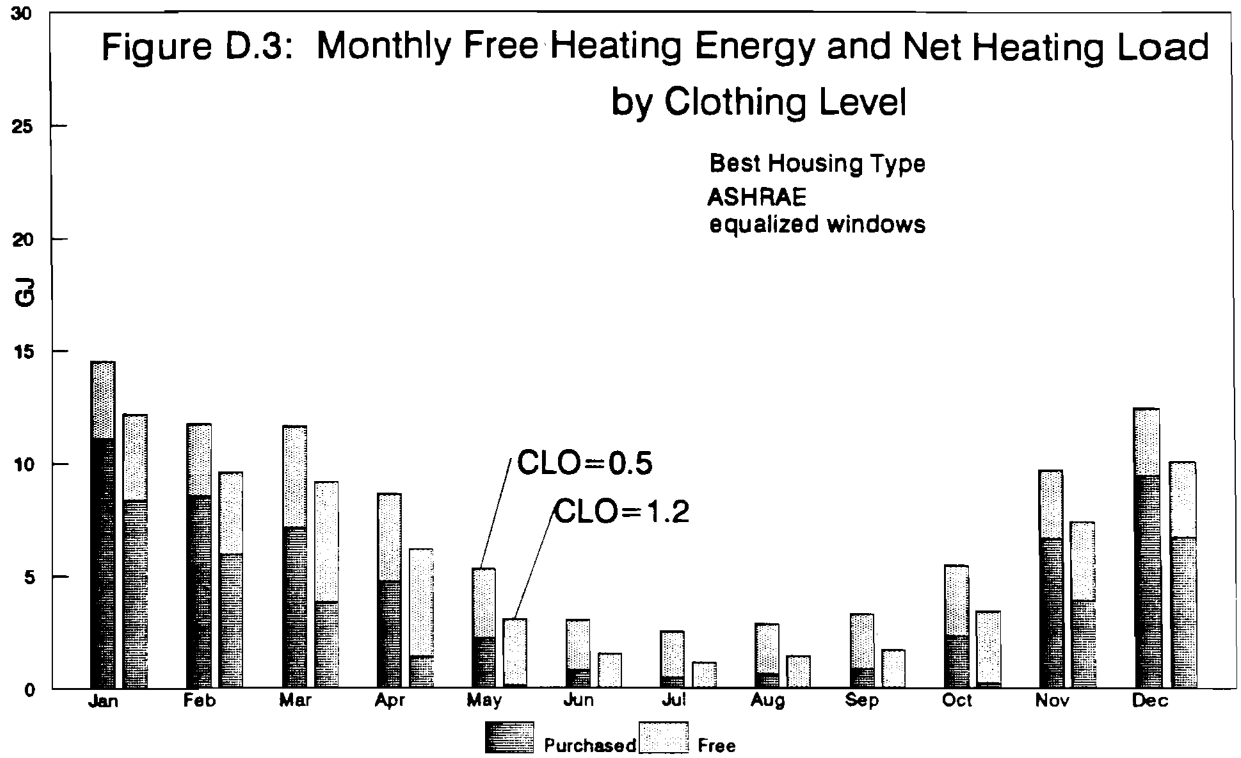
Figure D.3: Monthly Free Heating Energy and Net Heating Load
by Clothing Level
Best Housing Type
ASHRAE
equalized windows
CLO=0.5
CLO=1.2
GJ
30
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Purchased
Free

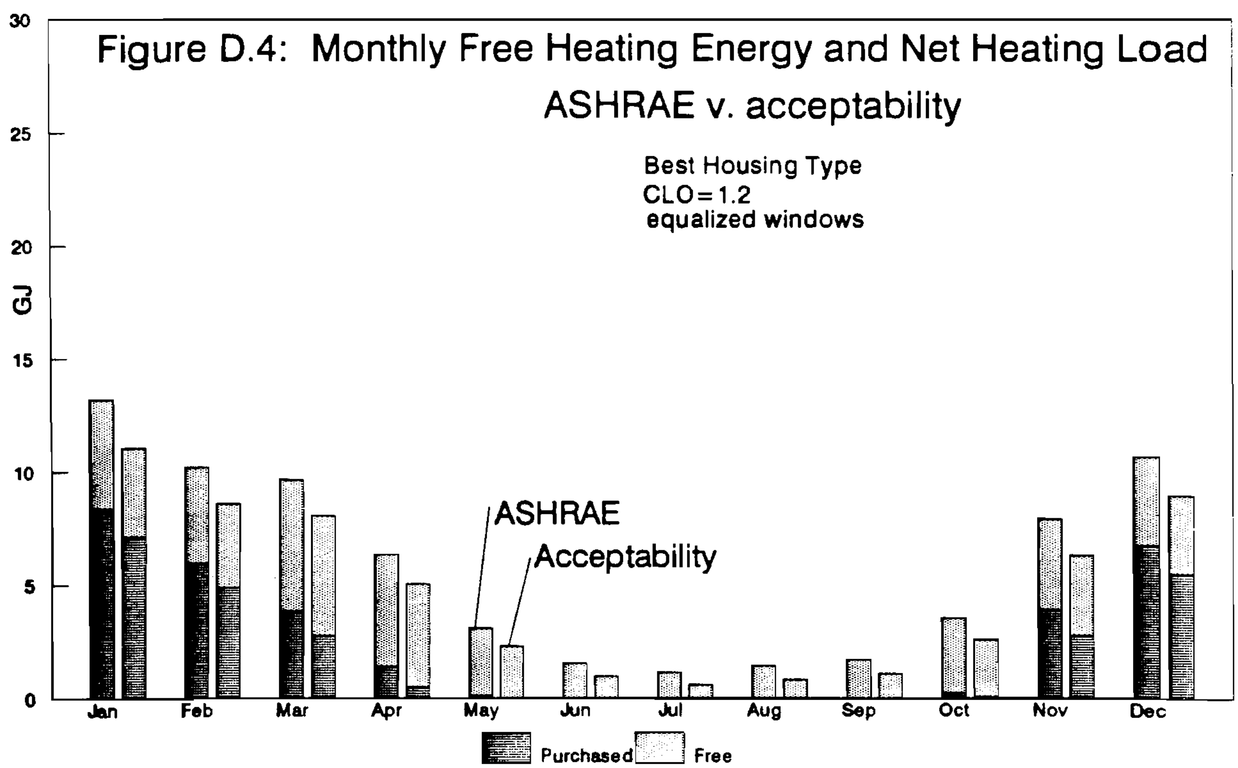
Figure D.4: Monthly Free Heating Energy and Net Heating Load
ASHRAE v. acceptability
Best Housing Type
CLO=1.2
equalized windows
ASHRAE
Acceptability
GJ
30
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Purchased
Free

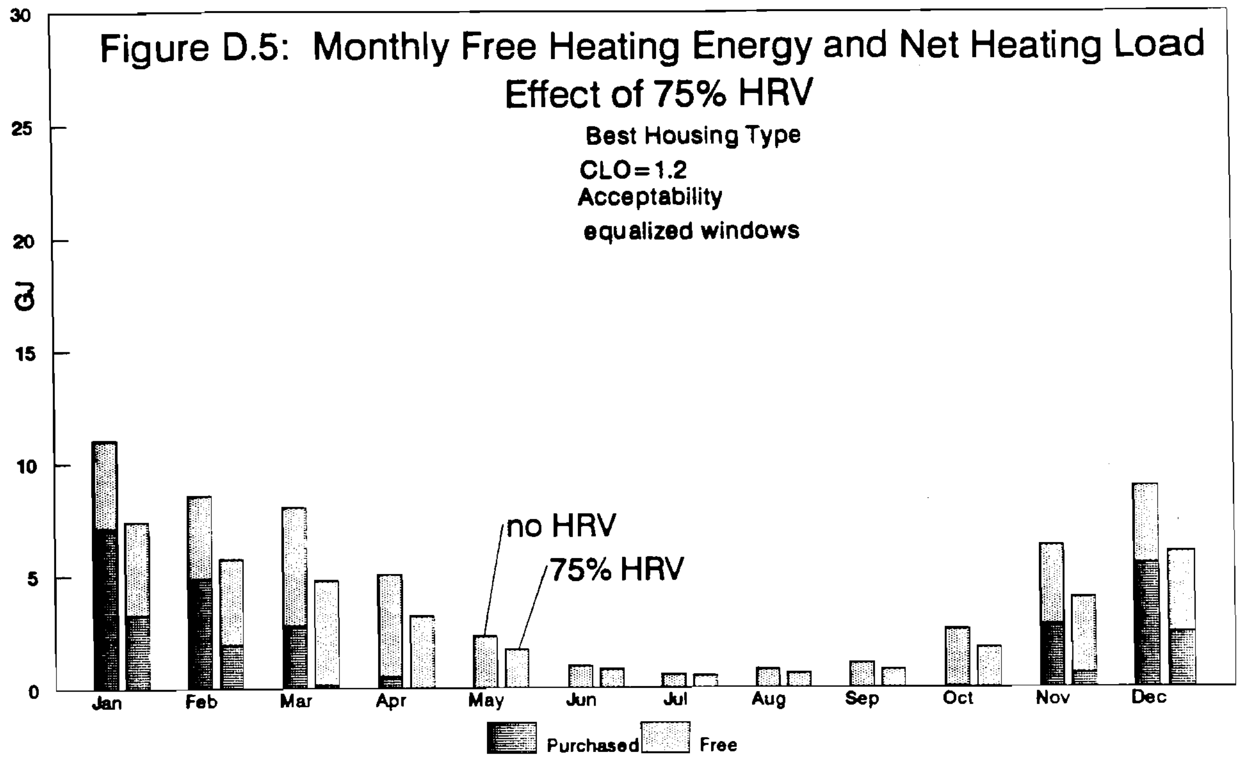
Figure D.5: Monthly Free Heating Energy and Net Heating Load
Effect of 75% HRV
Best Housing Type
CLO=1.2
Acceptability
equalized windows
GJ
30
25
20
15
10
5
0
no HRV
75% HRV
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Purchased
Free

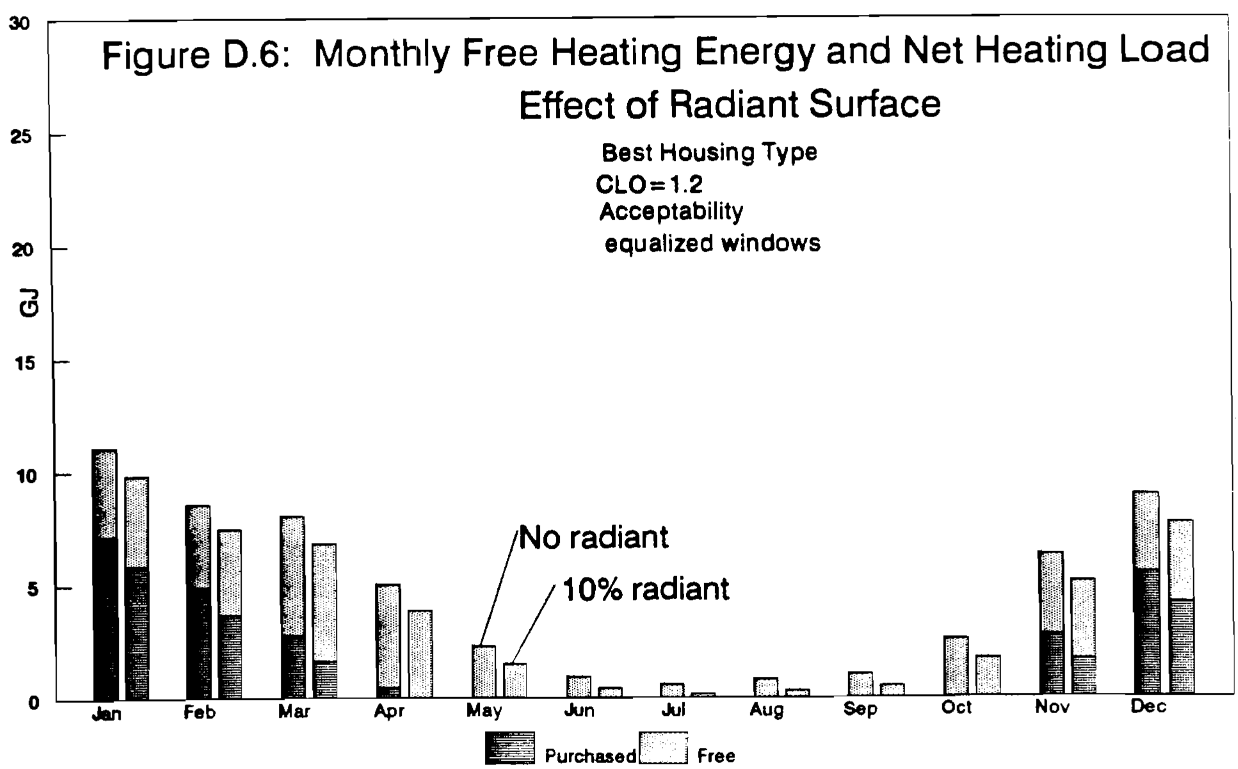
Figure D.6: Monthly Free Heating Energy and Net Heating Load
Effect of Radiant Surface
Best Housing Type
CLO=1.2
Acceptability
equalized windows
GJ
30
25
20
15
10
5
0
No radiant
10% radiant
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Purchased
Free

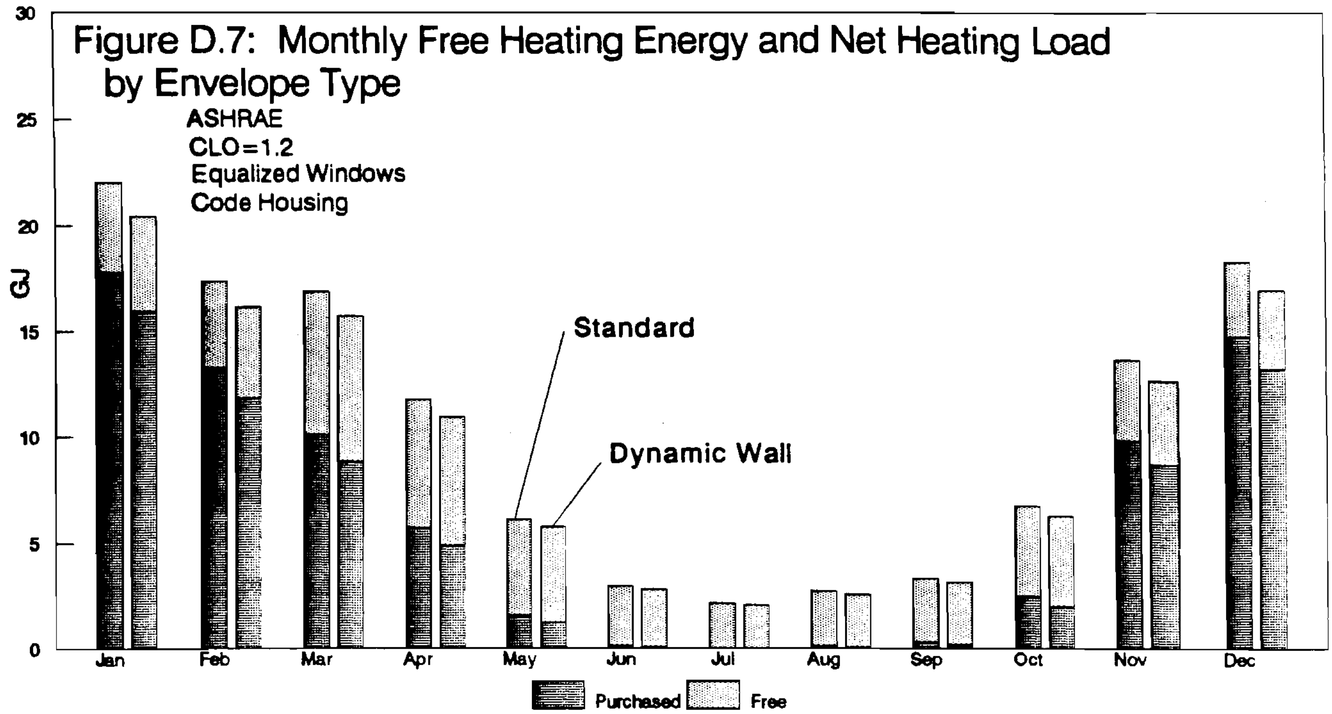
Figure D.7: Monthly Free Heating Energy and Net Heating Load by Envelope Type
ASHRAE
CLO=1.2
Equalized Windows
Code Housing
Standard
Dynamic Wall
GJ
30
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Purchased
Free

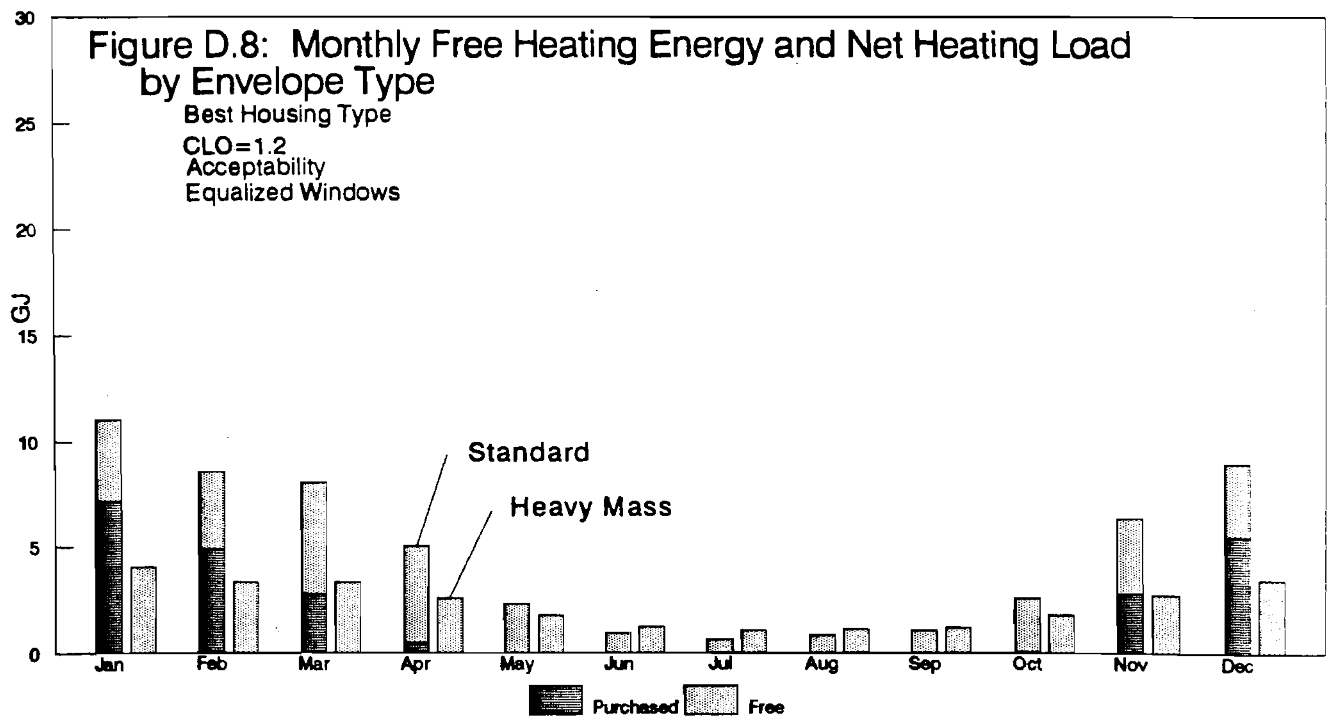
Figure D.8: Monthly Free Heating Energy and Net Heating Load by Envelope Type
Best Housing Type
CLO=1.2
Acceptability
Equalized Windows
Standard
Heavy Mass
GJ
30
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Purchased
Free

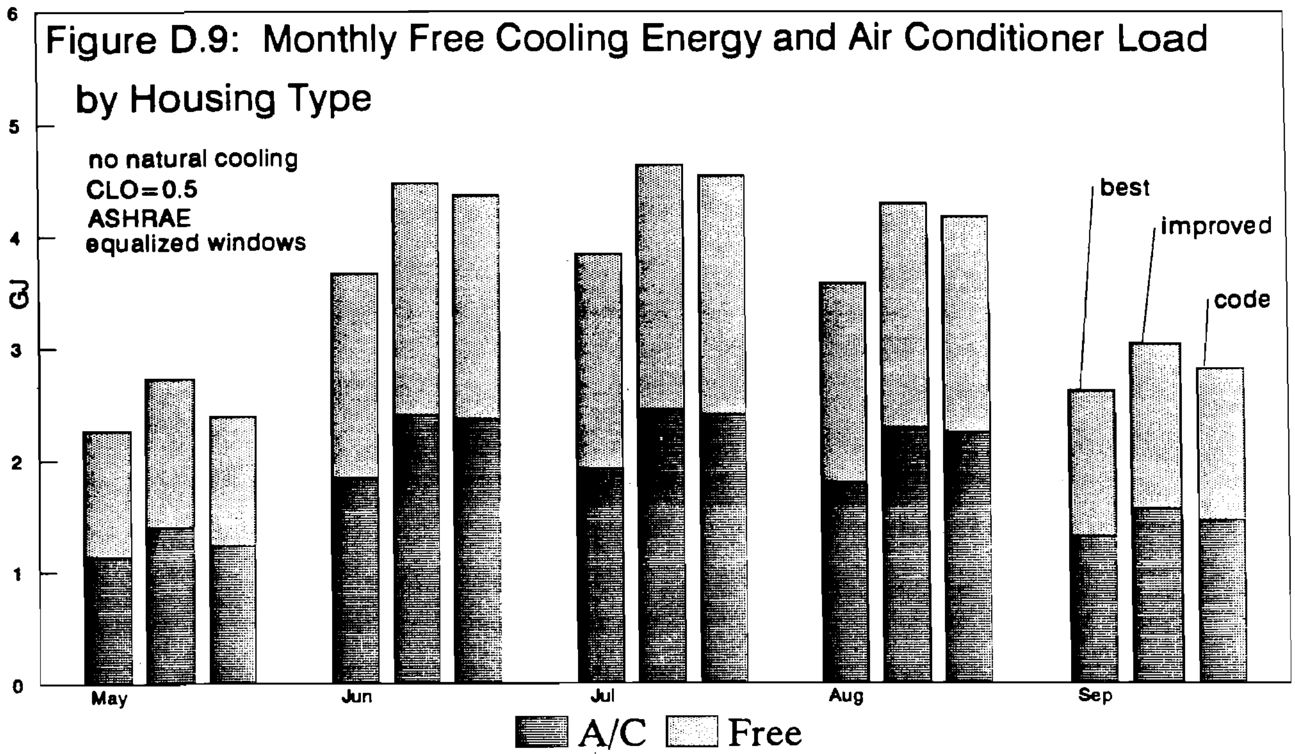
Figure D.9: Monthly Free Cooling Energy and Air Conditioner Load by Housing Type
no natural cooling
CLO=0.5
ASHRAE
equalized windows
best
improved
code
GJ
0
1
2
3
4
5
6
May
Jun
Jul
Aug
Sep
A/C
Free

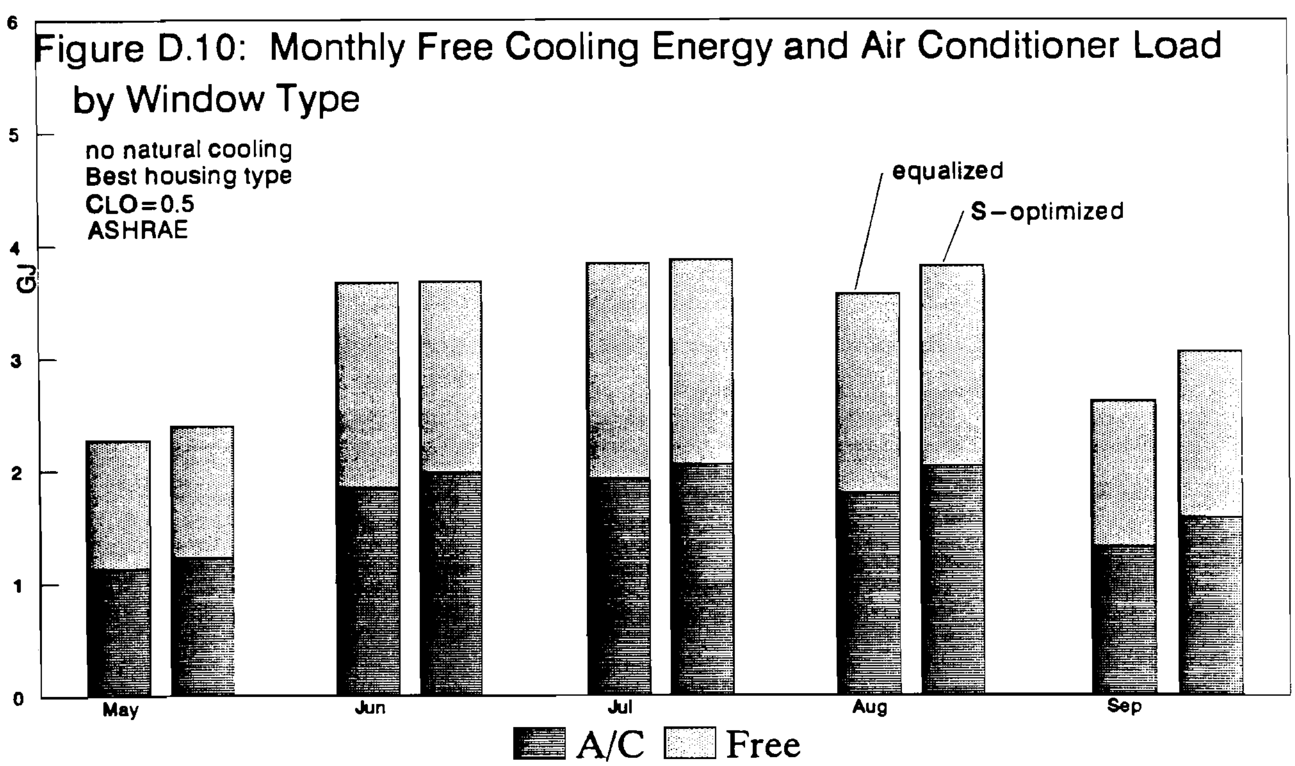
Figure D.10: Monthly Free Cooling Energy and Air Conditioner Load by Window Type
no natural cooling
Best housing type
CLO=0.5
ASHRAE
equalized
S-optimized
GJ
0
1
2
3
4
5
6
May
Jun
Jul
Aug
Sep
A/C
Free

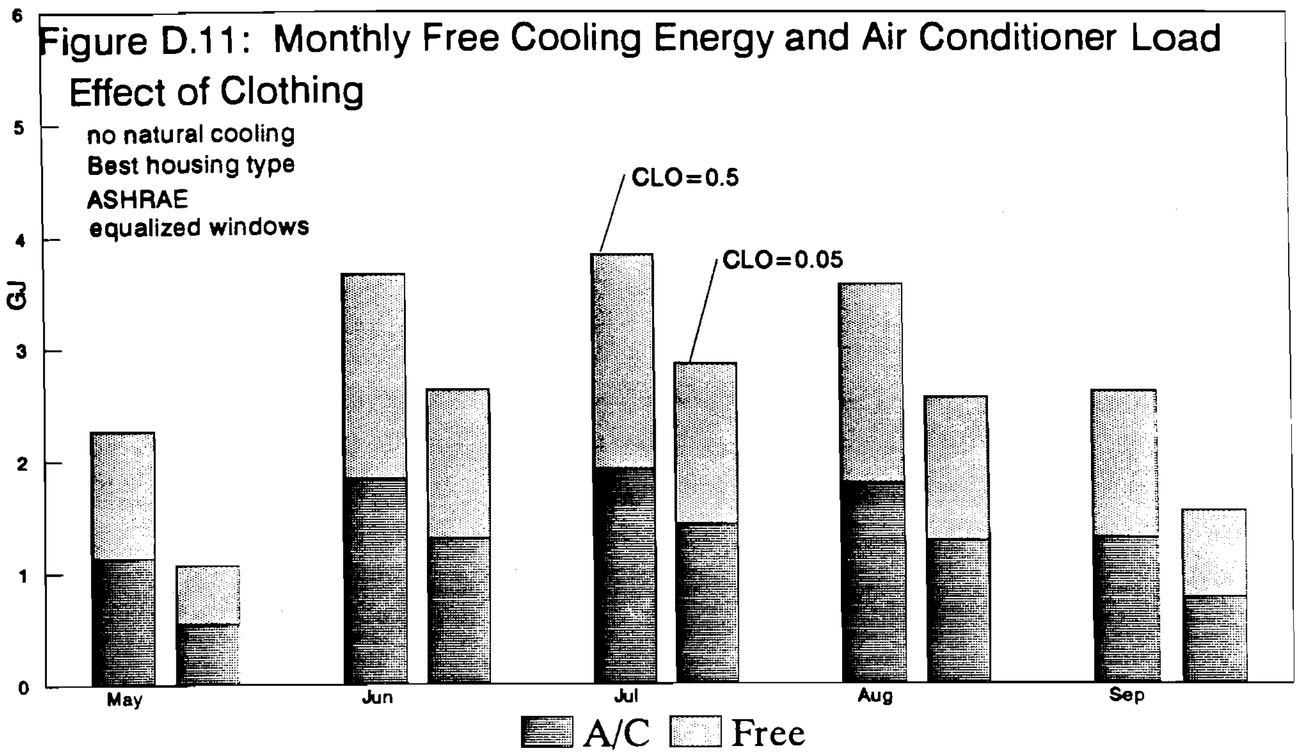
Figure D.11: Monthly Free Cooling Energy and Air Conditioner Load
Effect of Clothing
no natural cooling
Best housing type
ASHRAE
equalized windows
CLO=0.5
CLO=0.05
GJ
0
1
2
3
4
5
6
May
Jun
Jul
Aug
Sep
A/C
Free

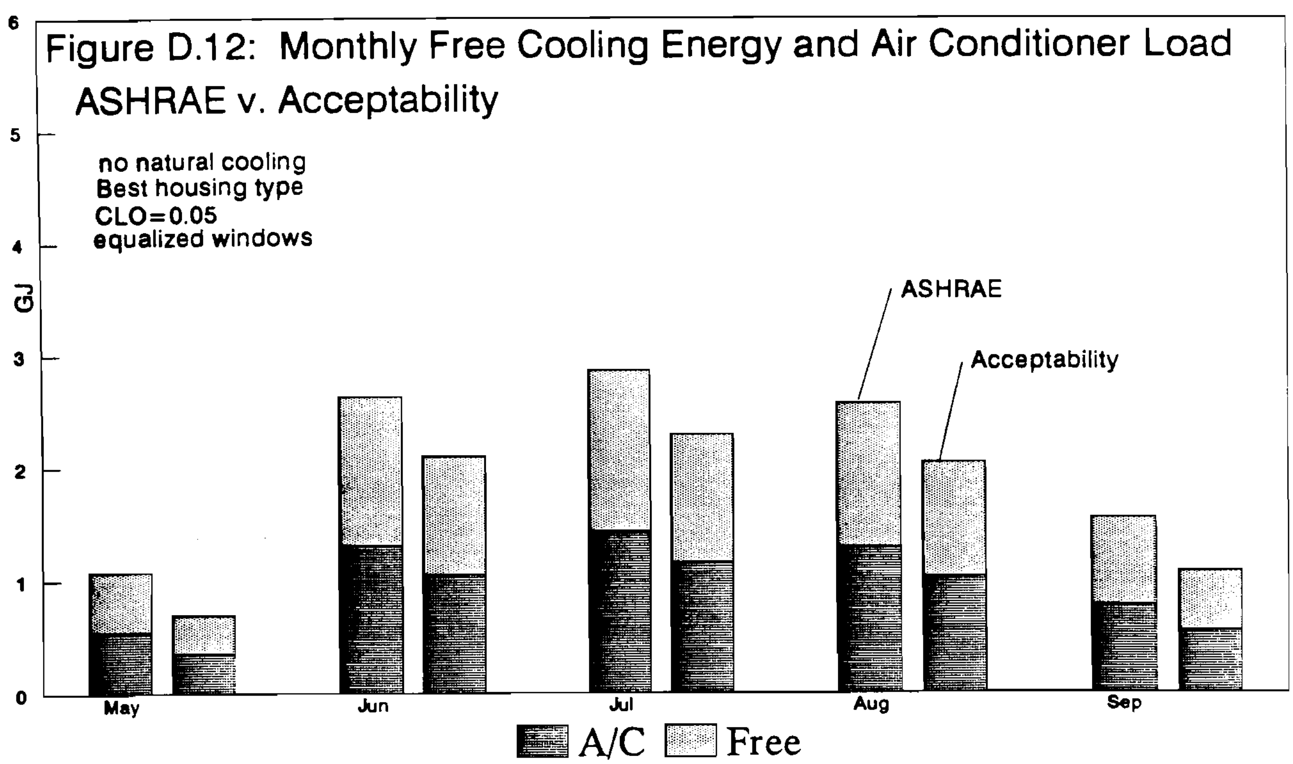
Figure D.12: Monthly Free Cooling Energy and Air Conditioner Load
ASHRAE v. Acceptability
no natural cooling
Best housing type
CLO=0.05
equalized windows
ASHRAE
Acceptability
GJ
0
1
2
3
4
5
6
May
Jun
Jul
Aug
Sep
A/C
Free

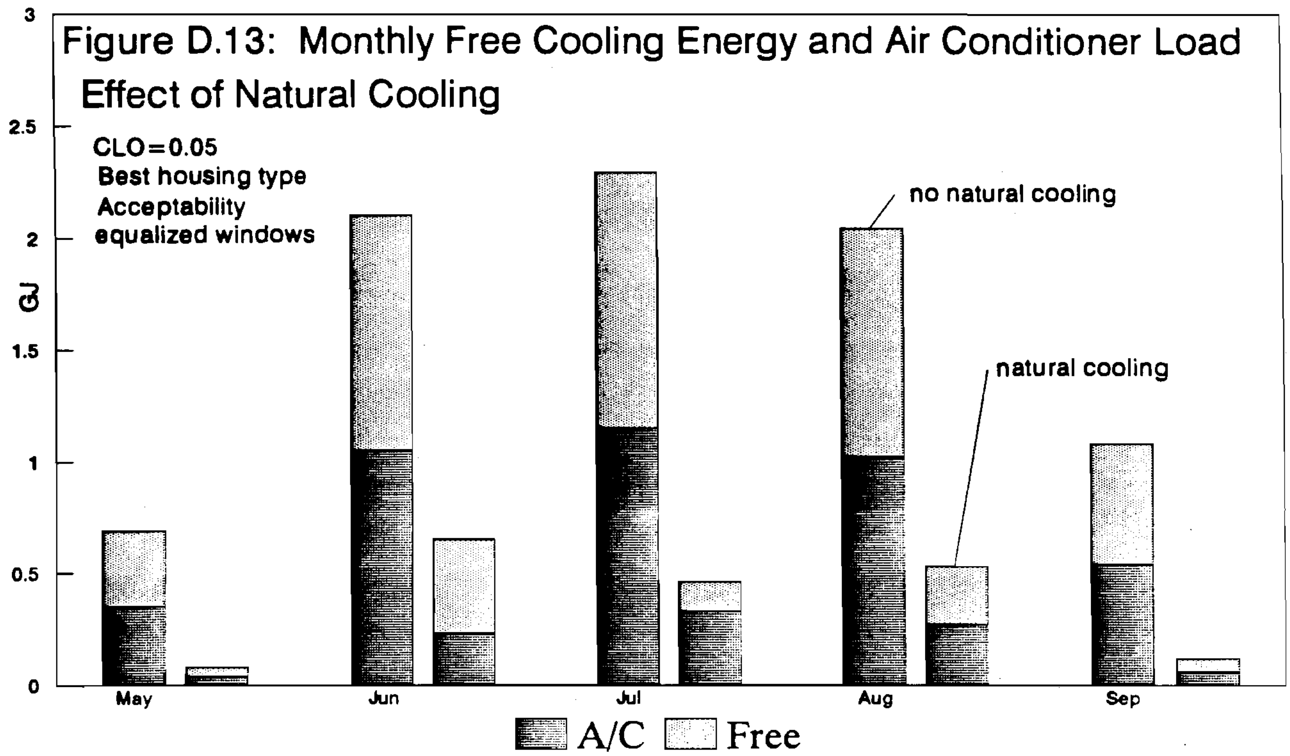
Figure D.13: Monthly Free Cooling Energy and Air Conditioner Load
Effect of Natural Cooling
CLO=0.05
Best housing type
Acceptability
equalized windows
no natural cooling
natural cooling
GJ
3
2.5
2
1.5
1
0.5
0
May
Jun
Jul
Aug
Sep
A/C
Free

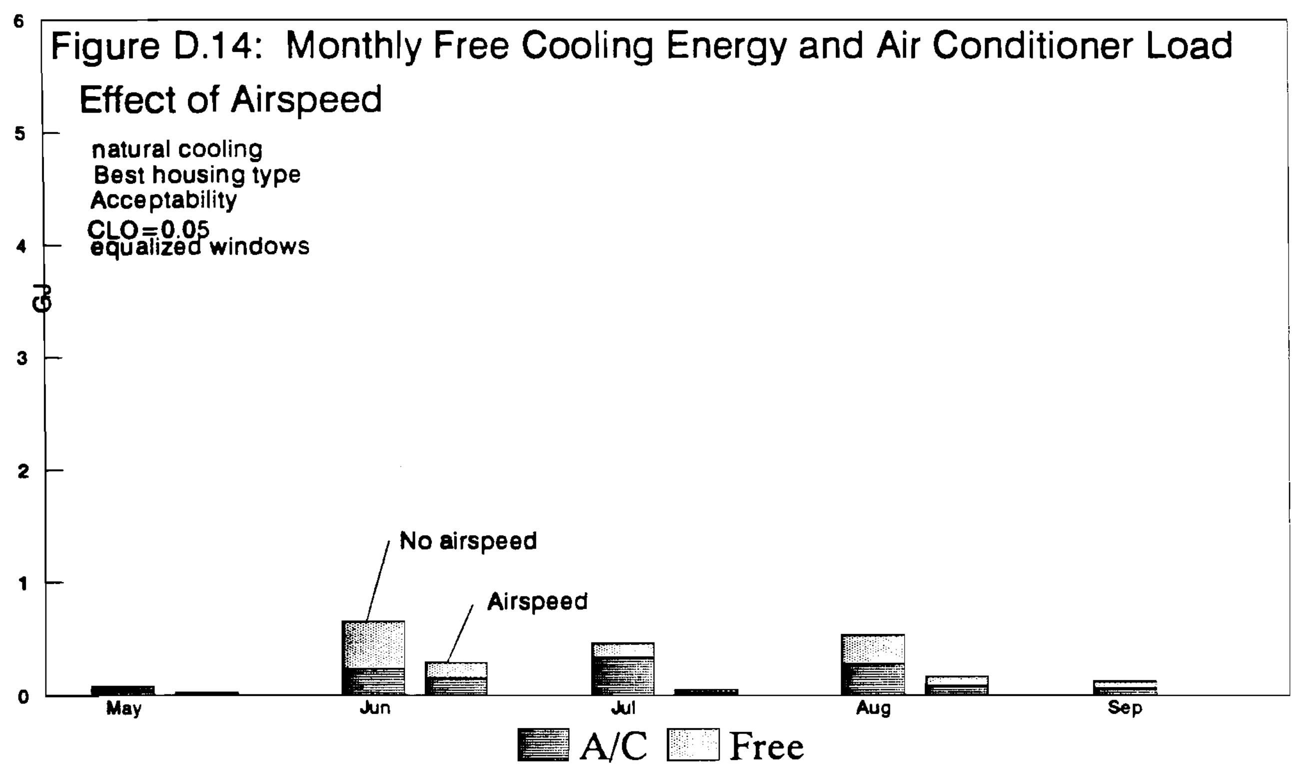
Figure D.14: Monthly Free Cooling Energy and Air Conditioner Load
Effect of Airspeed
natural cooling
Best housing type
Acceptability
CLO=0.05
equalized windows
No airspeed
Airspeed
GJ
6
5
4
3
2
1
0
May
Jun
Jul
Aug
Sep
A/C
Free

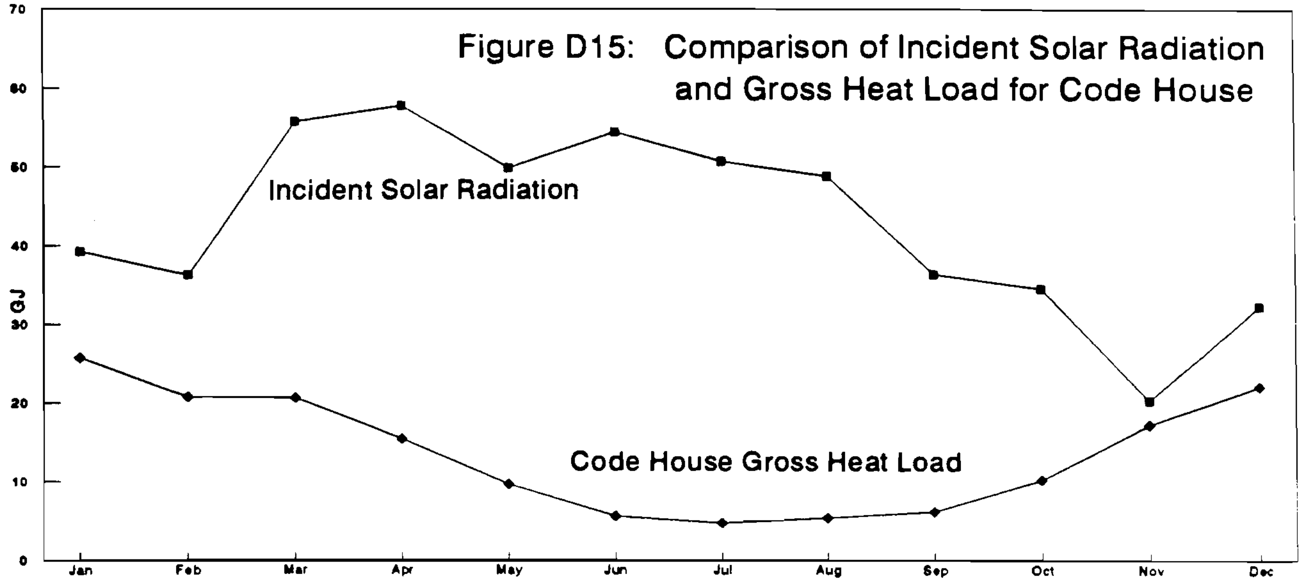

Figure D15: Comparison of Incident Solar Radiation
and Gross Heat Load for Code House
Incident Solar Radiation
Code House Gross Heat Load
GJ
70
60
50
40
30
20
10
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

APPENDIX E

OXYGEN SUPPLY AND CARBON DIOXIDE REMOVAL

Marbek

OXYGEN SUPPLY AND CARBON DIOXIDE REMOVAL

E1. Introduction

Oxygen Requirements in the Home

More than food or water, a ready supply of oxygen is essential to life support for every occupant of a home. Oxygen is required for the metabolism of food. The rate of consumption is directly related to the metabolic rate (met), and is expected to vary from one individual to another, depending primarily on activity level, age, and body weight. An empirical formula for the metabolic rate, based upon oxygen consumption, can be found in ASHRAE Fundamentals Handbook, 1989 (8.8). Average oxygen consumption for sedentary activities in the home environment would be approximately 0.6 l/min. Under extreme conditions, oxygen consumption rates can vary per person from 0.25 to more than 2 litres/minute. A more reasonable variation for a typical individual indoors, at home, would be a range from a low metabolic rate of 0.5 l/min to a high rate of 1.28 l/min.

Although breathing is periodic, the cycle is several seconds in length - so quick to require a continuous supply to the breathing zone. Consequently all levels of service must permit constant access to O_2, at least when occupants are at home.

Ambient air is typically 20.9% O_2, and 78% N_2 by volume. Maintaining these proportions in the breathing zone constitutes an *ideal* level of service. Reducing the relative proportion of O_2 in the air is one way of defining a reduced level of service. To the extent that expired air is mixed and recirculated with fresh air indoors, some decrease in O_2 concentrations is normal and inevitable. As O_2 levels are reduced, the haemoglobin is affected, and the body is forced to adapt.

The extent to which humans are capable of adapting to O_2 reductions is not well documented in Indoor Air Quality (IAQ) literature, primarily because other factors usually dictate the minimum ventilation rates. For example, the production of metabolic CO_2, which is almost directly proportional to O_2 consumption[15], produces a much greater **relative** change in the composition of air than does the consumption of O_2. Consequently, CO_2 control, through provision of outside air and exhaust of indoor air, has indirectly satisfied all requirements for oxygen. Only if CO_2 were controlled through some other means than air change, would it be necessary to design a ventilation system that specifically addressed the occupant's need for oxygen supply. And even in such a situation, the need to control formaldehyde, bio-effluent and other pollutants generated indoors would probably dictate the minimum rate for outdoor air supply.

[15]The ratio of CO_2 production to O_2 consumption is approximately 0.83, for a mixture of food types.

Despite the likelihood that most ventilation systems will satisfy O_2 requirements by default, O_2 is needed for life support, and carries its own fundamental energy requirement. In a closed environment such as a home, the energy requirement is greatly influenced by the extent to which reductions in O_2 concentrations can be tolerated.

Tolerances for Reduced O_2 Concentrations

A reduction in the inspired oxygen concentration causes a decrease in alveolar oxygen, and leads to reduction in arterial oxygen levels. Oxygen concentrations then move downwards, in a step-wise series of partial pressure gradients, until the oxygen finally reaches the mitochondria within the cells. A typical sequence of oxygen partial pressures is listed below:

Ambient air	21.0 kPa
Alveoli	14.7 kPa
Mixed pulmonary/capillary blood	14.0 to 14.4 kPa
Systemic Arterial blood	12.4 to 12.7 kPa
Mixed venous blood	5.1 kPa
Mitochondria	unknown.

If the partial pressure of O_2 in the ambient air is less than 21.0 kPa, then pressures will also drop proportionately throughout the series, with the possibility that quantities may eventually become inadequate to support cellular functions.

Clinical signs of inadequate oxygen include cyanosis, tachypnea, hypoventilation, diaphoresis and altered mental states. Oxygen deprivation is identical to altitude sickness, and is outwardly similar to carbon monoxide poisoning. The first impact of reduced O_2 is likely to be impaired brain function - euphoria, impaired judgement and loss of short term memory. By the time O_2 levels have dropped 50%, an individual will experience stupor, coma and death. Chronic exposure to reduced O_2 levels leads to adaptation within the body; it is for this reason that athletes will train for several weeks at high altitudes prior to competing at high altitude sporting arenas. At high altitude cities, (e.g. Mexico city at 5000 m), oxygen pressure are reduced by over 15%, without apparent problems for inhabitants or visitors. Longterm adaptation to reduced O_2 in the home environment is probably impractical, however, due to changes in occupancy and the frequency of trips out of the home.

A brief literature review has not revealed any recommendations for minimum O_2 levels within the home, or between different living areas. Without more extensive health studies on reduced O_2 in houses, a reduction of O_2 levels of more than 1% is probably unacceptable. This would limit the decrease in O_2 to a minimum of 20.7%. Higher concentrations may be desirable. For ventilation systems based on dilution, the impact of even a 1% variation in O_2 concentrations on total fresh air requirements is very great.

Tolerances for Increased O_2 Concentrations

For health and comfort, oxygen must be diluted with nitrogen, or another non-toxic non-reactive gas, to avoid oxygen toxicity. Inhalation of 100% oxygen for several hours or more can lead to central nervous system disorders. Longterm toxicity can occur if oxygen pressure exceeds about 50 kPa. Smaller fluctuations are not toxic, but may be desirable for some people (e.g. improved healing rates). In hospitals, the concentrations of oxygen provided to patients rarely exceed 35%.

For these reasons the life support function for oxygen requires that it be reasonably well mixed with nitrogen before entering the breathing zone. Ideally oxygen concentrations should be kept constant at 20.9%. Over the short term, concentrations should not drop below 18% or exceed 35%. Longterm average levels should be kept within a range of 20.7% to 20.9%.

Introduction to Carbon Dioxide Generation in the Home

Carbon dioxide is a metabolic by-product, and in a similar manner to oxygen, its production is determined by the metabolic rate of the individuals in the home. In fact, with only slight variations, carbon dioxide is produced as a ratio of oxygen consumption[16]. The ratio of CO_2 production to O_2 consumption is approximately 0.83, for a mixture of food types.

Ambient air contains approximately 0.035% CO_2. Indoor air can be contaminated by combustion sources, such as nearby car and truck traffic, spillage from combustion venting systems, and cigarette smoking. These sources commonly raise the indoor CO_2 levels in some homes to 0.1% or higher, without any contribution from human metabolism.

Tolerances for Increased CO_2 Concentrations

CO_2 is actually a fairly benign substance, that is easily tolerated by humans. The recommended indoor air quality limit for CO_2 is 0.35%. This contrasts with the concentrations permitted by many ventilation standards, which typically specify a maximum CO_2 concentration in the range from 0.06 to 0.1% CO_2.

[16] Variations will occur in the ratio of CO_2/O_2 as a result of the proportions of sugars, oils and proteins in the diet.

Ventilation standards have relied on CO_2 as an indicator of air quality, and consequently their limits are not relevant when considering the essential life support functions such as CO_2 removal.[17]

The lowest concentration at which adverse health effects have been observed in humans is 0.7%, at which level increased blood acidity has been observed after several weeks of continuous exposure. Based on this data, a maximum exposure level of 0.35 % has been recommended by the Federal Provincial Advisory Committee on Environmental and Occupational Health.

Energy Utilization

Both CO_2 and water vapour are produced in the home environment, and can be separated to produce oxygen. Alternatively, air can be replaced with fresh air to maintain oxygen levels.

Oxygen produced from CO_2 would require energy equivalent the stoichiometric combustion of carbon fuel. The heat value of carbon is 32.78 MJ/kg. This converts to a value for dioxygen of 6.435 MJ/m^3. Photosynthesis is a more efficient producer of oxygen from CO_2, requiring only 353 J to produce one cubic metre of gas. For a family of three using an average of 65,000 m^3/year of oxygen, the annual energy used to produce oxygen from plants would therefore be about 23 MJ/yr.

Oxygen produced from water vapour would require the delivery of water (condensing of the water vapour, or pumping of the water), and electrolysis of the liquid water. The oxidation reaction for water is:

$$2H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^-$$

A charge of 4 Faraday or 386000 Coulombs is required to produce 1 molar volume of O_2 (about 24 litres). Power requirements (W) can be calculated from Ohms law (P=Amperes^2*Ohms).[18]

[17] "...complaints have been documented at concentrations as low as 600 ppm. ...the effects observed are probably not attributable to the presence of elevated concentration of carbon dioxide, but rather to undesirable concentration of other substances that result from inadequate ventilation, and for which carbon dioxide provides a suitable surrogate parameter." **Exposure Guidelines for Residential Indoor Air Quality**, Health and Welfare Canada.

[18] One coulomb is equal to 1 Ampere/second. Ohms are equal to the resistivity of water.

E2. Energy Use in a Typical House Using a Mechanical Ventilation System to Supply Oxygen and Remove Carbon Dioxide

Estimating the energy used by the house and mechanical ventilation system when it acts as a device that supplies oxygen, requires many assumptions about the site, the house envelope, the mechanical systems and the climate and weather. To simplify the procedure, the energy transformations have been separated in key terms. The equation presented below lists these key terms. Each term is discussed in more detail in Section E3 below.

For summary purposes, typical values for each term are presented in Table E.1. These values have been used to calculate the energy use of an oxygen supply system in a typical house.

$$E_{oxygen} = \frac{Q_{air}}{V_e} \times (E_{gen} + E_{del} + E_{shelt} + E_{cond}) + E_{emb} + E_{adjust}$$

Where:

E_{oxygen} — the energy used by an oxygen supply system for a typical family of three annually (J)

Q_{air} — the flow of fresh air needed to satisfy the occupants' requirement for oxygen

V_e — the effectiveness of the ventilation system used for the house. This is the fraction of the fresh air delivered to the breathing zone of the occupants. The remainder short circuits back to the outdoors.

$E_{gen.}$ — energy used to generate the oxygen in a cubic metre of fresh air. This is derived from the solar radiation received by Canadian forest and grassland ecosystems, and from the oxygen renewal rate for the chlorophyll contained within the trees and plants.

$E_{del.}$ — energy used to mix the oxygen with air and deliver it to the site. In the case of natural wind forces, this energy is generated as a by-product of the solar radiation used for photosynthesis, and is assumed to be zero for the typical house system.

$E_{shel.}$ — energy used needed to push fresh air through the envelope of a house, and through the ventilation system, past the breathing zone of occupants. This energy is based on the pressure and air flow resulting from infiltration, opening of windows and vents, and operation of the ventilation fans and air distribution system. For a typical house $E_{shel.}$ is estimated to be 4617 J/m^3.

$E_{cond.}$ energy used to condition the fresh air so that it is warm and humid enough for comfort. This energy is estimated for heating and humidification only (no cooling).

$E_{emb.}$ energy used to produce, install and maintain the equipment used for supplying a given quantity of fresh air to occupants. This energy is derived from the energy intensity of the ventilation equipment and ducting materials used in a house, as well as the energy expended to install, repair and replace the equipment over its lifetime.

E_{adjust} energy used annually to make intermittent adjustments to the envelope resistance (or ELA), usually be means of manually opening and closing windows.

Table E.1

Key Terms for Calculating E_{oxygen}	Assumed Values (Typical House)	Annual energy transformation (MJ/yr)
Q_{air}[19]	0.0133 m^3/s (13.3 L/s)	*
E_{gen}	353 MJ/m^3	148
E_{del}	0	0
E_{shelt}	4.617 kJ/m^3	1,937
E_{cond}	30.09 kJ/m^3	12,960
E_{emb}	1392 MJ/yr	1,392
E_{adjust}	13kJ/yr	0.013
TOTAL: (E_{oxygen})	*	16,437

[19]Total air flow used for oxygen supply to a family with an average occupancy of 3 persons, a Ventilation effectiveness of 0.75, and a lower limit for oxygen of 20.7 %.

E3. Background on Energy Used and Assumptions for Typical Houses

Fresh Air Recommendations a Typical House

An average metabolic rate of 1.5 (met) is typical for sedentary/light work activities indoors. This corresponds to an oxygen consumption rate of 0.6 L/min, or 0.01 L/s. Not all of the O_2 in the air is captured by the lungs. An O_2 consumption of 0.6 corresponds to a breathing rate for fresh air of about 10 L/min[20].

The ventilation rate for a house must exceed these air flow requirements in order to prevent the concentrations of Oxygen from dropping below the prescribed minimum due to mixing and dilution with stale air. The ventilation rate per person required to maintain the indoor air above 20.7% is given by:

$$Q_{air} = \frac{F \times 0.1}{(C_L - C_O)}$$

Where

Q_{air}	is the total fresh air required per person (m^3/s * person)
F	is the consumption rate for O_2 (0.01 L/s * person)
C_O	is the outdoor concentration for O_2 (21%)
C_L	is the lower limit for O_2 concentration (20.7%)
0.1	is a unit conversion factor

Ventilation effectiveness (Ve) also must be considered, since the object is not just to push the fresh air through the shelter, but to reach the breathing zone of the occupants. In this context, Ve refers to the fraction of the outdoor air delivered to the home that reaches the breathing zone. Typically fresh air is delivered to occupants by mixing the outdoor air thoroughly with indoor air (for example by locating supply and exhaust grilles at opposite ends of a room). A mixing approach increases the absolute requirements for O_2, since perfect mixing is impossible to achieve. To the extent that fresh air short circuits around the breathing zone and is exhausted, or recirculated, ventilation effectiveness is reduced. Ventilation effectiveness increases if the system is zoned to direct outdoor air to areas where occupants are present, and where mixing with stale air is avoided (through such techniques as plug flow).

Ventilation effectiveness values have been established for typical dwellings in the ASHRAE 62-1989 standard, with perfect mixing given as a Ve of 1.0, and poor mixing as 1.0. For the

[20] If oxygen levels are permitted to drop to 20.7%, the air would be 'less fresh', and breathing rates could be expected to increase, over the short term. Since breathing rates are largely stimulated by CO_2 concentrations, and not oxygen levels, the precise increase in fresh air requirements is difficult to predict.

purpose of a reference scenario it is reasonable to assume a Ve of 0.75 for a typical existing house, and a Ve of 1.25 for the best zoned and designed systems. More details on the determination of Ve values can be found in Appendix F of the ASHRAE Standard 62-1989, **Ventilation for Acceptable Indoor Air Quality**.

Oxygen and fresh air flow recommended for a typical house are summarized below:

Summary of Oxygen and Fresh Air Recommendations:

Parameters	Oxygen required	Air Flow with lower limit of 20.7% O_2	Air Flow with V_e of 0.75
Person per second	0.01 L/s	3.3 L/s	4.4 L/s
Person per year	315 m^3/yr	105,120 m^3/yr	140,160 m^3/yr
3 person family	945 m^3/yr	315,360 m^3/yr	420,480 m^3/yr

The total air flow used to maintain these oxygen levels indoors for a typical family occupancy in a typical house is approximately 13.3 L/s.

Oxygen Generation

Oxygen is the most abundant element on the surface of the earth, (93% of the earth's crust by volume). However because oxygen is such a highly reactive element, gaseous O_2 is normally unavailable, except where released by plants during photosynthesis.

The AER of oxygen production by photosynthesis can be expressed as:

$$E_{gen} = \frac{4.27R}{C \times A \times t_f} \tag{4}$$

Where:

E_{gen} refers to the average oxygen (O_2) renewal rate of a typical Canadian ecosystem in terms of Joules/m^3 of fresh air;

R refers to the average intensity of solar radiation received on a horizontal surface during the growing season. For a 48' north latitude this is approximately 800 W/m2;

C refers to quantity of chlorophyll in a given area of the ecosystem. This varies from 0.4 to 3 grams, and averages about 1.7 g/m2.;

A refers to the assimilation rate for the ecosystem in terms of m^3 of oxygen per gram of chlorophyll per second. This rate is approximately 1.5 x 10^{-5} m^3/s.[21];

4.27 refers to the quantity of fresh air produced by pure oxygen (m^3/m^3);

t_f refers to fraction of the annual solar energy received during the growing season. This is approximated at 0.7.

Oxygen delivery to the lot (E_{dd})

Oxygen could be bottled and transported to the home, or piped from an oxygen utility, or generated by means of a green house within the home, or electrolysis of water generated within the home, or by recycling and 'cracking' the metabolic by-products (e.g. CO_2). However in almost all conceivable situations the supply of oxygen on the lot is more than adequate for needs of occupants, and therefore removes any requirement to examine these other more complicated and energy intensive approaches. A typical lot of 20m x 40m , to a height of 5m, has a volume of 4000 m^3 air (or 836,000 L of O_2), (without any consideration for the additional volume in adjoining public spaces). If this volume is allowed to mix freely, it can supply 2 people for one week, without using up more than 1% of the volume of oxygen.

Normal variations in weather are sure to produce considerable air change with surrounding spaces over the course of a week. Therefore it is reasonable to assume that ambient lot concentrations of O_2 will always remain very close to 21%, and serve occupants with an "ambient" supply of O_2. An exception might be heavily populated and polluted areas, where automobile use and other combustion processes have significantly reduced oxygen concentrations throughout the neighbourhood, but this is highly unusual situation (e.g. downtown Los Angeles during an inversion) likely to entail other more serious IAQ problems, and will not be considered in the scope of this analysis. Thus the first assumption is that energy for oxygen delivery will be supplied by means of the natural weather cycles.

The energy required to push oxygen from the plant ecosystem to the site is largely a byproduct of the energy required for photosynthesis. The forests and grasslands surrounding a Canadian city capture with chlorophyll, only 0.5 to 5 % of the light even during growing periods. The remainder is somewhat equally divided between reflection, evapotranspiration and

[21]The actual ratio of chlorophyll to oxygen is usually expressed in grams: between 0.4 and 4 grams O2 per hour for each gram of chlorophyll). One gram of oxygen produces 34 Litres of gas.

conduction/convection routes. As argued by Odum (1971)[22], the waste energy from photosynthesis and respiration of plants helps to bring rain (and mineral nutrients) to the plants, and helps to drive processes of the biosphere including heat, wind and water currants. For this reason no consideration is given to Oxygen delivery for a typical house.

Restrictions to air flow caused by the shelter ($E_{shelter}$)

The flow of fresh air through the envelope of a house is driven partly by weather, and partly by mechanical ventilation systems. The first, and most critical step in energy analysis, is to establish the relative proportions of each energy transformation for a particular house.

Weather driven air change

The weather driven air change is influenced primarily by the pressure forces of wind and stack, and the restriction or friction factor created by the envelope of the dwelling (i.e. the location and size of the Equivalent Leakage Area or ELA). This energy transformation involves primarily ambient energy sources, (the winds and the heated air within the dwelling). The rate of energy transformation (or Power) is simply a product of the total air flow, and the pressure differential.

The air flow provided through natural ventilation can be modelled using for example, the infiltration model presented in ASHRAE Fundamentals, F23.3, 1992. For a specific house, climate and site condition, it is possible to establish the proportion of Q_{air} that is forced through the envelope in this manner. In many houses natural ventilation may be sufficient to deliver 100% of the requirements for oxygen, a majority of the time. As houses become more airtight, of course, this energy transformation becomes less significant, but only as long as the house is operated with all the windows and doors and vents closed up tightly, (i.e. in a 'closed' position).

Most houses are frequently operated in an 'open' position, as occupants open windows, or doors, or vents during the summer months and in periods of milder temperatures. The effect is to adjust the ELA of the house, with an additional energy transformation required for the opening and losing work (see E_{adjust} below). The larger ELA may permit the use of ambient energy sources in place of mechanical ventilation.

The most difficult component of energy analysis for natural ventilation is establishing the ELA for a house, both in the closed and open positions, and matching the ELA to weather conditions throughout the year.

In a closed position, the ELA for Canadian house will vary from airtight 'R2000' construction, at about 350 cm^2, to levels typical of older Vancouver houses - with ELAs of 3500 cm^2. The

[22]Odum, Howard T., Environment, Power and Society, 1971, page 15.

Table 1 below lists typical variations in ELA, along with the naturally induced air flow rates for different seasons, the average driving pressure, and the corresponding energy transformation. The variations in the Table indicate the danger in trying to simplify or summarize the envelope restriction.

The envelope is a device or technology, and the energy requirements will be unique for each type of system employed. In most existing houses, the envelope design is intended to provide shelter from wind and temperature extremes, but is otherwise unrelated to systems for maintaining indoor air quality. However, in a few cases (e.g. airtight construction, dynamic wall houses, houses built with passive inlets and dummy chimneys), the envelope has been carefully designed to permit effective and/or energy efficient fresh air supply.

The compartmentalization of a house into rooms may impede access to oxygen, even where envelope restrictions are not a major factor. To the extent that the fresh air must be distributed throughout the house, the restriction to air flow will increase. Typically this restriction related to the ductwork, and is calculated as a factor of the **effective length** of the distribution system. It is easy to imagine a system with "through-the-wall" fresh air supply, that can deliver the oxygen as required with no additional resistance from air distribution systems. A distributed fresh air supply system for oxygen supply may be considered as an improved level of service, since it offers (given present technology) better potential for sound control, air filtration, convenient maintenance and flow control, tempering of the fresh air and integration with other systems in the house.

Mechanically driven air change

The energy transformations involved with mechanically moving fresh air to occupants will be related to:

motor efficiencies at varying loads and speeds;
aerodynamic characteristics of the fan blades and housing;
effective length of ducting; and,
the range of ambient air pressures and densities.

Consequently the energy used to move a given quantity of fresh air through the dwelling can be expected to vary significantly depending on the system design. The energy can be empirically established by measuring the wattage draw for the mechanical system at specific air flows. Table E.2 offers some rough estimates of the energy transformation used to move air through a variety of conventional ventilation systems.

Table E.2

Type of System	Air Flow (L/s)
HRV high speed	200
HRV low speed	100
CEV	75
Bathroom Fan	50

A crude model for estimating the energy component of fresh air supply is presented below. This is intended for rough order of magnitude estimating, since accurate ventilation models require some degree of dynamic modelling over more discrete time periods.

$$E_{shelt} = f_{Qi} \times dP_{seas} + f_{Qw} \times dP_{temp} + f_{Qv} \times \frac{W_{fan}}{Q_{air}}$$

Where: E_{shelt} refers to the average energy used to push fresh air through a specific type of envelope and ventilation system, and past the breathing zone, over the course of the year (J/m^3)

f_{Qi} refers to the fraction of Qair provided through natural infiltration via unintentional air leakage openings. For a typical new house with a designed ventilation system, the natural unintended air change is assumed to be 0.4 (ie. providing 40% of the fresh air required for oxygen).

dP_{seas} refers to the average pressure difference across the envelope over the heating season, and is assumed to be 4 Pascals for the typical house.

f_{Qw} refers to the fraction of Qair provided through windows or other passive vents that have been opened by occupants. For a typical house this is assumed to be 0.1 m^3/m^3 (ie 10 %).

dP_{temp} refers to the average pressure differential across the envelope during temperate periods when windows are likely to be open. This is assumed to be 2Pa.

f_{Qv} refers to the fraction of Q_{air} provided by the mechanical ventilation system. For a typical house this is assumed to be 0.5 (ie 50%).

W_{fan} refers to the wattage draw of the ventilation system at an air flow sufficient to provide the oxygen requirements of the occupants (ie.at Q_{air}).

Q_{air} is the total fresh air required per person (m^3/s * person).

Tempering or conditioning of fresh air (AER_c)

Using ambient supplies of oxygen implies a delivery of large quantities of fresh air at outdoor temperatures. In order for the occupants to remain thermally comfortable (i.e. achieve a steady state temperature of about 37°C), it will be essential to condition the incoming air at certain times of the year.

The need for controlling occupant temperatures is a fundamental need on its own right, and to varying degrees the natural infiltration of fresh air generates a heating and cooling load, regardless of any need for oxygen supply. However, to the extent that natural ventilation and mechanical ventilation is used to supply oxygen, air conditioning becomes part of the energy used to supply oxygen using air exchange. It should be noted that if oxygen was to be provided in some other device - through utility pipes in the ground or by means of photosynthesis, the air conditioning load would be much less.

Two energy transformations occur in the conditioning of the incoming fresh air: increasing (or decreasing) the sensible heat, and vaporizing (or condensing) water vapour to control humidity. In both cases it is likely that synergies will exist with other energy needs, such that the house as a system will become far more energy efficient when heating and humidifying fresh air. However for purposes of this simplified example, the ventilation system is viewed in isolation.

The E_{cond} value for a typical house can be calculated as follows:

$$E_{cond}=f_{heating}\times[1.204\times(1.006+1.84W_o)\times(T_i-T_o)+1.204\times2500\times(W_i-W_o)]$$

Where

E_{cond} refers to the total energy required to heat and humidify incoming fresh air for oxygen supply (J/m^3).

$f_{heating}$ refers to the fraction of the year in which fresh air requires heating and humidification, and is assumed to be 0.5 for the typical house.

1.204 refers to the density of outdoor air (kg/m^3).

1.006 refers to the specific heat of dry air (kJ/kg).

1.84 refers to the specific heat of water vapour (kJ/kg)

T_i refers to the average temperature outdoors over the heating season (C) and for the typical house is assumed to be 19°C (equivalent to about 3500 Degree Days).

T_o refers to the minimum acceptable temperature of air for occupant comfort (C) and is assumed to be 18°C for the typical house.

W_i refers to the ratio of water vapour to air indoors (kg/kg air) and is assumed to be 0.0065 for a typical house.

W_o refers to the ration of water vapour to air outdoors (kg/kg air), and is assumed to be 0.001 for a typical house during the heating season.

2500 refers to the approximate heat content of 50% relative humidity vapour at 24°C, less the heat content of water at 10°C, and is a default value commonly used for design calculations (kJ/kg)

The minimum acceptable indoor air temperature is a variable that may vary with the features of the house and the age, gender and lifestyle of the occupants. For simplicity, it is possible to adopt norms established by ASHRAE for comfort. For typical people and typical clothing ensembles, the coolest sensible air temperatures for comfort, (only 6% of people dissatisfied), at 50%RH is about 19°C. The warmest air temperature, at 30%RH, is about 27°C.[23]

In an indoor environment, where air velocities and humidities are seldom extreme, the single biggest factor influencing perception of comfort when altering air temperatures is the typical range of variations in the clothing ensemble. It is necessary therefore to establish levels of service based on clothing. A **conserver lifestyle**, for oxygen supply, would entail a seasonal wardrobe change. To some extent this occurs automatically (few people wear thick wool sweaters in the middle of summer). But there still exists a significant difference between the average indoor clothing ensemble (with an intrinsic insulation value of about 0.45), and an ensemble which includes long underwear, a sweater and a suit jacket (at 1.30). The effect of altering the level of service is quite significant from an energy point of view, since the result is a greater range in acceptable temperatures. Because of the complexity of calculations it is,

[23]Refer to ASHRAE Fundamentals Handbook, 1989, SI, Page 8.14, Figure 5, Standard Effective Temperature and ASHRAE Comfort Zones

for the moment, not possible to calculate the full impact of wardrobe changes. For illustrative purposes it is assumed that clothing changes can increase the acceptable temperature by at least one degree on each side (i.e. a winter temperature of 18^0 and a summer temperature of 28^0C). These parameters will affect both the amount of energy used to condition the air, as well as the total fraction of the year in which ventilation systems are used in houses where occupants are otherwise willing to simply open vents or windows.

Embodied Energy of Ventilation Systems

A simplified equation for embodied energy is presented below:

$$E_{emb}=\sum_{i..n}\frac{(E_{intensity}*M+E_{install}+E_{maintain}+E_{repair})}{t_{life}}$$

Where for each component of the ventilation system:

$E_{intensity}$ refers to the energy intensity of the material or equipment (J/kg), and includes all the energy transformed as a result of extracting raw materials, fabricating the equipment, and transporting, selling and handling the equipment. For the typical house, ventilators are given a value of 68.9[24], and metal ductwork is given a value of 83.8.

M refers to the mass of the material (kg). The typical house is assumed to have ventilation equipment and controls for fresh air supply total 50 kg., and ductwork for fresh air distribution totalling 500 kg.

$E_{install}$ refers to the energy transformed as a result of installing the system, including transportation of tradesmen, use of power tools, etc. This is not calculated for the typical house.

$E_{maintain/repair}$ refers to the energy transformed as a result of maintaining and repairing the equipment over the lifetime of the system. This is not calculated for the typical house, although it could be substantial.

t refers to the expected lifetime of the equipment in years. This is assumed to be 10 years for the ventilator, and 40 years for the ductwork, in a typical house.

[24]from **Optimize**, Sheltair, for CMHC, 1991, based on 1984 Statistics Canada Input-Output data.

Energy Used for Adjustment of the System

Window opening and closing is the main adjustment for ventilation in most houses, especially where a dehumidistat or other automatic control is used for the mechanical system.

A simple equation for calculating the energy transformation over the year is given below:

$$E_{adjust} = \frac{F \times d \times C_f \times n}{e_e}$$

Where:

F refers to the force used to move the vents, (N), and is assumed to be 10 N for a typical window mass moved by a person.

d refers to the distance a window or vent must be opened to provide additional ventilation (m), and is assumed to be 0.3 m for a typical home.

C_f refers to the coefficient of friction for a window, and is assumed to be about 1.2 (wood on wood).

n refers to the number of window adjustments (openings and closings) occurring over the year. This is assumed to be 360.

e_e is the energy conversion efficiency for the device moving the vents, and is assumed to be 0.1 for the human being in the typical house.

The equation gives a very small amount of energy for adjusting the size of opening in a house over the year.

APPENDIX F

LIGHTING NEEDS AND USE

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LIGHTING NEEDS AND USE

F1. Defining the Need for Light

Visible light (often together with other wavelengths of the electromagnetic spectrum) is produced either directly, through combustion and/or other physicochemical processes (e.g. nuclear fission in the sun), or it may be generated by the excitation of electrons of an appropriate element, as occurs within a fluorescent lamp. Every light source produces a spectrum of wavelengths that is characteristic of that source; what is perceived by a human observer to be a single colour "temperature" is usually a blend of many different wavelengths (see various spectra in Lighting, Appendix 4). For example, a common incandescent lamp has a colour temperature of about 3000°K, while a blue sky can have a light temperature of 10,000 to 20,000°K.

If optimum lighting levels are to be defined for human tasks, therefore, both the quality and quantity of these levels must be defined; these qualities being analogous to intensity or illuminance, measured in lux, and temperature, measured in degrees kelvin. The IES Lighting Handbook has defined statistical ranges of "acceptable" (i.e. acceptable to most people) lighting levels for the range of colours within the visible part of the spectrum. These can help in defining minimum lighting requirements; essentially it shows that high intensities of low temperature light (yellows, oranges and reds) are not acceptable for most people, while low intensities of lights towards the blue end of the spectrum are not comfortable either.

In order to define energy requirements for lighting it is first necessary to define the amount, type and duration of lighting needs in a typical household. The total lighting need is a function firstly of the type of activities undertaken, and secondly of the duration of those activities.

For this analysis, the household activities selected were those catalogued in the IES Lighting Handbook (Application Volume, 1981). Time spent for each activity was estimated, but the underlying principle applied here was that *the absolute lighting requirement for a particular task is only the amount required to perform a given task comfortably, and that this need ceases immediately when the task or activity ceases*. For example, the light required to read a book is only the light needed to illuminate the page comfortably, not the peripheral, ambient or background lighting.

The standard measure of light power is the lumen, defined as 683 watts of 555 nanometre light (yellow-green in colour). The intensity figures (lumens/m^2) from IES were converted to joules, and multiplied by the estimated minimum space requirements and durations to produce a daily energy requirements in joules per task.

F2. Electric Lighting

The efficiency of a lamp (including any ballast) is normally defined in terms of its efficacy - the number of lumens produced per watt input. The efficacy is a function of the lamp type and its ballast power draw. Incandescent lamps produce about 20 lumens/watt, while standard fluorescents achieve a far higher 70 to 90 lumens/watt. Advanced induction lamps now under development are expected to produce 200 lumens per watt. A perfect lamp which transforms all electrical energy to light would produce 683 lumens (at 555 nanometres) with a one watt input.

The efficiency of a lighting fixture is normally defined by its coefficient of utilization (CU); the fraction of the light produced by the lamp which falls on the area to be illuminated. This is a function of the reflector design and other design features. Typical CUs range from 25% to 40%. Fixture efficiency can be defined as equal to coefficient of utilization times efficiency.

Most lighting systems, however, are designed to illuminate complete rooms or at least relatively large areas, much more than is needed. A reading light, for example usually illuminates an area far larger than the page being read.

Lighting systems are also left on when they are not needed, and lighting levels are usually set at the highest required in that room or area. As indicated above, light is only needed when a person is carrying out a specific task. A food preparation area only needs to be lit when food is being prepared. If there is only one person in the house at this time, no other light is needed.

Finally, lighting systems also distort the power system frequency spectrum (as measured by the power factor of the device).

The perfect lighting control system would illuminate only the area needed, only when it is "in use", only to the lighting level required, and with minimum frequency distortion. Control systems designed to come close to this ideal are available for use in commercial buildings using task tuning, infra-red occupancy sensors, dimmable lamps, and high power factor equipment.

Table F.1 provides a table of fixture coefficients of utilization and lamp efficiencies for a range of standard and high efficiency electric lighting devices, including incandescent, fluorescent and the new two photon (induction) lamps currently under development. Table F.1 shows that as far as the lighting lamp and fixture is concerned, great improvements can be made in efficiency. Even with induction lamps (with an efficacy of 230 lumens/watt), reflectors, and electronic ballasts, the overall fixture efficiency is only 11.1% (compared with a perfect fixture which would have a lamp efficacy of 683 lumens/watt and coefficient of performance of 1.0).

F3. Daylighting

Table F.2 provides an analysis of the amount of daylighting passing through the windows of the reference house that can be matched to the lighting needs of the dwelling. The table shows that more than half of the lighting needs of the dwelling can be met with daylighting.

F4. Absolute Efficiencies

Table F.3 shows the derivation of absolute efficiencies for electric lighting used in a typical dwelling.

TABLE F.1

Efficiencies of Typical Lighting Fixtures

Assumed Room Cavity Ratio of .8

FIXTURE	Coefficient of Utilization	Lamp Efficacy (lm/W)	Fixture Efficiency (%)
Pendant Diffusing Sphere with Incandescent Lamp	0.23	20	0.7%
Pendant Diffusing Sphere with Compact Fluorescent Lamp	0.23	60	2.0%
R-40 Flood Without Shielding	0.62	20	1.8%
Recessed Incandescent Unit with Dropped Diffusing Glass	0.22	20	0.6%
Recessed Compact Fluorescent Unit with Dropped Diffusing Glass	0.22	60	1.9%
Porcelain-enameled Reflector with 35 degree CW shielding (/w F40 lamp)	0.36	72	3.8%
Porcelain-enameled Reflector with 35 degree CW shielding (/w T8 lamp)	0.36	90	4.7%
Diffuse Aluminium Reflector with 35 degree CW and 35 degree LW shielding (F40)	0.33	72	3.5%
Diffuse Aluminium Reflector with 35 degree CW and 35 degree LW shielding (T8)	0.33	90	4.3%
"High Bay" wide dist. ventilated reflector w/ clear HID lamp	0.40	47	2.8%
Fixture using Two Photon (induction) Lamp	0.33	230	11.1%

TABLE F.2

Daylighting Contribution

Activity	Intensity (Lux) (Lumens/m²)	Required Space (m2)	Time of Day Category	Distance From Window (metres)	Light from Window (Lux)	Lighting Deficit (Lux)	Task Coincidence (Hrs)	Daylight Contribution (kJ)	Artificial Light Required (kJ)
General Lighting	75	5	NIGHT		0	75	0	0.0	7.9
Dining	150	4	A	5	394	0	0.2	0.6	1.7
Grooming	300	3	NIGHT		0	300	0.5	0.0	9.5
Workbench									
Ordinary	300	4	D	5	1166	0	0.1	0.6	0.9
Difficult	750	2	D	5	1166	0	0	0.0	2.0
Critical	1500	0.5	D	5	1166	334	0	0.0	1.0
Easel hobbies	750	2	A	NEAR	2367	0	0.2	1.6	2.4
Ironing	300	3	B	NEAR	3939	0	0.2	0.9	1.4
Kitchen Counter									
Critical	750	0.5	A	NEAR	2367	0	0	0.0	2.0
Noncritical	300	2	A	NEAR	2367	0	0	0.0	9.5
Kitchen Range									
Critical	750	0.75	A	2	789	0	0	0.0	0.7
Noncritical	300	0.75	A	2	789	0	0	0.0	0.3
Kitchen Sink									
Critical	750	0.5	A	NEAR	2367	0	0	0.0	0.5
Noncritical	300	0.5	A	NEAR	2367	0	0	0.0	0.1
Laundry	300	1	E	5	1240	0	0	0.0	0.2
Music Study	750	1	NIGHT		0	750	0	0.0	3.0
Reading	300	0.2	NIGHT		0	300	2	0.0	1.9
Sewing	750	0.5	A	5	394	356	0	0.0	0.5
Sleep			NIGHT			0		0.0	0.0
House Empty			DAY			0		0.0	0.0

Total Daily Daylighting Contribution	3.8	kJ
Total Yearly Contribution	1.4	MJ
Total Daily Artificial Lighting Need	45.5	kJ
Total Yearly Artificial Lighting Need	16.6	MJ

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TABLE F.3

Actual Electric Lighting Energy Use in a Typical Dwelling

Activity	Duration of Use (hours)	Fixture Type	Coeff. of Utilization	Bulb Type	Bulb Efficacy (lms/W)	Fixture Lighting Efficiency (2)	Lighting Intensity (lms/m²)	Area Lit (m²)	Bulb Wattage	Artificial Light Used (kJ)	Fixture Electricity Used (kJ)	Total Energy Use (kJ) (3)	Absolute Lighting Efficiency (4)
General Lighting	4	Ceiling	0.25	Incand.	20	0.7%	75	20	300	7.9	4,320	8,640	0.09%
Dining	1	Ceiling	0.25	Incand.	20	0.7%	150	5	150	1.7	540	1,080	0.16%
Grooming	2	Ceiling	0.25	Incand.	20	0.7%	300	3	180	9.5	1,296	2,592	0.37%
Workbench													
Ordinary	0.5	Ceiling	0.32	Fluor.	72	3.4%	300	4	52	0.9	94	188	0.51%
Difficult	0.5	Ceiling	0.32	Fluor.	72	3.4%	750	2	65	2.0	117	234	0.84%
Critical	0.25	Ceiling	0.32	Fluor.	72	3.4%	1500	2	130	1.0	117	234	0.42%
Easel hobbies	0.5	Ceiling	0.25	Incand.	20	0.7%	750	3	450	2.4	810	1,620	0.15%
Ironing	0.5	Ceiling	0.25	Incand.	20	0.7%	300	3	180	1.4	324	648	0.22%
Kitchen Counter													
Critical	1	Ceiling	0.25	Incand.	20	0.7%	750	2	300	2.0	1,080	2,160	0.09%
Noncritical	3	Ceiling	0.25	Incand.	20	0.7%	300	3	180	9.5	1,944	3,888	0.24%
Kitchen Range													
Critical	1	Hood	0.4	Incand.	20	1.2%	750	1	94	0.7	338	675	0.11%
Noncritical	1	Hood	0.4	Incand.	20	1.2%	300	1	38	0.3	135	270	0.11%
Kitchen Sink													
Critical	1	Ceiling	0.25	Incand.	20	0.7%	750	0.5	75	0.5	270	540	0.09%
Noncritical	1	Ceiling	0.25	Incand.	20	0.7%	300	0.5	30	0.1	108	216	0.05%
Laundry	1	Ceiling	0.32	Fluor.	72	3.4%	300	10	130	0.2	469	938	0.02%
Music Study	1	Lamp	0.5	Fluor.	72	5.3%	750	4	83	3.0	300	600	0.49%
Reading	2	Lamp	0.25	Incand.	20	0.7%	300	2	120	1.9	864	1,728	0.11%
Sewing	1	Ceiling	0.32	Fluor.	72	3.4%	750	3	98	0.5	352	703	0.07%
Sleep	8										0		
House Empty	7.5										0		
TOTAL											13,477	26,954	

SUMMARY

	Daily	Yearly
Total Electricity Use:	13.5 MJ	4.9 GJ
Total Energy Use [3]:	27.0 MJ	9.8 GJ
Absolute Lighting Efficiency [4]	0.37%	

Notes:

1) The Coefficient of Utilization denotes the percentage of light emitted fromthe fixture that illuminates the activity area.
2) The Fixture Lighting Efficiency denotes the portion of the energy consumed that reaches the surface of the lit area.
3) Total energy use includes fixture electricity use plus upstream losses. (full fuel cycle efficiency)
4) The Absolute Lighting Efficiency is the lighting energy actually needed (Absolute Energy) divided by the total energy used for fixtures only.

APPENDIX G

WATER HEATING

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WATER HEATING

G1. Hot Water Use

In most households hot water is used for personal cleaning, dishwashing and clothes washing; heating water generally increases its cleaning power, and improves the comfort of personal cleaning. As noted in the main body of this report, hot water is not a household need in itself but a means of meeting other needs such as clothes cleaning and personal washing.

The energy required to heat water for domestic use is just the simple heat energy necessary to raise the temperature of water from its intake source temperature (normally ground temperature) to a temperature which is useful for cleaning purposes. In Canada most households are fitted with storage-type water heaters, and these are generally set at temperatures of 55 to 65°C, in part for health reasons (the *Legionella* bacterium can flourish at temperatures under 50°C), and in part because the water heater thermostat has traditionally been set at the highest temperature used by any of the domestic appliances in the house; most dishwashers and many washing machines have been set to use water which is at least this hot. Nevertheless, with the introduction of better detergents, the need for higher temperature water has diminished considerably, to the point where personal cleaning may have the highest water temperature requirements, at around 35 to 40°C.

G2. Water Heating Devices

All domestic water heating systems can be considered to have three components: these being the production device, the storage/distribution network and, in some cases, a (greywater) heat recovery drainage device. All systems incur some losses. This appendix reviews six different systems and estimates losses for each of the three components. A solar water heater uses electricity to supplement the energy supplied by solar energy. The heat pump water heater uses waste ventilation heat from the home, but is powered by electricity. The relative efficiency of each unit therefore must take the energy quality of each source into account.

G3. Water Heater Efficiency Calculations

Thermodynamic efficiencies for various hot water heating devices have been summarized in Table G1. The efficiency of each type of device has been estimated with and without a grey water heat recovery unit. The following definition of thermodynamic efficiency has been used.

Thermodynamic Efficiency =

$$\frac{\text{Energy Produced x Exergy Factor of Hot Water}}{\text{External Energy Used x Exergy Factor of Source x Fuel Cycle Efficiency of Service}}$$

The External Energy Used is net of the ambient contribution from solar, ambient air or heat recovery. The exergy factor of hot water (at 45°C) is assumed to be "0.05". The exergy factor for electricity and gas are both assumed to be "1.0". Fuel cycle efficiencies are given in Appendix C.

Table G.1
Estimated Efficiencies for Various Domestic Water Heating Systems

Water Heater System	Efficiency* w/o GWHR**	with GWHR**
1. 180 l Electric storage heater, Standing loss = 120 W, standard plumbing run, uninsulated.	2.06%	2.6%
2. 180 l Electric storage heater, Standing loss = 65 W, insulated copper piping.	2.1%	2.8%
3. Electric instantaneous heaters at points of use.	2.5%	2.9%
4. 180 l Gas Storage Heater, Standing loss = 120 W, uninsulated copper piping	2.5%	2.9%
5. Solar heater with electric backup, 180 l storage heater, insulated piping, Solar fraction = 50%	3.9%	6.8%
6. Heat pump water heater 180 l storage heater insulated piping COP = 3.0	5.3%	12.5%

Notes: * Efficiencies have been calculated assuming an average daily hot water demand of 240 litres, for a four-person household.
** Greywater Heat Recovery

The derivation of each efficiency is provided below:

Electric storage heater, uninsulated copper-pipe distribution network

Specs: 180 litre tank, Standing loss = 120 Watts, uninsulated pipe run, daily draw = 240 litres;

Energy produced by system = 240 kg * 4.18 kJ/kg°C * 45°C = 45 MJ
Losses from conversion system = 0 MJ; Efficiency = 100%

Losses from storage system = 120 J/s * 3600 * 24 = 10.4 MJ
Losses from distribution system = 1.0 MJ[25]

a) Efficiency without Greywater Heat Recovery

Total heat input = (45 + 10.4 + 1.0 - 0) = 56 MJ
Exergy Ratio = 0.05
Fuel Cycle Efficiency = 0.5
Thermodynamic Efficiency = (45/56)(0.05)(0.5) = 2.0%

b) Efficiency with Greywater Heat Recovery

Recoverable Heat From Greywater = 50% of heat from avg. outlet temperature (33.9°C) to inlet temperature (10°C)

= 0.5 (240 kg * 4.18 kJ/kg°C * (33.9 - 10)°C)
= 12 MJ

Total heat input = 56-12 = 44MJ

Efficiency of system = (45/44)(0.05)(0.5) = 2.6%

Efficient Electric storage heater, insulated copper-pipe distribution network

Specs: 180 litre tank, Standing loss = 65 Watts, insulated pipe run, daily draw = 240 litres

Purchased Heat input to conversion system = 240 kg * 4.18 kJ/kg°C * 45°C = 45.14 MJ
Losses from conversion system = 0 MJ; Efficiency = 100%
Losses from storage system = 65 J/s * 3600 * 24 = 5.62 MJ
Losses from distribution system = 0.33 MJ[26]

a) Efficiency without greywater heat recovery

Total heat input per litre delivered = (45 + 5.62 + 0.33) = 52 MJ
Efficiency of system = (45/52)(0.05)(0.5) = 2.1%

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[25]Ibid

[26]Ibid

b) Efficiency with greywater heat recovery

Heat recovery from drainage = 0.5(240 kg * 4.18 kJ/kg°C * (33.9 - 10))
= 12.0 MJ

Total heat input per litre delivered = 52 - 12 = 40 MJ
Efficiency of system = (45/40)(0.05)(0.5) = 2.8%

Electric instantaneous heaters at points of use

Specs: no storage tank, situated adjacent to points of hot water use, daily draw = 240 litres;

Purchased Heat input to conversion system = 240 kg * 4.18 kJ/kg°C * 45°C = 45 MJ
Losses from conversion system = 0 MJ; Efficiency = 100%
Losses from storage system = 0 MJ
Losses from distribution system = 0 MJ[27]
Total heat input = 45 MJ

a) Efficiency without greywater heat recovery

Total heat input = 45 MJ
Efficiency of system = (45/45)(0.05)(0.5) = 2.5%

b) Efficiency with greywater heat recovery

Heat recovery from drainage = 12 MJ

Total heat input = (45 - 12) = 33 MJ

Efficiency of system = (45/33)(0.05)(0.5) = 3.4%

Gas storage heater, uninsulated copper-pipe distribution network

Specs: 180 litre tank, combustion efficiency = 70%, Standing loss = 120 Watts, uninsulated pipe run, daily draw = 240 litres;

Purchased Heat input to conversion system = 1/.7(240 kg * 4.18 kJ/kg°C * 45°C) = 65 MJ
Stack Losses from conversion system = 19.35 MJ; Efficiency = 70%
Losses from storage system = 120 J/s * 3600 * 24 = 10.4 MJ

[27] Ibid.

Losses from distribution system = 1.0 MJ[28]
Heat recovery from drainage = 0 MJ

a) Efficiency without greywater heat recovery

Total heat input per litre delivered = (65 + 10 + 1) = 76 MJ
Exergy ratio = 0.05
Fuel cycle efficiency = 0.84
Efficiency = (46/76)(0.05)(0.84) = 2.5%

b) Efficiency with greywater heat recovery

Heat recovery from drainage = 12 MJ

Total heat input per litre delivered = (76 - 12) = 64 MJ

Efficiency of system = (45/64)(0.05)(0.84) = 2.9%

Solar heater with electric backup, insulated copper-pipe distribution network

Specs: Solar flat plate collector, 180 litre storage tank, Standing loss = 65 Watts, uninsulated pipe run, daily draw = 240 litres; solar fraction 50%

a) Efficiency without heat recovery

Purchased Heat input to conversion system = 0.5(240 kg * 4.18 kJ/kg°C * 45°C) = 22.5 MJ
Losses from backup conversion system = 0 MJ; Efficiency = 100%
Losses from storage system = 65 J/s * 3600 * 24 = 5.62 MJ
Losses from distribution system = 0.33 MJ

Total heat input = (22.5 + 5.6 + .33) = 28.5 MJ
Efficiency of system = (45/28.5)(0.05)(0.5) = 3.9%

b) Efficiency with greywater heat recovery

Heat recovery from drainage = 12 MJ

Total heat input = (28.5 - 12)/240 = 16.5 MJ

[28]Ibid.

Efficiency of system = (45/16.5)(0.05)(0.5) = 6.8%

Heat Pump Water Heater

Specs: 180 litre tank, COP = 3.0, Standing loss = 65 watts, insulated pipe run, daily draw 240 litres.

a) Efficiency without heat recovery

Purchased heat input to system = 0.33 (240 kg x 4.18 KJ/kg ^{0}C x 45^{0}C) = 15 MJ
Losses from storage = 65 watts x 3600 x 24 = 5.6 MJ
Losses from distribution system = 0.3 MJ

Total energy input = (15+5.6+0.3) = 21 MJ
Efficiency = (45/21)(0.05)(0.5) = 5.3%

b) Efficiency with greywater heat recovery

Heat recovery from drainage = 12 MJ

Total energy input = 9 MJ

Efficiency = (45/9)(0.05)(0.5) = 12.5%

APPENDIX H

METABOLISM AND HUMAN POWER

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METABOLISM AND HUMAN POWER

H1. Thermal Interchanges between Humans and their Environment

The average temperature of the human body depends on a balance between net heat produced and net heat loss to the environment. The body's principal heat source is oxidation of food elements (i.e. metabolism). At the same time the body may be doing one, more or all of the following:

1. Performing work
2. Losing heat by evaporation of body fluids
3. Exchanging heat by radiation and convection

During rest and exercise these processes result in an average deep body temperature of around 37°C. The fundamental thermodynamic process in heat exchange between the body and the environment can be described by a general heat balance equation (all terms are measured in Watts):

$$S = M - (\pm W) \pm E \pm R \pm C \qquad \text{-- (1)}$$

where:
- S = rate of heat storage
- M = rate of metabolism, which is proportional to rate of oxygen consumption
- E = rate of total evaporative heat loss, due to evaporation of body fluids
- $R + C$ = dry heat exchange with the environment
- W = mechanical work accomplished

When S, the rate of heat storage is positive, average body temperature is rising; when negative, it is falling, and when zero it is in thermal equilibrium. Work (W) is positive when accomplished by the body, but is considered negative when potential energy is used. In this case the potential energy used must be subtracted from body energy produced (M) to find the net heat developed within the body core.

Since the amount of heat produced by a human is dependent both on metabolism and body size, it is useful to be able to estimate skin surface area. One empirical equation which does so was developed by DuBois:

$$A_D = 0.202\, w^{0.425}\, h^{0.725} \qquad \text{--(2)}$$

where:
- A_D = body surface area (or "Dubois body surface area")
- w = body weight in kilograms
- h = body height in metres

For an average sized man, of 1.7m (5' 8") in height, and weighing 70 kg (154 lbs) this equation gives a skin surface area of 1.8 m^2 (19.4 ft^2).

H2. Work

The unit for rate of human work (W) (i.e. delivered power) is usually designated by exercise physiologists as the *kilopondmetre per minute* (kpm). A kilopondmetre is a one kilogram mass which is raised through a distance of 1 metre. Since one Joule is equivalent to one Newton.metre, and one Watt is one Joule/second, it can be shown that 100 kpm is equivalent to 16.3 Watts. A value of 100 kpm/min is considered to be light exercise, and 1200 kpm heavy exercise for an average sized man[29]; 1200 kpm therefore represents a work output of 196 Watts.

The observed work rate can be calculated or estimated for any human work activity. Two examples are given below, for hammering nails and for step-up exercising.

Example: Hammering

Assumptions:

Weight of Hammer	=	1 kg
Distance raised	=	0.5m
Rate (blows/sec)	=	2 /sec

It is further assumed that the human power exerted on the hammer when it is brought down is 1.5 times the power required to lift it against normal gravitational force.

Force Downward	= 9.8 ms^{-2} (1.0 kg)	= 9.8 kgm^{-2} = 9.8 N
Force Upward	= 1.5 (9.8)	= 14.7 N
Distance Up/sec	= Distance Down/sec	= 1.0 m
Work	= Force * Distance = 9.8 (1.0) + 14.7 (1.0) = 24.5 N.m/sec = 24.5 Watts	

This rate of work would represent the maximum achieved at the given rate of hammering. On average, carpentry work which included hammering might be expected to average out at rather less than this amount.

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[29]Ibid.

Example: Step-up exercising Assumptions:

Weight of Person	= 70 kg
Height of bench	= 0.35m
Rate (steps/sec)	= 1 /sec

Force Downward $= 9.8\ ms^{-2}\ (70.0\ kg) = 686\ kgms^{-2} = 686\ N$

Distance Up/sec = Distance Down/sec = 0.35 m

Work = Force * Distance
= 686 (0.35)
= 240 N.m/sec
= 240 Watts

Table H.1 outlines estimated work/power outputs for various human activities. The values used are derived in part from tables of metabolic rates for these activities, as presented in ASHRAE *Fundamentals* Handbook, 1981.

Table H.1
Estimated Work Output for Various Activities

Type of Activity	*Level of Effort*	*Estimated Work Rate (watts)*
Carpentry - hammering	high	20 - 30
- sawing	moderate	15 - 20
Step-up exercises	high	200 - 250
Prepare food	light	4 - 15
Handwash clothes	moderate	10 - 20
Wash dishes	light	4 - 10
Wash floors	moderate	10 - 20
Shovel snow	high	15 - 50
Sweep leaves	moderate	10 - 30
Use Lawnmower - push type	high	20 - 50
- powered	moderate	10 - 20

H3. Metabolism

The metabolic heat produced by the body is normally measured by the rate of oxygen consumption[30] as:

$$M = (0.23\ (RQ) + 0.77) * (5.87\ V_{02}) * (60/A_D) \qquad \text{--(3)}$$

where:

M	=	metabolic heat production rate (W/m^2 skin area)
(RQ)	=	the respiration quotient, or volume ratio of CO_2 to O_2 inhaled, which may vary from 0.83 (resting) to over 1.0 (heavy exercise)
V_{O2}	=	oxygen consumption in litres/min at standard conditions (0 °C, 760 mm Hg)
5.87	=	the energy equivalent of 1 litre oxygen, in watt-hours per litre when RQ = 1.0

In a human, deep body temperature is preserved over a wide range of external conditions at the expense of either a fall or a rise in skin (and peripheral tissue) temperature, and either an increase or decrease in energy expenditure. Cooling is also achieved by exhaling water vapour and by sweating, so any factor which affects evaporation of water from the skin will also affect regulation in heat. Atmospheric water vapour pressure, air movement and clothing all affect the rate of sweating and therefore rate of heat loss.

H4. Metabolism and Efficiency During Rest and Exercise

The mechanical efficiency (ϵ) of a human performing work can therefore be defined as the work rate divided by the metabolic rate, or W/M. The amount of work involved in actually lifting arms and legs is usually ignored. Sometimes efficiency is defined as the ratio W/(M - 44), where 44 is the basal metabolic rate in W/m^2.

The mechanical efficiency achieved by different human activities is dependent on the configuration of muscle work. For example, the mechanical efficiency of walking at between 3.2 and 6.4 km/h on a 5% grade is estimated at around 10%[31]. If the grade is increased to 20% the efficiency doubles, to about 20%, since the leg muscles involved work more directly.

Table H.2 classifies different levels of human physical effort in terms of breathing and ventilation volumes, rate of oxygen consumption, human metabolic rates expressed as multiples of the standard resting energy expenditure, and typical heart rate. The values for metabolic rates

[30] ASHRAE *Fundamentals*, Ch.8, 1981

[31] Ibid.

are given in *met* units, where one met is defined as 58.2 W/m^2 (or 50 kcal/m^2). This baseline unit is taken to be the heat produced by an average sized sedentary man.

Table H.2
Classification of Physical Effort

Classification of Effort	Ventilation Volume (l/min)	Oxygen Consumption (l/min)	Metabolic Rate (mets*)	Heart Rate (bpm)
Very Light	10	0.5	1.6	80
Light	10 - 20	0.5 - 1.0	1.6 - 3.3	80 - 100
Moderate	20 - 35	1.0 - 1.5	3.3 - 5.0	100 - 120
Heavy	35 - 50	1.5 - 2.0	5.0 - 6.7	120 - 140
Very Heavy	50 - 65	2.0 - 2.5	6.7 - 8.3	140 - 160
Exhausting	80+	3.0+	10.0+	180

* 1 met = 58.5 W/m^2

Source: ASHRAE, *Fundamentals* Handbook, 1981

H5. Typical Daily Human Metabolic Heat Production

Over the course of any day, a human will therefore generate heat energy in direct proportion to the type, duration and nature of the activities he or she performs. By adding each of these heat components it is therefore possible to estimate the total heat produced daily. The values given in Table H.3 assume a daily regime which comprises 8 hours sleeping, 10 hours sitting down doing various things such as working at a computer, writing, telephoning, watching TV etc, 2 hours standing (preparing food, shelving books, sorting laundry, etc.), one hour of walking, and one hour of more intense exercise (walking up stairs, lifting heavy objects, exercising etc).

As shown in the table, the total daily metabolic heat production for an average sized man undertaking these activities is approximately 10 MJ. A family of 4 persons - 2 adults and 2 children - would produce about 30 MJ of heat energy over a 24 hour period if each followed the same regime. This figure is considerably higher than the HOT2000 estimate of internal heat gain, which estimates metabolic heat gain for a family of 4 at around 16 MJ/day. The HOT2000 estimate assumes a constant (and low) metabolic heat output equivalent to that given off by a seated person performing a light task.

It is interesting to compare the amount of metabolic heat produced by a human against food energy intake from a "normal" diet. For an adult male a calorific intake of 2500 kcal might be considered normal; this is 10.5 MJ. Given that some of the above daily activities require a significant work output (e.g. laundry, cooking, heavy exercise), it follows that 2500 calories would be 500 calories in excess of the daily energy demands of a man undertaking this set of activities. This extra energy would theoretically, therefore, be stored in the body as fat.

H6. Calculated Efficiencies for Various Household Activities

Table H.3 shows a listing of different metabolic rates, based on the above, for various household and working activities. The activities shown are those which tend to be performed steadily rather than intermittently. The highest energy level a person can maintain for any continuous length of time is approximately 50% of his capacity to utilize oxygen (i.e. maximum energy capacity). A normal, healthy man has a maximum energy capacity of around 12 mets at 20 years of age, which drops to 7 mets at age 70. Women tend to have levels around 30% lower. Long distance runners and highly trained athletes can have levels as high as 20 mets, but for an untrained person at age 35 the overall average can be considered as 10 mets. Activities performed above the 5-met level by an untrained 35 year old man may be exhausting and uncomfortable.

Table H.4 shows estimates of overall human efficiency in performing the various tasks. Efficiency has been calculated in two ways: in the first case it is defined as (W/M), while in the second case it becomes (W/M-44), therefore subtracting the resting metabolic rate from that of the activity.

Table H.3

Estimated Daily Human Metabolic Heat Output

Person	Activity	Person Height (m)	Person Weight (kg)	Skin Surface Area (A) (m2)	Metabolic Rate for activity (W/m2)	Total Metabolic Heat Output (M) (Watts)	Duration (hrs/day)	Total Metabolic Heat Output (M) (MJ/day)
Average Man	Sleeping	1.7	70	1.80	41.0	73.8	8	2.125
	Sitting – light work/ leisure				60.0	108.0	12	4.666
	Standing – light work				105.0	189.0	2	1.361
	Walking				123.0	221.4	1	0.797
	Heavy Exercise				290.0	522.0	1	1.879
	Total							10.828
Average Woman	Sleeping	1.55	58	1.56	41.0	64.0	8	1.842
	Sitting – light work or leisure				60.0	93.6	12	4.044
	Standing – light work				105.0	163.8	2	1.179
	Walking				123.0	191.9	1	0.691
	Heavy Exercise				290.0	452.4	1	1.629
	Total							9.384
Child	Sleeping	1.05	25	0.82	41.0	33.6	8	0.968
	Sitting – light work or leisure				60.0	49.2	12	2.125
	Standing – light work				105.0	86.1	2	0.620
	Walking				123.0	100.9	1	0.363
	Heavy Exercise				290.0	237.8	1	0.856
	Total							4.933
Household 2 adults + 2 children	*Total*							30.078

Table H.4

Human Kinetics – Estimated Energy Efficiency for Various Activities

Activity / Person	Person Height (m)	Person Weight (kg)	Skin Surface Area (A) (m^2)	Metabolic Rate for activity (mets)*	Total Metabolic Heat Output (M) (Watts)	Resting Metabolic Heat Output (R) (Watts)	Estimated Power Delivered (W) (Watts)	Time Taken (mins)	Energy Delivered (MJ)	Energy Used (MJ)	Human Efficiency (%)
Carpentry – Hammering/Sawing											
Above–Average Sized Man	1.9	95	2.23	5.0	648.9	68.7	24.5	15.0	0.022	0.52	4.2%
Average Sized Man	1.7	70	1.80	5.0	523.8	55.4	24.5	15.0	0.022	0.42	5.2%
Average Sized Woman	1.55	58	1.56	5.0	454.0	48.0	24.5	15.0	0.022	0.37	6.0%
Step–up exercising											
Average Sized Man	1.7	70	1.80	8.5	890.5	55.4	240.0	1.0	0.014	0.05	28.6%
Child	1.05	25	0.82	8.5	405.7	25.3	85.8	1.0	0.005	0.02	22.7%
Floor Washing											
Average Sized Man	1.7	70	1.80	3.0	314.3	55.4	8.0	20.0	0.010	0.31	3.2%
Carpet Cleaning											
Average Sized Man	1.7	70	1.80	3.5	366.7	55.4	10	20.0	0.012	0.37	3.2%
Snow Shovelling											
Average Sized Man	1.7	70	1.80	6	628.6	55.4	20	30.0	0.036	1.03	3.5%
Sweeping Leaves											
Average Sized Man	1.7	70	1.80	4	419.0	55.4	12	45.0	0.032	0.98	3.3%
Hedge Cutting											
Average Sized Man	1.7	70	1.80	3.5	366.7	55.4	6	60.0	0.022	1.12	2.0%
Grass Cutting											
Average Sized Man	1.7	70	1.80	5	523.8	55.4	15	30.0	0.027	0.84	3.2%
Hand washing											
Average Sized Man	1.7	70	1.8	3	314.3	55.4	7	5.0	0.002	0.08	2.7%
Personal Washing											
Average Sized Man	1.7	70	1.8	2	209.5	55.4	5	3.0	0.001	0.03	3.3%

* 1 met = 58.5 W/m2

Note: All activities shown are assumed to be done "by hand" i.e. not using powered tools. Estimates of metabolic rate and delivered work are based on values shown in ASHRAE Fundamentals, 1981 Chapter 8.

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APPENDIX I

CLEANING

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CLEANING

I1. Clothes Washing

Absolute Energy Requirements

The surrogate absolute energy requirement used for clothes washing has been defined in this report as the amount of energy required to wash a given quantity of mixed fabric clothing by hand in cold water, using a specialised cold water detergent. The energy required to rinse the clothes is included, but not that necessary for wringing, spinning or other drying processes. It is assumed (and has been proven) that washing performance is as good using a quality cold water detergent as using a hot water detergent. Soil removal during washing is enhanced by increases in mechanical input, wash time and water temperature. Pigments are the most difficult soils to remove from most clothing, but fats and waxes can also cause problems. The removal of soil from a surface may be purely mechanical, but usually this is coupled with a chemical reaction. A full analysis of the actions of a modern detergent would be highly complex, so the energy required to wash clothes by hand has been calculated and is used as a surrogate for minimum energy and efficiency comparisons.

If moderate soiling is assumed for 1 kg mixed fabric clothing, washed in cold water using hand agitation, energy requirements can be calculated in at least two ways. Firstly, the average resistive force applied during the washing process can be estimated, together with the speed of the washing action, to produce a Force x Distance estimate of energy used. Secondly, delivered work during hand washing in watts can be estimated, together with the time taken.

Force Applied to Clothes

Average resistive force applied to clothing = 20 N; speed of washing motion = 0.8 m/s; minimum time taken/kg laundry washed = 30 min; rinsing energy = 0.25 * washing energy

Total washing/rinsing energy/kg = 37.5 min * 60 s/min * 0.8 m/s * 20 N = 36 kJ/kg

Delivered Power During Hand Washing

Assuming a delivered power rate of 7 W = 7 J/s (see Appendix H)
Energy delivered per minute = 840 J;

Assuming 30 minute wash and 7.5 minute rinse
Total mechanical energy/kg = 31.5 kJ/kg

Surrogate absolute handwash/rinse energy per kg clothing = average of above two calculated values = 34 kJ/kg.

For an average washing load of 3.5 kg the absolute requirement is: 120 kJ.

Energy Type/Quality: Mechanical plus embodied energy of detergent.

Devices and Strategies

Clothes washing devices are used both to facilitate the washing process (i.e. save human effort) and to speed it up. Most clothes washing in Canada is, of course, done by automatic machines. Most use cycles specifying hot or warm water wash, together with warm or cold rinse. This practise increases the energy requirements dramatically. The most energy intensive washing devices in use are the common N.American vertical axis models which can wash large loads but which also use large volumes of hot water. Horizontal axis, European-type models use far less hot (and cold) water per cycle and normally less than 50% of the energy.

Significant further savings can be realised by using cold water detergents and by advanced washing techniques such as "spray washing", in which a detergent solution is continually sprayed onto the clothing while it is agitated. This technique cuts down on hot water use still further.

Other techniques such as ultrasonic and electrolytic washing, do not presently offer the same level of service provided by water/detergent/agitation, and will likely not do so in the foreseeable future. Estimates of the total energy used per washing cycle and the absolute (surrogate) efficiencies for various devices/cycles, including washing, rinsing and spin drying to 50% or 70% moisture content, are as follows:

Device	Cycle	Hot Water (MJ)	Mechanical (MJ)	Total (MJ)	Absolute (Surrogate) Efficiency (%)
Handwash	cold/cold	0.0	0.12	0.12	100
Ver. axis	hot/warm	13.9	0.43	14.3	0.8
Vert. axis	warm/cold	6.7	0.43	7.1	1.7
Horiz. axis	cold/cold	0.0	0.50	0.5	24
Horiz. spray	warm/cold	1.8	0.50	2.3	5.2
Vert. axis**	warm/cold	3.3	0.43	3.7	3.2

** This machine makes use of a "sudsaver" or hot water reuse to recover 50% of the hot water heat input.

Despite the larger loads washed by vertical axis machines it is estimated that the horizontal axis units use more energy for spin drying, because horizontal machines have higher spin speeds (1100 to 1300 rpm vs. 600 to 800 for vertical units) and longer spin cycles. The spin dry energy has been calculated from assumptions of motor size and cycle length, as follows:

Spin Dry Motor Size:	Vertical axis machines: 250 W Horizontal axis machines: 650 W
Spin Cycle Duration:	Vertical: 7 minutes Horizontal: 10 minutes
Spin Dry Energy/Cycle:	Vertical: 250W @ 7 mins = 0.11 MJ Horizontal: 650W @ 10 mins = 0.39 MJ

I2. Clothes Drying

Absolute Energy Requirements

Two approaches can be used to estimate the absolute energy associated with clothes drying -- the energy required to evaporate water, and the energy required to mechanically remove water.

The absolute energy requirement for clothes drying, assuming evaporation of moisture, is the sum of both the specific heat and latent heat of vaporization. The energy required to vaporize water is 2,454 kJ/kg at 40^{0}C and standard atmospheric pressure. The specific heat capacity of water is 4.19 kJ/kg ^{0}C. A typical heat capacity for dry clothes is 2 kJ/kg^{0}C.

The energy required for clothes drying can be defined simply as the mass of water remaining in clothing after washing, rinsing and draining, multiplied by the latent heat of vaporization, plus the energy required to raise the temperature of the water and clothing to the evaporation temperature. The evaporation temperature is a function of the device used (see below) and will determine the rate at which water is evaporated, and therefore the power level. This absolute energy requirement can then be compared against the energy usage of various clothes drying devices to calculate their absolute efficiencies.

A typical load for drying consists of about 1.9 kg of dry clothing, and contains between 50% and 70% water.[32]

[32]Powertech Labs Inc., Evaluation of Gas Versus Electric Clothes Dryers, Project 1654-40, May 1990.

A 1.9 kg of dry mixed fabric clothing at 60% moisture content will hold 1.1 kg of water. If this water is evaporated by raising the temperature from 20⁰C to 40⁰C then the heat energy required for vaporization is the following:

$$\text{Water vaporisation Energy} : (1.1 \text{ kg} \times 4.19 \text{ kJ/kg}^0\text{C} \times (40\text{-}20) + (1.1 \text{ kg} \times 2454 \text{ kJ/kg}) = 2792 \text{ kJ}$$

If the specific heat capacity of clothing is 2 kJ/kg^0C, then the energy required to heat the clothing is:

$$\text{Clothing Energy:} \quad [1.9 \text{ kg} \times 2 \times (40\text{-}20)]/3600 = 76 \text{ kJ}$$

Therefore, the absolute energy requirement is 2.9 MJ.

While estimates of spin drying energy requirements are available for clothes washers (see I1 above), no estimates of the energy required to remove all water mechanically could be found.

Devices and Strategies

The 1989 CSA Test Procedure for tumble clothes dryers (CAN/CSA C-361-M89) assumes that clothes entering a dryer have an average moisture content of 70% on a dry basis.

The energy use associated with dryers will consist of drying (heat) energy and mechanical (tumbling) energy. The drying heat consists of the amount of energy needed by the dryer to evaporate water. This is equal to the energy drawn into the dryer in the form of warm house air plus the energy produced from electricity or the combustion of gas. Some newer dryers recover heat from exhaust air, greatly reducing energy requirements, and therefore increasing the efficiency. The proportion of energy supplied from "preheated" house air becomes more significant in heat recovery dryers. Absolute efficiencies will be a function of this proportion and the amount of free energy utilized by the house comfort control devices.

Table I.1 shows calculated values for energy consumption for various clothes drying devices. An outside clothes line uses no energy, since it uses free energy and only enough energy to evaporate water from the clothes. When used inside, this energy is provided from house heat. When used outside, the energy is totally provided by solar, wind and ambient air energy.

Table I.1

Estimates of Moisture Content and Energy Consumption for Various Clothes Drying Technologies

Clothes Dryer type (all loads 1.9 kg dry mixed fabric)	Moisture Cont. (%)	Moisture Weight (kg)*	Dryer Power Input (kW)**	Drying Time (mins)	Drying Energy Use (kWh)	Total Energy Use (MJ) ***
1. Clothes line	58	1.1	0.0	100 – 1000+	0.0	0.0
2. Conventional Electric Tumble Dryer	58	1.1	5.7	48	4.6	54.7
3. (2.) with moisture sensure	58	1.1	5.7	35	3.3	39.9
4. (2.) with moisture sensure	50	1.0	5.7	25	2.4	28.5
5. Heat Recovery Electric Dryer (with moisture sensure)	58	1.1	4.3	35	2.5	29.9
6. Heat Pump Dryer (with moisture sensure)	58	1.1	3.7	35	2.2	25.9
7. Gas Dryer	58	1.1	7.1	40	4.7	20.3
8. Microwave Dryer	58	1.1	16.3	11	3.0	35.9

NOTES:

Estimated Energy Use for drying clothes on clothesline assumes a latent heat of vaporization for water @20°C of 2252 kJ/kg

* The CAN/CSA test standard for clothes dryers (C–361–M89) assumes a starting moisture content of between 66.6% and 73.5%; this is based on a conventional spin dry cycle of 6 for a vertical axis washer. Competitek (The State of the Art: Appliances, RMI 1989) reports that the best horizontal axis washer achieves moisture content of 50% dry wt, for a 1200 According to an independent study performed for BC Gas, the average amount of water removed form clothes during a drying cycle was 58% of the dry weight. It is assumed that drying time is directly proportional to moisture content.

** The kW inputs for Heat Recovery and Heat Pump dryers are estimates, based on Competitek's figures which report a 25% and 35% reduction in energy over the standard model r

*** Includes full fuel cycle efficiencies: 50% for electricity, 84% for gas.

Drying Energy is defined as: dryer power (kW) * cycle time (hours)

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I3. Personal Washing

Absolute Energy Requirements

Two processes are involved in personal washing, the use of warm water and personal scrubbing.

Use of Warm Water

If a temperature drop of 10°C is assumed during washing from the 40°C for the wash water, then the heat energy used is:

$$Q_1 = 4180 \text{ J/kg°C} * 10\text{°C} = 40 \text{ kJ/Kg}$$

Personal Scrubbing

If a delivered work rate of 5 watts is assumed to be output by the body (see Appendix 4), and the washing/rinsing process takes 3 minutes, then the energy used is as follows:

$$Q_2 = 5 \text{ J/s} * 3 \text{ mins} * 60 \text{ s/min} = 900 \text{ J} = 0.9 \text{ kJ}$$

Combining these two components and assuming the use of 6 litres (6 kg) of warm water per wash:

Absolute Energy Requirement = $Q_1 + Q_2$ = 250 kJ/wash

As shown, the amount of energy required to reheat 6 litres of water far exceeds that required to scrub a person down, suggesting that if personal washing were assumed not to require hot water use, then absolute energy requirements would be a fraction of this amount.

Devices and Strategies

For a shower device, the amount of water used is assumed to be at a temperature of 38°C, heated from a mains water temperature of 9°C, assuming a flow rate of 5 litres per minute for 5 minutes. Assuming 3% losses (standing hot water in pipes at end of shower) this corresponds to 26 litres of hot water use. The amount of energy used per cycle is therefore 26 kg x 4180 J/kg.°C x 29 °C or 3.1 MJ/cycle.

A bath commonly contains 200 litres and is heated to 38°C, therefore the energy needed is 24.2 MJ/cycle.

If a sauna is used for personal cleaning, the overall efficiency will depend on the number of people who use it when it has been heated to operating temperature. An average sized sauna (6ft x 7ft x 7ft), if electrically heated, will be fitted with a 6 kW heater[33], which will warm the enclosure within 15 mins, after which the heater will cycle on and off. Assuming 30 mins. total heating time, the power drawn by the sauna is 11 MJ.

Assuming that one person uses this heat for personal cleaning, energy use per person is 11 MJ. If, for example, four persons use the sauna, energy use becomes 2.7 MJ per person.

I4. Personal Drying

Absolute Energy Requirements

If it is assumed that a person carries 0.25 litres (0.25 kg) of water out of the shower with them, on their body and hair, then this is the amount of water which will need to be removed, either from a towel or directly from the body. The mechanical energy required to "towel down" can be calculated by assuming a similar delivered power output as estimated for the personal washing process: 5 watts. If someone dries themselves with a towel for 10 minutes (the time estimated to fully dry body and hair) at this work rate, then the energy delivered to the wet body is:

$$Q_2 = 5 \text{ J/s} * 10 \text{ mins} * 60 \text{ s/min} = 3 \text{ kJ}$$

The latent energy required to evaporate water is 2450 kJ/kg, at a temperature of 20°C and atmospheric pressure.

Evaporative energy required is therefore:

$$Q_1 = 0.25 * 2450 = 600 \text{ J}$$

The absolute energy requirement for personal drying is therefore:

$$Q_1 + Q_2 = 3.6 \text{ kJ}$$

Devices

The amount of energy used by two electrical devices used for drying is as follows:

Hand-held hairdryer: 1000 W @ 1 min = 61 kJ
1000 W @ 2 min = 122 kJ

Infra-red lamp: 500 W @ 2 min = 0.017 kWh or 61 kJ

[33] Based on communication with Golden Glow Saunas Ltd, Oakville, Ont. Sept '92

Total energy used for each of the strategies is as follows:

1. Towel only = 3.6 kJ

2. Towel + hand dryer = 1.5 + 122 = 124 kJ

3. Infra-red + hand dryer = 61 + 61 = 122 kJ

APPENDIX J

FOOD PREPARATION AND PRESERVATION

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FOOD PREPARATION AND PRESERVATION

J1. Mechanical Food Prep

Absolute Energy Requirements

Food preparation processes are assumed to be purely mechanical. The human energy used by a person performing various kitchen tasks can be estimated firstly by assessing the actual delivered power of a task, then by relating it to the metabolic rate of the person doing that task. The accepted unit for rate of human work (i.e. delivered power) among exercise physiologists is the *kilopondmetre per minute* (kpm), equivalent to raising a 1 kg mass through a distance of 1 metre. One hundred kpm is equivalent to 16.3 watts; this is considered to be light exercise, while an output of 1200 kpm (196 watts) would be considered heavy exercise for an average sized man.

A table of measured metabolic rates for various activities and tasks is presented in ASHRAE's *Fundamentals* Handbook, 1981 (Chapter 8.11, Table 4A). This table is presented in terms of *met* units, defined as 58.2 watts/m^2 of body area; heat output for an activity is therefore assumed to be directly proportional to body size.

The variability of food preparation requirements is as wide as the range of foods available in a modern supermarket. Daily meal preparation can take many hours of each day, or it can be as simple as removing the cover from a TV dinner and placing it in the microwave. Net energy requirements for food preparation are clearly as diverse as diets, from one house to another. For this analysis, three different food preparation tasks have been examined; chopping/cutting (e.g. vegetables, bread), stirring and beating.

ASHRAE reports a metabolic rate of between 1.6 to 2.3 mets for food preparation activities (1981 Fundamentals Handbook, 8.11, Table 4a). This corresponds to an actual heat output, for an average sized male[34], of (1.8 * 58.2 * 1.6, 2.3) i.e. 170 W to 240 W. Using these values for metabolic heat output, estimates can then be made of delivered work, in watts or kpm. The profile on Metabolism and Human Power (Appendix C) includes estimates of delivered work rate, and shows a rate of 4 to 15 watts for food preparation. Based on this range, work rates for the three food preparation tasks can be assigned as follows:

chopping vegetables - 5 watts
stirring soups, stews, etc. - 6 watts
beating cake mix - 13 watts.

[34]Using the DuBois equation, the skin area of an average sized male is 1.8 m^2.

Since energy is equivalent to (power * time), the energy used to perform these tasks can easily be estimated as follows:

Chopping: Time taken = 12 minutes; Energy = 3.6 kJ
Stirring: Time taken = 12 minutes; Energy = 4.3 kJ
Beating: Time taken = 4 minutes; Energy = 3.1 kJ

J2. Cooking

Absolute Energy Requirements

During cooking three basic changes occur in most foods:

- the temperature of each food molecule is raised to a required cooking temperature
- a complex series of physio-chemical reactions take place at the cooking temperature
- water is (usually) lost, and fats may drain out

Therefore the total heat absorbed by food during cooking can be summarized as:

Total Heat = sensible heat + net heat of reaction + latent heat

The amount of sensible heat required to heat a quantity of food (i.e. specific heat capacity) is largely proportional to its water content. Fats have approximately half the specific heat of water, and solids around one-third. Cooking methods which remove a greater proportion of water from food (e.g. frying) will therefore require more cooking energy per unit weight cooked, due to their higher latent heat components - more water is vaporized. Some foods require a higher quality of energy (i.e. temperature) than others for proper cooking, while others require only boiling water temperatures. Bread or pizza, for example, can only be properly cooked in a hot oven, whereas rice, soups, meats, beans, etc. require lower temperatures.

Cooking is considered complete when each food molecule has reached a sufficient temperature equivalent to the degree of "doneness" required. Cooking time is therefore a function of the speed at which this temperature can be reached, i.e., it is a function of the original temperature of the food, how it has been prepared for cooking (chopped, etc.), and the final degree of doneness (temperature) required.

Devices and Strategies

The efficiency of a cooking device is primarily a function of the losses it incurs during the cooking process and the original preparation of the food. A conventional oven, for example, transfers heat to the food by maintaining a hot environment around the food which is normally not cut into small pieces. It loses significant amounts of heat both at a steady state, and when heating up its heavy metal shell. It takes a long time to heat all molecules to the required temperature and therefore losses are high. A microwave oven on the other hand heats only the food molecules. Heat transfer is faster and losses are lower. Power levels are higher, however. Insulated convection ovens also greatly reduce the heat loss before and during cooking. A wok which uses finely diced food, has high power levels but cooking is accomplished quickly leading to much higher efficiencies.

Measurement of the steady-state energy used to bake each of five food samples in a conventional oven (i.e. once the oven has reached its maximum temperature), including losses, shows a cooking efficiency of between 31% and 43%. However this does not include the energy used to heat the oven and its shell to its operating efficiency. When this is added, the effective efficiency of the baking process falls to between 5% and 7%, meaning that only 5% to 7% of the energy input to a conventional oven is actually used to cook the food samples, the rest being lost to the surrounding environment as heat. Oven insulation reduces heat losses during the warm up period and during cooking.

Studies of microwave energy use during cooking have shown that around 40% to 45% of the input electricity is converted by the magnetron into microwaves. Since there are no other significant losses in a microwave, this range represents the effective cooking efficiency of microwave cooking.

The Rocky Mountain Institute has investigated the efficiency of conventional electric stovetop elements and found that only 30% to 40% of the heat input is actually transferred to the cookware[35], the rest being lost beneath and around the element. Further energy losses occur if the cookware is not fitted with a lid (assumed as 50%), and also from the walls of the vessel (assumed as 15%). The product of these losses is an effective cooking efficiency of around 15%; if the cookware is fitted with a lid which cuts its losses by 75% then this efficiency rises to 26%. If a 1500 W electric kettle is filled with 1 litre of water, and it takes 4.4 minutes to boil, then the efficiency of the kettle is approximately 95%, assuming an initial temperature of 10°C. This much higher efficiency results from having the electric coil immersed in the water it is heating, which reduces losses in transferring heat energy to zero; the only losses are those from the shell of the kettle itself, and these are small in relation to the heating load.

If a slow cooker or crockpot is used, having internal heating elements, a close-fitting lid and some insulation in the vessel walls, Competitek estimates that heat transfer efficiency over the cooking cycle is around 80%, giving an effective cooking efficiency of 65% once losses from the vessel walls are taken into account.

[35]Competitek: The State of the Art - Appliances, RMI 1989

J3. Refrigeration

The need for food refrigeration is highly subjective and difficult to define, since it depends on diet, lifestyle, climate and many social factors. The perceived "need" for refrigeration in North America is simply a reflection of the dietary norms: large quantities of meat, dairy products and other perishables are consumed weekly by most households. The large size of most refrigerators reflects another significant trend, the tendency for a family to shop once per week at a supermarket, which produces the need for sufficient storage of a week's groceries.

The refrigeration industry has evolved as a result of the need to prolong the storage life of foods after harvest, processing and purchase. While refrigeration is used for purposes other than food preservation, such as the desire for cold drinks on hot days, its primary application is for the retardation or prevention of microbial, physiological and chemical changes in foods. Fruits, vegetables, meats, eggs and dairy products are all subject to microbiological deterioration when unfrozen. Loss of quality in fruits and vegetables, however, is usually due to physiological changes such as dehydration.

The main source of bacteria present on meats is the skin or hide of the animal; when meat is cut into retail portions this source is spread to each of the cut surfaces. Milk contains small numbers of bacteria when produced, but is often contaminated from external sources during milking. Milk pasteurization normally destroys about 95% of bacteria present. Freezing also destroys large numbers of bacteria, and below -12°C no bacterial growth occurs.

A weekly mixed load of food weighing 7.75 kg is typically as follows:

Tomatoes - fresh: 1 kg
Apples - fresh: 1 kg
Berries: 0.5 kg
Fish: 0.5 kg
Meat: 1.0 kg
Butter: 0.25 kg
Cheese - cheddar: 0.5 kg
Milk - fresh: 2.0 kg
Water: 1 kg

This food load represents the total thermal cooling load for one week, for a single domestic refrigerator. Each food item is assumed to be cubic in shape, with known density and specific heat capacity. The energy required to cool down and maintain this food load each week is shown in Table J1.

Devices that could be used to meet this refrigeration load, are as follows:

1. Standard Refrigerator: An 18 cu. ft. refrigerator typical of stock sold up until the 1980's. Energy consumption is in the 1200 kWh/a range (ENERGUIDE RATING).

Table J.1
Typical Heat-Load of Domestic Refrigerator

Food Type	Quantity ~ (kg)	Density kg/litre	Food Volume (litres)**	Specific Heat (kJ/kgC)	Cooling Energy for dt=16C (kJ/week)	Surface Area of Food Cube (cm2)	Heat Loss rate for dt=16C (W)*	Heat Loss rate for dt=(kJ/day)*	Energy per month (kJ)
Tomatoes-fresh	1.000	0.94	1.06	4.02	64	625	0.083	7.20	16.39
Apples-fresh	1.000	0.84	1.19	3.77	60	674	0.090	7.76	16.38
Blackberries	0.500	0.85	0.59	3.79	30	421	0.056	4.85	9.18
Haddock	0.500	1.07	5.88	3.62	29	361	0.048	4.16	8.30
Beef Round	1.000	1.09	5.81	3.35	54	566	0.075	6.52	14.18
Butter	0.250	1.10	6.25	2.07	8	223	0.030	2.57	3.76
Cheese-Cheddar	0.500	1.03	32.42	2.95	24	371	0.049	4.27	7.64
Milk-fresh	2.000	0.90	2.22	3.85	123	1021	0.136	11.76	29.37
Water	1.000	1.00	1.00	4.18	67	600	0.080	6.90	16.46
TOTAL	7.75		8.16		459			56.01	121.7

The micro refrigerator is a device most commonly used to preserve medical supplies (e.g. serums).

~ It is assumed that this "basket" of food is purchased and used entirely each week, and does not wary (at least in terms of thermal mass) throughout the year.

* A constant rate of heat loss is assumed i.e. unvarying temperature and humidity levels both outside and inside the refrigerator. The 16 C temperature difference is therefore assumed to be constant.

** Volume assumes no airspaces or bulking, which will not be the case for foods such as fruits and vegetables.

2. Standard Refrigerator (1992): The best 18 cu. ft. refrigerator sold in 1992 with improved insulation and other features and an ENERGUIDE RATING of 700 kWh/a.

3. High Efficiency Refrigerator: An 18 cu. ft. adaption of the top mounted multi-stage compressor model now sold for remote cottages, etc. Expected annual rating 275 kWh/a.

4. Heat Pipe Adaptation for HE Refrigerator: As per unit #3 but using a "through-the-wall" heat pipe to utilize outside air to cool the refrigerator when air temperatures are low enough. Expected annual rating 200 kWh/a.

5. A Small High Efficiency Refrigerator designed to match the food load: A 7 cu. ft. high efficiency refrigerator with an annual rating of less than 50 kWh/a.

J4. Freezing

Foods do not freeze at constant temperature. Beef, for example, begins to freeze at about -1°C, but 25% of the latent heat is still to be removed at -4°C, and fresh beef is still not completely frozen at -60°C. In haddock, some water is bound to proteins and does not freeze at -40°C. In calculating the energy required to freeze foods, ASHRAE recommends the total heat content or enthalpy approach, using tabulated values for enthalpy at different temperatures below zero. Using this method, there is no need to calculate latent and sensible heat values, since the two are combined in one number, which is based on (measured) unfrozen water content.

A typical monthly freezer food load to be frozen from room temperature (20°C) down to -18°C is as follows:

Bread	2 kg
Beef	4 kg
Fish	3 kg
Blueberries	5 kg
Strawberries	5 kg
French Beans	5 kg

The energy requirements to lower the temperature of the food to the freezing point and to sustain it there over a 38°C temperature difference are shown in Table J.2. Firstly, the volume of each food is calculated, based on measured weight and density; assuming a cubic shape the surface

Table J.2
Typical Heat-Load of Domestic Freezer

Food Type	Quantity ~ (kg)	Density kg/litre	Food Volume (litres)**	Specific Heat >0°C (kJ/kgC)	Cooling Energy for dt=20°C (kJ/day)	Surface Area of Food Cube (cm²)	Heat Loss rate for dt=20°C (W)*	Heat Loss rate for dt=20°C(kJ/day)*	Enthalpy @ 0°C (kJ/kg)	Enthalpy @ -18°C (kJ/kg)	Latent Heat (kJ/day)	Energy per Day (kJ)
Bread	2.0	0.25	8.00	4.02	5.3	2400	0.40	34.5	150	40	7.2	47
Beef-fresh	4.0	1.09	3.67	3.77	9.9	1427	0.24	20.5	304	47	33.8	64
Cod Fish	3.0	1.07	2.80	3.79	7.5	1193	0.20	17.2	323	47	27.2	52
Blueberries	5.0	0.85	5.88	3.62	11.9	1955	0.33	28.1	352	50	49.6	90
Straw-berries	5.0	0.86	5.81	3.35	11.0	1940	0.32	27.9	367	49	52.3	91
French Beans	5.0	0.80	6.25	2.07	6.8	2036	0.34	29.3	323	56	43.9	80
TOTAL	24.0		32.42		52.3			157.6				424

~ It is assumed that this "basket" of food is frozen and used entirely each month, and does not wary (at least in terms of thermal mass) throughout the year.

* A constant rate of heat loss is assumed i.e. unvarying temperature and humidity levels both outside and inside the freezer. The 38 C temperature difference is therefore assumed to be constant.

** Volume assumes no airspaces or bulking, which will not be the case for foods such as fruits and vegetables.

area of each is then obtained, and the steady state heat loss calculated across the equivalent thermal resistance of a horizontal air film. Hence the total heat loss per unit time is found over this surface area and thermal gradient. Secondly, the latent heat or enthalpy load is found by reference to ASHRAE tabulated values for each food type (*Fundamentals*, 1981, 31.9 Table 5) at both zero and -18°C. The latent heat load is then the product of the food mass and the difference in enthalpy.

Lastly, the sensible heat component of freezing (lowering the temperature of the food from 20°C to 0°C) is the product of the mass and specific weight of each food. Absolute energy values for freezing are the sum of all three heat components, expressed in Table J.2 in kJ per month.

Devices used to provide freezing include the following:

1. Standard Freezer: This model is a standard 13 cu.ft. freezer, which uses 1400 kWh per year (2.9 kWh/day). It represents an average stock model of early-80s vintage.

2. Standard Freezer (1992): This model is representative of freezers sold in 1992 with high insulation and improved compressor efficiency. A typical 13 cu. ft. unit has an annual electricity use of 680 kWh.

3. High Efficiency Freezer: This 13 cu.ft. freezer is fitted with a high efficiency compressor of EER 4.5, plus improved insulation to a thickness of 3", and electronic load detection. It has an annual consumption of about 320 KWh.

4. High Efficiency Freezer with Evacuated Panels: Identical to number 3 above, except that it is fitted with evacuated vacuum panels to cut down heat gain further. This model is still under development but is expected to have an annual energy consumption of about 320 KWh.

J5. Food Drying

The unit absolute energy requirement for food drying is the latent heat of evaporation of water multiplied by the water content of the food. The following table lists water content and absolute energy requirements for three food types: fresh beef, blueberries and french beans.

Assuming that the latent heat of evaporation for water at 20°C is 2252 kJ/kg, the absolute energy for food drying can be calculated as follows:

Food Type	Weight (kg)	Water Content		Mass of Water Evaporated (kg)	Absolute Energy (kJ)
		Before	After		
Beef strips	2.0	75	25	1.00	2252
Blueberries	2.0	88	15	1.46	3288
French Beans	2.0	76	15	1.22	2747

Therefore, the total absolute energy for drying these three foods is 8287 kJ.

The efficiencies of two devices are briefly reviewed here: a solar/ambient dryer and an electric food dryer. If the solar/ambient device is used indoors during the heating season, then it will ultimately draw all its heat energy from the house heating system, but if it is used at other times of the year it will be drawing heat from ambient sources (i.e. solar, ambient air).

The electric food dryer looks similar to a large toaster oven; it is heated with a resistance element and fitted with shelves onto which food is placed for drying. A rated power output of 500 to 600 watts is common.

It is assumed that the 6 kg of food shown above can be dried from a fresh condition to these moisture contents in batches, using the food dryer. A total drying time of 16 hours is estimated for this, at an average electrical output of 450 watts.

Total electrical input is therefore (0.45 * 16) = 7.2 kWh (26 MJ). Absolute efficiency is defined as absolute requirement divided by power used, or 8287/26,000 = 32%, or 9.6% allowing for upstream losses for electricity.

If solar energy is used for food drying, drying times will be longer, and the energy use will be, say, 32 hours at 100 watts. The absolute efficiency will be 100%. Neither of these efficiencies takes into account energy requirements for rehydration, but soaking any dried food in water for 2 to 4 hours before cooking will restore much of the original water content.

APPENDIX K

AUDIO VISUAL

AUDIO VISUAL

A fundamental characteristic of an acoustic source is its ability to radiate power, whether weak and small in size (like a cricket) or strong and large (like a jet engine). An energy input excites the source, and it radiates this energy in acoustic form. This acoustic power is expressed in watts.

If, at an arbitrary distance from a sound source, a sphere is circumscribed around it, all the energy radiated from the source must pass through it. Power flow through a unit area of the sphere is defined as *intensity*, measured in watts/m^2. This leads to the inverse square law: *intensity varies inversely as the square of distance from the source.* The intensity and the pressure (actually the root mean square of the pressure squared) are nearly identical numerically when proper units are used[36], namely W/m^2 for intensity and micropascals for pressure. Therefore sound intensity can usefully be thought of as sound pressure. Sound power cannot be measured directly, but must be calculated from sound pressure measurements.

The human ear is extremely sensitive to sound, and it responds across a broad range. The ratio of threshold of hearing to threshold of pain is around 10^{14}:1. Due to this wide range, a logarithmic scale is used to measure sound intensity, known as the decibel (dB) scale. For this scale, the base 10 logarithm of a source power output, multiplied by 10 is the sound power level in decibels, referenced to 10^{-12} watt.

The frequency of a sound in a given medium is equal to the velocity of the sound waves in that medium, divided by their wavelength. The audible frequency ranges up to about 20 kHz (20,000 cycles per second) for the human ear. Sound waves of frequencies greater than this are defined as ultrasound.

The human perception of sound is more sensitive in the middle frequency range than at the extremes when all sounds are at the same level. Objective determination of the subjective reaction to sound in terms of loudness is basically a matter of statistical reaction in a group of human observers. To determine the loudness of a sound, a standard sound is chosen (normally a pure tone of 1000 Hz), and the reactions of a number of people to different sounds are noted. Loudness level is measured in *phons*, with the loudness level of any sound being equal to the sound pressure level in dB of an equally "loud" standard sound. Therefore a sound that is judged to be as loud as a 40 dB, 1000 Hz tone has a loudness level of 40 phons.

[36]ASHRAE *Fundamentals* Handbook, 1989

APPENDIX L

OUTDOOR SERVICES

Marbek

OUTDOOR SERVICES

In most cases powered devices save some time over the hand tools, and they certainly save a lot of effort. Typical rated power values for power tools are as follows:

Snowblower (assumed to be electric): 3000 W
Electric Lawn Mower: 700 - 1000 W
Hedge Trimmer: 250 - 300 W
Leaf Blower: 850 - 1200 W

According to ASHRAE *Fundamentals* snow shovelling, depending on the rate at which it is done, is heavy work, requiring high metabolic output. A value of 6.0 mets[37] will be assigned to this level of effort, which assumes that the person shovelling is working hard and continuously. Total energy requirements for by-hand snow shovelling will include the metabolic heat generated by the shoveller, plus the work output by their shovel. Assuming an average sized male worker, total heat output is (skin area * mets * unit heat output) = 1.8 m^2 * 6.0 * 58.5 = 630 W or 575 W incremental over the resting state (see Appendix H). The "efficiency" of the human worker, in terms of energy consumed (metabolic heat) to that delivered is thus: 20/575 = 3.5%, although these work rates and metabolic rates are only estimates.

The efficiency of a mechanical device can be calculated by dividing total energy needed for shovelling by the total input to the device, including the amount required to push it. A work rate of 3.0 mets is assumed for the metabolic input of a person using a snowblower, which, for an average sized man, corresponds to 316 watts. Over 20 minutes of shovelling at this rate of work, the total energy burned by the worker = (316 W - 55) * 0.33 hr = 0.086 kWh.

[37]See Profile on Metabolism and Human Power, Appendix H