Domestic Hot Water Heating and Water Heater Energy Consumption in Canada

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April 2005

CBEEDAC 2005–RP-02

Executive Summary

The purpose of this study is to review relevant literature and technology concerning energy consumption for domestic water heating. Domestic water heating is estimated to be the second largest energy end-use for Canadian households, accounting for approximately 22 percent of total household energy consumption. Although the proportion of houses from 1945 to 1990 that uses natural gas for water heating and the proportion that uses electricity for this purpose are similar, in aggregate the general tendency is for new houses to increasingly use natural gas rather than electricity for domestic water heating requirements, even though natural gas is not available in all areas.

Current domestic water heater standards and efficiencies are reviewed, and the various types of water heaters available, and the extent to which they are in use, are examined. Conventional tank water heater systems are by far the most common type of system used throughout Canada, although there is greater variation in water heater equipment in the Atlantic Provinces. Interestingly, preliminary evidence from the EnerGuide for Houses database reveals that very few retrofits involve changes in the fuel that is being used for domestic water heating. In addition to fuel type, a number of other factors that influence the choice of water heating system are also evaluated. These include water and energy consumption levels – with Canada having among the highest levels of per-capita water consumption worldwide, seasonal effects, occupancy characteristics including occupant age and income, as well as the efficiency of hot-water-using appliances – particularly clothes washers and dishwashers..

Models of appliance domestic hot water consumption and of the energy consumption associated with the production of hot water are also reviewed, including WATSIM, TANK, and WHAM, the three models used by the US DOE in examining electric, natural gas, and oil based

water heaters, respectively. In addition, WHAM is used to estimate the residential water heater consumption for all types of heaters that the US DOE uses as part of their life cycle cost analysis of various water heater modifications or of changes in the standards that water heaters are required to meet.

Finally, the domestic water heating component of the Residential End-Use Model (REUM) is examined in some detail. The structure of this component is reviewed, and the assumptions that are needed to determine the energy required for domestic water heating, and their role, are noted. Using available evidence in the literature and various technical documents, each of these assumptions is analyzed. Particular attention is focused on the determination of the energy required per year per household for water heating for personal use – showers, baths, and faucets – as well as the baseload energy that is required, that is, the energy that is used by a water heater that is connected but where hot water is not being drawn from the unit. It is argued that in view of the REUM model formulation, where hot water energy requirements are determined by end use – for water-using appliances and for personal use, the baseload requirements should refer to all energy use for water heating that is not captured in these specific end uses, including standby heat losses as well as distribution losses and leakage.

We find that the values currently used in REUM for the amount of energy required per household for baseload requirements and for personal use are broadly consistent with values that we calculate based on information which in many cases may be only of limited direct applicability. Nevertheless, we find that in contrast to the REUM model, these values differ according to the fuel type that is used for water heating as well as other factors such as the type of household. Since REUM has a rich enough structure to allow differences if this type, it would appear that this type of generalization would be worth considering.

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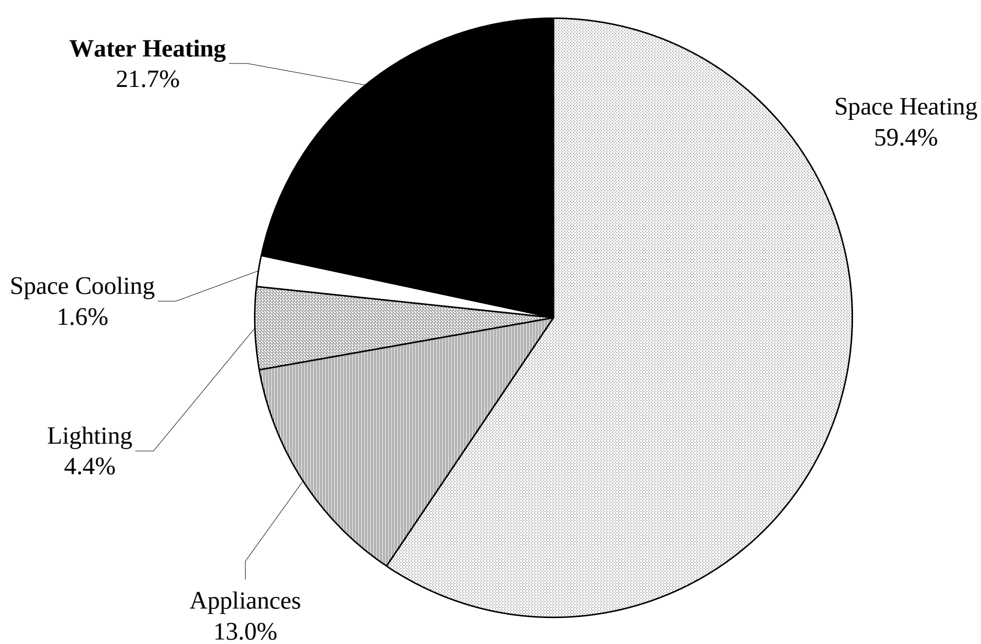
1. Introduction

Current Canadian estimates of domestic hot water heating energy consumption, energy intensity, and greenhouse gas emissions, prepared by Natural Resource Canada (NRCan), are based on NRCan's Residential End-Use Model (REUM) and the 2002 Survey of Household Spending (NRCan, 2004a,b,c). Domestic water heating is estimated to be the second largest energy end-use for Canadian households, exceeded only by space heating, and as shown in Figure 1, accounts for approximately 22 percent of total household energy consumption (NRCan, 2004a). In 2002, approximately 22 % of total Canadian residential greenhouse gas emissions were attributed to domestic water heating (DWH), an estimated increase of 13% since 1990 (NRCan, 2004b).

Figure 1.1: Canadian Residential Secondary Energy Consumption in 2002 by End Use



Source: Natural Resources Canada, *Energy Use Data Handbook, 1990 and 1996 to 2002*, June 2004.

While these numbers indicate that hot water heating is a major component of energy consumption for Canadian households, it is important to note that the information presented above is based, at least in part, on a model of energy end-use. In common with other models, the Residential End Use Model (REUM) embodies a number of methodologies and assumptions. Typically these assumptions reflect the best available information at the time they were imposed, but as technology and use patterns change over time, the particular assumptions that are embodied in the model may no longer be appropriate. Therefore, from time to time it is necessary to review the assumptions and methodologies embodied in a model and to make any changes that might better reflect the technology and/or use patterns that have evolved. The purpose of this study is to review the relevant literature and technology concerning energy consumption for domestic water heating.

The remainder of this paper is organized as follows. Section 2 contains background information on current domestic hot water consumption estimates. The current standards and efficiencies of water heaters and hot water consuming appliances are summarized in Section 3, while Section 4 contains a review of domestic water heaters commonly in use. A brief overview of measurement and estimation techniques for domestic hot water consumption is presented in Section 5, with factors influencing domestic hot water consumption and associated energy consumption discussed in Section 6. Models of appliance domestic hot water consumption and energy consumption associated with the production of hot water are reviewed in Section 7. Finally, Section 8 focuses on domestic water heating in REUM, including the particular assumptions embodied in this component of the model and available information on values for these assumptions.

2. Background

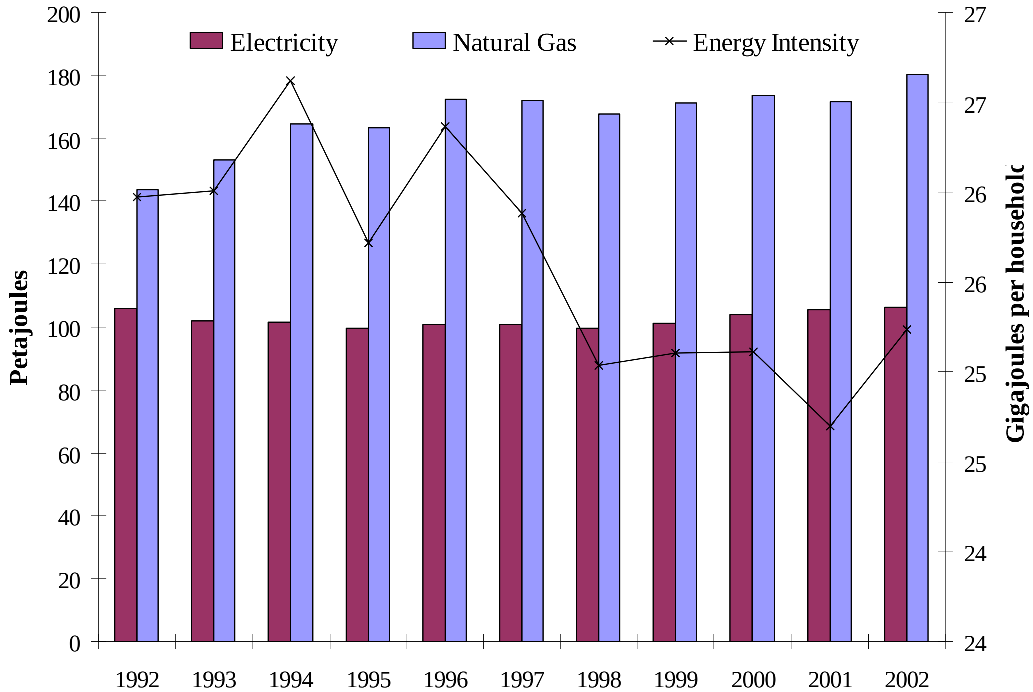
Domestic water heating energy intensity for Canadian households in 2002 was estimated at 25.2 GJ/household (NRCan, 2004b). Electricity and natural gas are the major fuels reported in use for domestic water heating – in 2002, 106.5 PJ of electricity and 180.4 PJ of natural gas were used for this purpose, with electricity contributing 35% and natural gas 59% of the energy required for domestic water heating in Canada (Fig. 2.1). Data from the Survey of Household Spending (2002) show (Fig. 2.2) that for houses constructed between 1945 and 1990, the percentage of homes heating water using electricity and the percentage heating water using natural gas are virtually identical. However, for homes constructed in the decade since 1990, the use of electricity to heat water has fallen while the use of natural gas for this purpose has increased.

However, similar information obtained from the *Energuide* (2004) database differs somewhat. As Figure 2.4 shows, according to the records in this database, for all periods of house construction the proportion of houses in which natural gas is used to heat water is more than twice as large (and in some periods more than three times as large) as the proportion of houses in which electricity is used for this purpose. To investigate this issue further, Fig. 2.4 presents similar information from the two databases for houses constructed between 1991 and 2002. This includes 2043 households from SHS (representing 1,761,356 Canadian households) and 8217 households from the EG database. As Fig. 2.4 shows, there are considerable differences between the two databases even for houses constructed in this most recent decade, with EG indicating that 72% of these heat water with natural gas and 23.5% with electricity, while the corresponding figures in SHS are 58% natural gas and 36.5% electricity.

These differences in findings may reflect the different characteristics of the two databases. The Survey of Household Spending (SHS) involves a stratified random sample of households (14,704 households in 2002), where the weight assigned to each observation reflects the number of houses that each observation represents in the national total (of 12,021,018 households in 2002). However, the EnerGuide (EG) database, which in 2004 included 103672 households, is non-random. Rather, to be included in this database the only requirement is that the household has an energy audit undertaken. Since there are monetary reimbursements to the household if they are found to have achieved certain energy savings by the time they undertake a second audit, the households that choose to have an energy audit (and be included in the database) are likely to be those that expect that have large potential energy savings, as well as those that are particularly energy conscious.

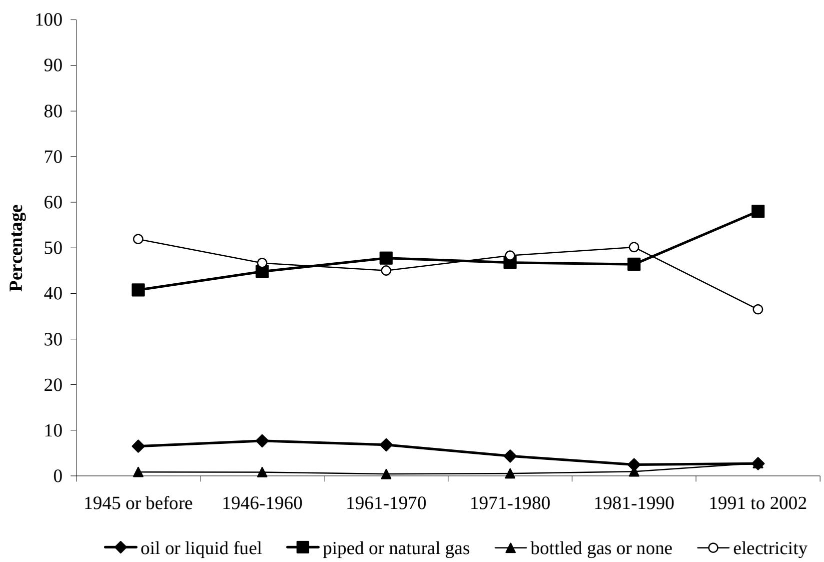
The estimated market shares of Canadian water heaters (Fig 2.5) tend to reflect the general tendency for new houses to increasingly use natural gas rather than electricity for domestic water heating requirements. The market share of electric water heaters is higher than for natural gas waters heaters, but this share is steadily declining over time for electricity and increasing for natural gas (Fig. 2.4). This result appears to be more consistent with the trends in the SHS data (Fig 2.2) rather than in the EG data (Fig 2.3).

Figure 2.1: Canadian Domestic Water Heater Major Fuel Consumption & Energy Intensity (1992-2002)



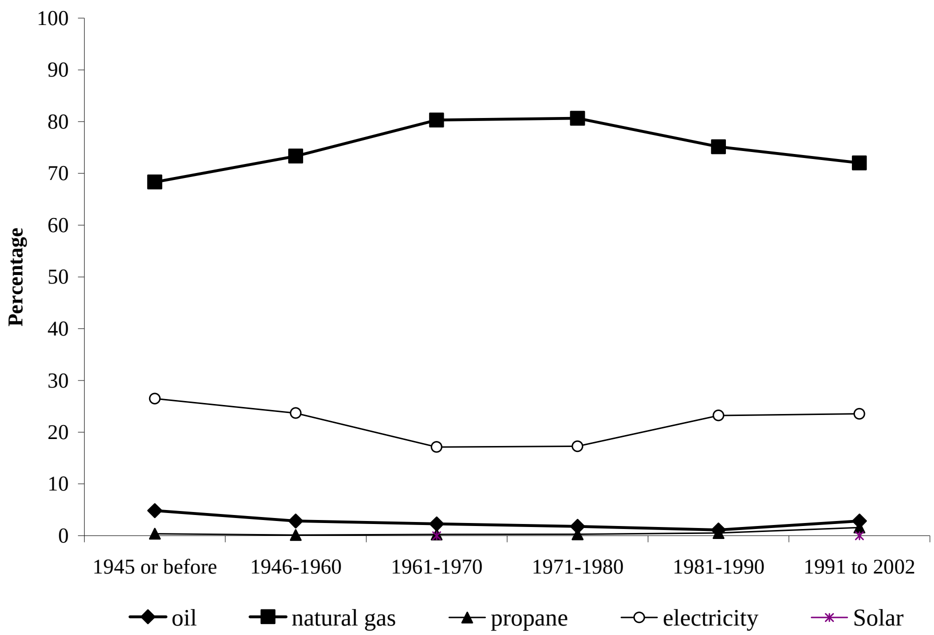
Source: Natural Resources Canada, *Energy Use Data Handbook, 1990 and 1996 to 2002*, June 2004.

Figure 2.2: Canadian Domestic Water Heater Fuel Type by Period of House Construction (Survey of Household Spending, 2002)



Source: Survey of Household Spending, 2002 (weighted data).

Figure 2.3: Canadian Domestic Water Heater Fuel Type by Period of House Construction (EnerGuide Data, 2004)



Source: EnerGuide Data (2004).

Figure 2.4: Comparison of Domestic Water Heater Fuel Type for Homes Constructed 1991-2002: Survey of Household Spending (2002) and EnerGuide (2004)

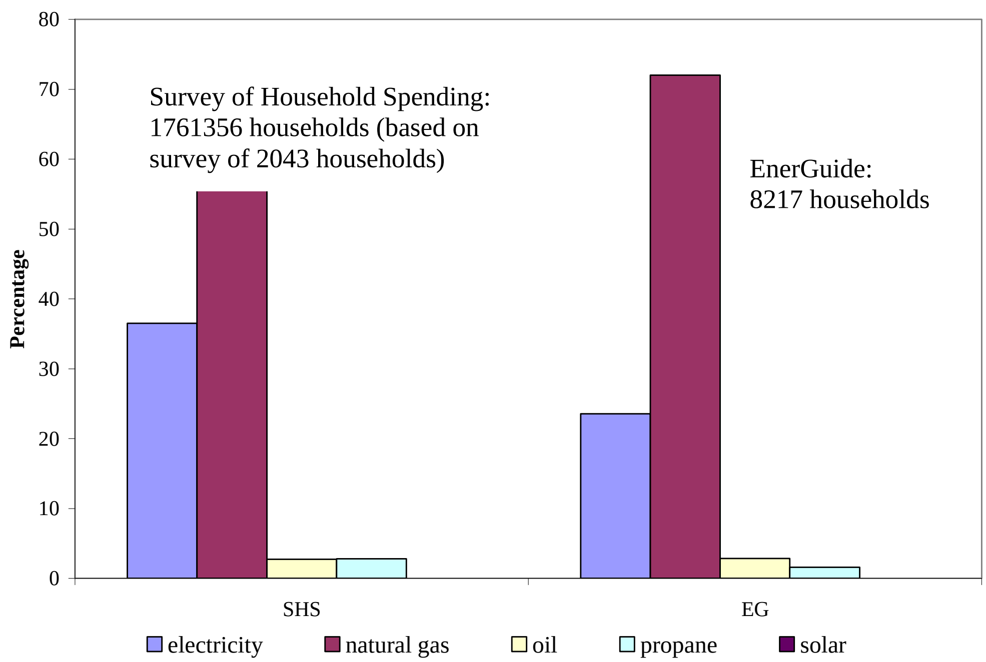
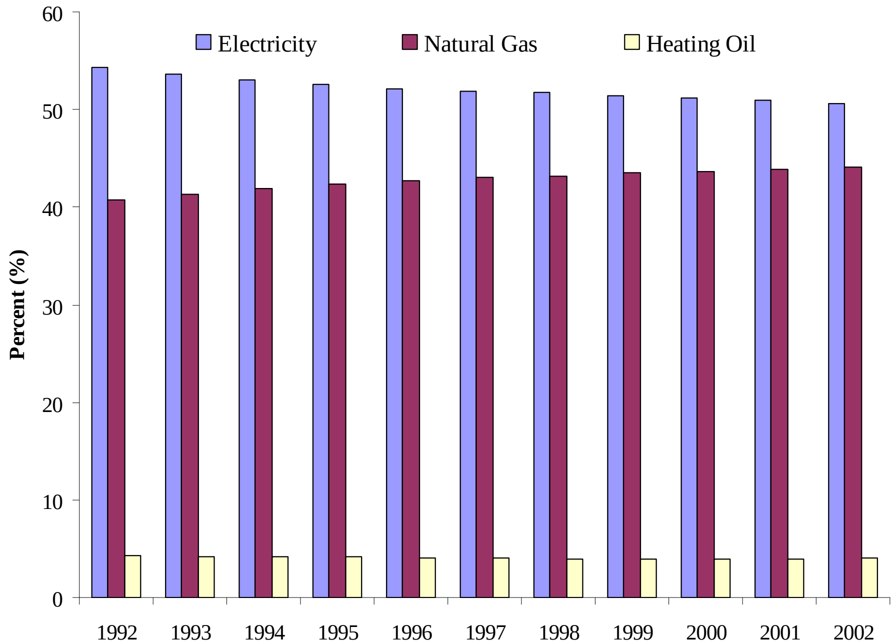


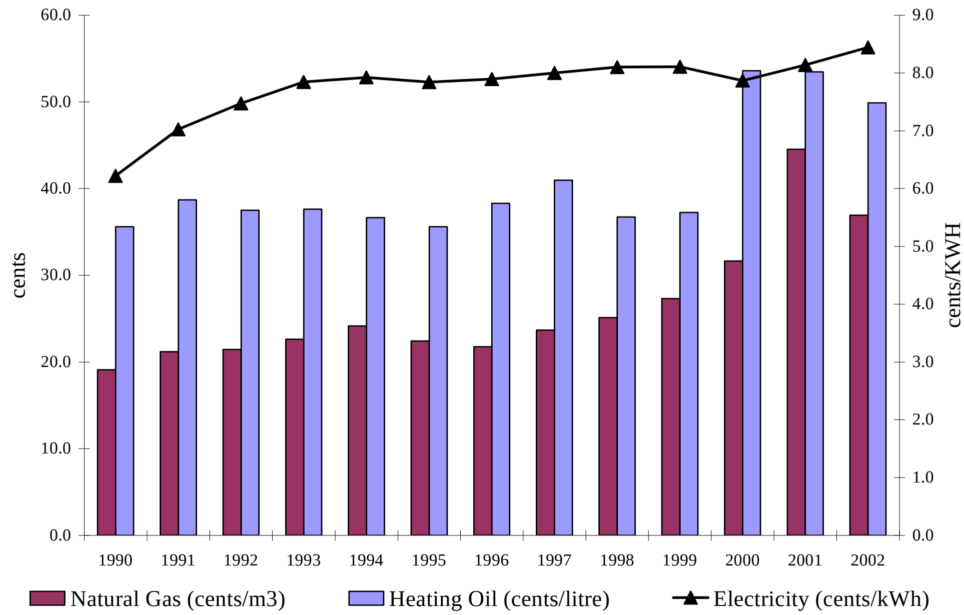
Figure 2.5: Market Shares of Canadian Domestic Water Heater Stock 1992 to 2002



Source: Natural Resources Canada, *Energy Use Data Handbook, 1990 and 1996 to 2002*, June 2004.

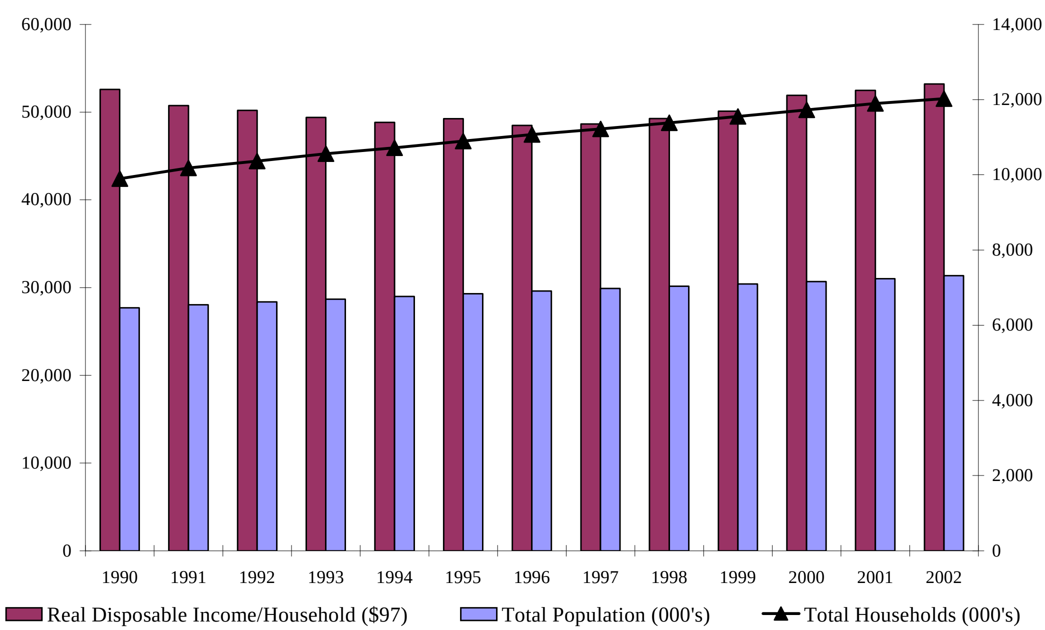
Of course, over the past 10 years or so a number of factors have changed, and these have no doubt contributed to changes in domestic water heating. Average natural gas prices including taxes increased by 93% between 1990 and 2002, while average electricity prices increased by 36% and heating oil prices rose by 40% (Natural Resources Canada, 2004b) (Fig. 2.6). During the same time period, the number of Canadian households has increased by 22%, real personal disposable income increased by 1.2% and the total population increased by 13% (Fig. 2.7). Mean household size was calculated at 2.55 persons from the 2001 Census, (Statistics Canada, 2001) while a slightly larger value of 2.57 is obtained using weighted data from the Survey of Household Spending (2002).

Figure 2.6: Average Fuel Prices Including Taxes (1990-2002)



Source: Natural Resources Canada, *Energy Use Data Handbook*, *1990 and 1996 to 2002*, June 2004.

Figure 2.7: Canadian Population Disposable Income & Total Households (1990-2002)



Source: Natural Resources Canada, *Energy Use Data Handbook, 1990 and 1996 to 2002,* June 2004.

In the United States, domestic hot water heating is estimated to account for approximately 15% of electricity usage and 25% of natural gas consumption (Wenzel et al, 1997). The market share of electric water heaters in the U.S. rose in the period of 1981-1993, while market shares of oil, natural gas, and LPG fueled water heaters fell over the same period. By 1993, the natural gas water-heating share was approximately 52% followed by electricity at 39% (Wenzel et al., 1997). More recent estimates from the 2001 Residential Energy Consumption Survey (RECS), suggest that the natural gas water-heating share is approximately 54% followed by electricity at 38%, oil at 4% and LPG at less than 3% (U.S. DOE, 2004b)

There is considerable variation in the relative importance of different fuels used for domestic water heating in other countries. In Australia, 40 percent of the energy consumption in the average home is attributed to water heating (Aye et al., 2002), with the main sources of energy for this purpose being electricity (79%) and natural gas (16%). A Norwegian comparison of engineering and econometric methods of estimating end use using 1990 energy survey data found that electricity consumption for water heating varied from 14 to 24 % of total residential electricity consumption (Larsen and Nesbakken, 2004). In South Africa, hot water heating is the largest residential use of energy, with up to 50% of monthly electricity consumption being used for this purpose (Meyer and Tshimankinda, 1998). Water heating accounts for approximately 30% of New Zealand’s residential energy use, with electricity being the major energy source for this purpose (Pollard et al, 2002).

3. Domestic Water Heater Efficiency and Current Standards

Domestic water heating (DWH) units are generally categorized using energy efficiency factor ratings. These relative efficiencies are then used as guidelines for current manufacturing standards.

3.1 Energy Efficiency and Load Factors

The energy factor (*EF*) is the measure used to rate the overall efficiency of a DWH unit. It is the ratio of the energy output of (that is, heat delivered as hot water by) the water heater to the total amount of energy consumed by the water heater. More specifically, *EF* is the added energy content of the water drawn from the water heater divided by the energy required to heat and maintain the water at the water heater's setpoint temperature (U.S. DOE, 2000):

$$EF = \frac{M \text{ x } C_p \text{ x } (T_{tank} - T_{inlet})}{Q_{dm}} \quad (1)$$

where:

EF = energy factor
M = mass of water drawn (lbs or kg)
C_p = specific heat of water (Btu/lb using °F or kWh/kg using °C)
T_{tank} = water heater thermostat setpoint temperature (°F or °C)
T_{inlet} = inlet water temperature (°F or °C)
Q_{dm} = water heater's daily energy consumption (Btu or kWh)

The *EF* also takes into account standby losses that are estimated as the percentage of heat lost per hour from the stored water compared to the heat content of the water (U.S. DOE, 1995). While higher *EF* ratings are equated with higher efficiency, they do not include operating costs. Higher EF values may not always mean lower operating costs, especially when fuel sources are compared (U.S. DOE, 2001b). However, in general, the lower the *EF* rating, the higher the operating costs (NRCan, 2003).

Through the use of outlet monitoring, Wiehagen and Sikora (2002b) provide an alternative measure of electric DWH unit efficiency. They determine heater energy at the outlet from the water heater, Q_{hw}, and at each location (outlet) where the hot water is delivered, $Q_{out,i}$, where total outlet energy delivered, Q_{out} is the sum across outlets of the energy delivered at each outlet. Specifically,

(2) $$Q_{hw} = (T_{hw} - T_{cw}) \text{ x } m_T \text{ x } C_p$$

where: T_{hw} = the water temperature at the outlet of the water heater
T_{cw} = cold water inlet temperature
m_T = the total system flow rate
C_p = a measure of the specific heat of the water

while total outlet energy, Q_{out}, is given by:

(3) $$Q_{out} = \sum_{i=1}^{n} (T_{out,i} - T_{cw}) \text{ x } m_i \text{ x } C_p$$

where: $T_{out,i}$ = outlet temperature at outlet *i*
m_i = assigned flow rate at outlet *i*
n = number of outlets,

and where the difference between Q_{hw} and Q_{out} indicates energy losses through piping. Based on these efficiency measures, water heater unit efficiency, Eff_{wh}, is calculated as:

(4) $$Eff_{hw} = Q_{hw} / Q_{elec}$$

where: Q_{elec} = total electric input energy

while overall system efficiency, Eff_{sys} is calculated as:

(5) $$Eff_{sys} = Q_{out} / Q_{elec}$$

In general, the efficiency of a tank water heater decreases as the tank gets larger, so that smaller tanks consume less energy per gallon (or litre) of water heated (Weingarten and

Weingarten, 1996). The larger standby losses of a larger tank reduce the EF more than is the case with a smaller tank (U.S. DOE, 2000).

In the context of evaluating alternative types of hot water heating systems in Florida, Merrigan and Parker (1990) use the load factor as a measure of efficiency. The load factor is defined as the ratio of the average kilowatt demand over a specified period of time to the maximum demand over the same period:

(6) Load Factor (%) = Average Demand (kW) / Peak Demand (kW)

This is a measure of how well the electric demand of the water heater unit is utilized over a period of time (which in the Merrigan and Parker (1990) study is taken to be a day, based on averages over 15-minute intervals). Since a higher load factor reflects a more even demand for electricity, this could be viewed as indicating a more efficient type of water heater. However, the authors found that this factor did not vary greatly across different types of water heaters.

3.2 Domestic Water Heater Standards

Canada's previous standards for domestic hot water heaters came into effect in February 1995. Amendments to these regulations followed in September 2004. These requirements are in the form of minimum *EF* values and maximum allowable standby losses, and are dependent on the size of the storage water tank (Canada, 2004). Table 3.1 outlines the efficiency standards to which storage tank hot water heaters must adhere. Electric storage tank regulations refer to maximum allowable standby losses, while gas and oil heater regulations refer to minimum energy factors.

Table 3.1 Energy Efficiency Regulations for Canadian Storage Tank Heaters

Fuel Type	Tank Size (litres)	Maximum Allowable Standby Loss (Watts)	Minimum Energy Factor (EF)
Electricity	For tanks with bottom inlet:		
	50 ≤ V ≤ 270 litres	40 + 0.20 V	
	270 < V ≤ 454 litres	0.472 V – 33.5	
	For tanks with top inlet:		
	50 ≤ V ≤ 270 litres	35 + 0.20 V	
	270 < V ≤ 454 litres	0.472 V – 38.5	
Propane or Natural Gas	76 to 380 litres (input rating ≤ 21.97 kW)		0.67 – 0.0005*V
Oil	≤ 190 litres (input rating ≤ 30.5 kW)		0.59 – 0.0005*V

Note: V = Volume of storage tank in litres.
Source: Canada (2004), NRCan (2003).

In the United States, efficiency standards for water heaters fall under the National Appliance Energy Conservation Act (NAECA), with the efficiency standards in place until 2003 being implemented in 1990 with small revisions in 1991. Effective January 2004, these energy conservation standards were revised (U.S. DOE, 2001a). These efficiency standards specify a minimum energy factor to which water heaters must adhere, depending on their size. Current values are displayed in Table 3.2. U.S. manufacturers are required by federal law to determine the Energy Factor (*EF*) for all products and to label all products with this information (U.S. DOE, 2001b).

Table 3.2 Energy Efficiency Regulations for U.S. Storage Tank and Demand Water Heaters

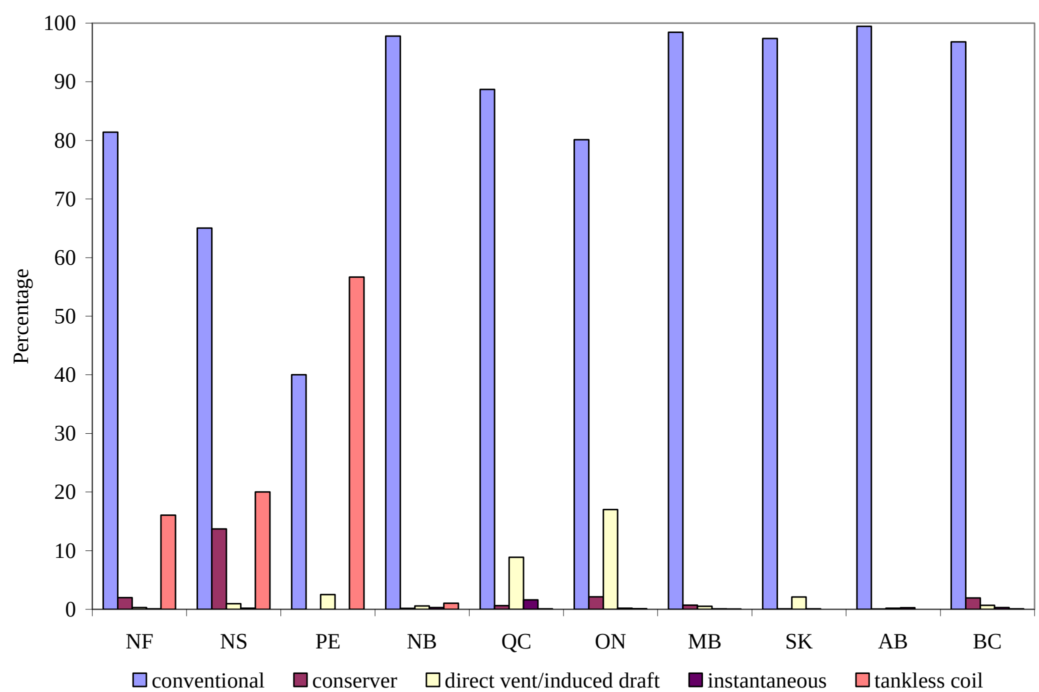
Fuel Type	Energy Factor as of January 20, 2004
Electric Water Heater	0.97 – (0.00132 x Rated Storage Volume in gallons)
Gas-fired Water Heater	0.67 - (0.0019 x Rated Storage Volume in gallons)
Oil-fired Water Heater	0.59 – (0.0019 x Rated Storage Volume in gallons)
Instantaneous Gas-fired Water Heater	0.62 – (0.0019 x Rated Storage Volume in gallons)
Instantaneous Electric Water Heater	0.93 – (0.00132 x Rated Storage Volume in gallons)

Rated storage volume is the water storage capacity of a water heater in gallons as specified by the manufacturer.
Source: U.S. DOE (2001a).

4. Domestic Water Heater Types, Relative Cost Efficiencies, and Incidence of Use

Domestic water heater types include: conventional storage tanks, direct vent/induced draft storage tanks, heat pump, solar, and integrated or duel appliance storage systems, and demand or instantaneous systems. In Canada, the most prevalent type of water heater is the conventional storage tank fueled by natural gas or electricity (Fig. 4.1). While electric and natural gas fueled storage tanks have relatively similar initial costs, electric storage tanks are more costly to operate on an annual basis. Expected lifetime estimates vary from 13 years for both to 15 years for electric and 12 years for gas-fired heaters (NRCan, 2004, ACEEE, 2004). Instantaneous or demand type water heaters have considerably longer expected lifetimes of 20 years, while oil-fired heaters (8 years), and indirect-with-boiler heaters (30 years) have the shortest and longest lifetimes, respectively (Table 4.1).

Figure 4.1: Canadian Domestic Hot Water Equipment Types



Source: EnerGuide data (2004).

Table 4.1: U.S. Life Cycle Costs of Different Types of Water Heaters

Water Heater Type	Avg. Cost US$	Expected Life	Annual Energy Cost US$	Cost Over 13 years US$
Gas Conventional Tank	$ 425	13	$165	$2,544
Gas High Efficiency Tank	$ 500	13	$145	$2,385
Gas Demand	$ 650	20	$140	$2,243
Oil Conventional Tank	$1100	8	$230	$4,777
Electric Conventional Tank	$ 425	13	$500	$6,925
Electric High Efficiency Tank	$ 500	13	$480	$6,740
Electric Demand	$ 600	20	$510	$7,020
Heat Pump	$1200	20	$190	$3,670
Indirect with Boiler	$ 700	30	$150	$2,253
Solar with Electric Back-up	$2500	20	$140	$3,445

Calculations are based on average prices of 10 cents/kWh for electricity, 60 cents/therm of gas (1 therm=0.1055 GJ), and 90 cents per gallon of oil. Future annual energy costs are not discounted. The calculations also involve an unstated assumption concerning the hot water needs of the household.

Source: American Council for an Energy-Efficient Economy (2004).

4.1 Storage Water Heaters

Storage water heaters typically function through the consumption of electricity, natural gas, oil, or propane (NRCan, 2003), with the particular energy source that is chosen varying according to fuel availability (and presumably costs). These domestic water heaters have a large storage capacity – 20 to 80 gallons or 75.7 to 302.8 litres (U.S. DOE, 1995) – and are able to supply high flow rates of hot water, though only for limited periods of time (Wiehagen and Sikora, 2002b). As water heating is constantly maintained, regardless of an existing demand for hot water, these types of water heaters are subject to standby as well as distribution heat losses.[1] Residential buildings in the U.S. Pacific Northwest were found to have an average standby water heater energy consumption of 1200 kWh/yr (Pratt et al., 1993). Homes with low use patterns

[1] The term stand-by heat loss refers to heat lost through the walls of the storage tank while water is being heated, given tank insulation (NRCan, 2003). Distribution heat losses refer to heat losses through the piping system.

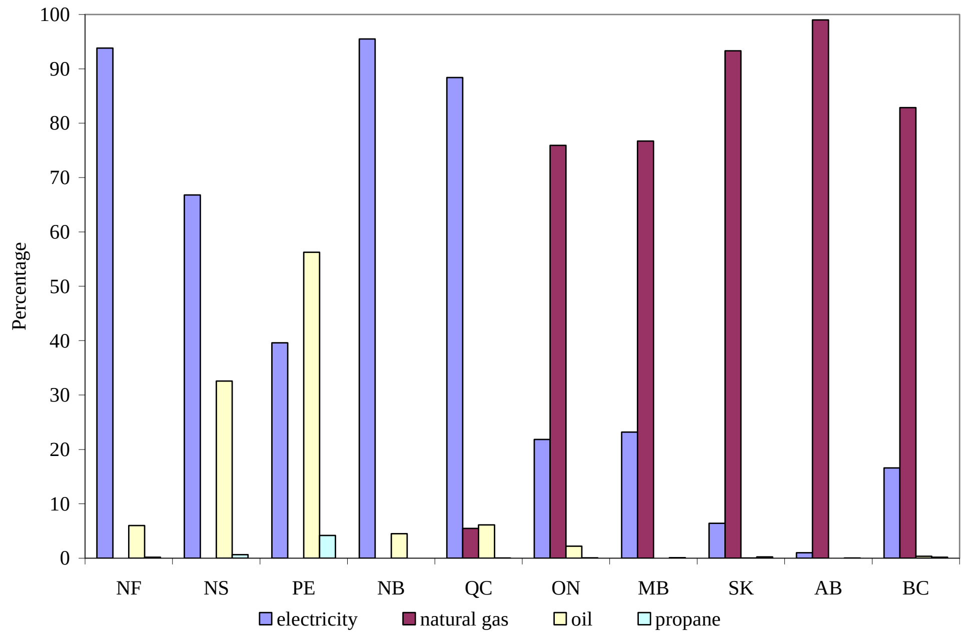
have higher standby and distribution losses with tank systems (Wiehagen and Sikora, 2002b). Of all water heating options, electric-fueled conventional storage tanks have one of the highest values of annual operating costs and of projected costs over 13 years of operation (Table 4.1).

Gas-fired conventional tanks heat water faster and have lower annual and projected lifetime costs. The conventional atmospheric draft gas heater is subject to heat loss as airflows up the flue remove heat from the heater tank. Energy Factors for a 40-gallon (150 litre) gas-fired unit range from 0.42 to 0.86, with most less than 0.65 (U.S. DOE, 2000). Direct vent or induced draft gas fired heaters have a draft inducer fan that controls the draft and reduces excess airflows to a minimum, thus increasing efficiency. These latter types of gas heaters are starting to capture market share in Quebec, Ontario, Saskatchewan and Alberta (Fig. 4.2) and have EF values up to 0.75 (U.S. DOE, 2000). In the condensing boiler type of gas fired water heater, the combustion products in the flue gas are condensed and more heat is extracted in the form of latent energy. These units capture almost all of the heat value of condensing flue gas water vapor. The forced draft burners in these units also eliminate off-cycle heat transfer to the flue. This increased efficiency results in EF values of up to 0.90 (U.S. DOE, 2000).

Tank water heater efficiency is improved by increasing tank insulation and flue baffling, using an anti-convection valve or heat trap, or by using sealed combustion designs. Research and testing has also been performed to evaluate various configurations of dual-tank (electric) systems where each tank has one or two operational heating elements (Hiller, 1996). Dual tank configurations may offer potential advantages for achieving desirable electrical load shapes and for maximizing cost-effectiveness when used with high efficiency alternative water-heating systems such as heat pump water heaters, desuperheaters,[2] and solar water heaters.

[2] Desuperheaters recover the waste heat of the refrigerant in a residence's air conditioning equipment (Merrigan and Parker, 1990), or from a heat pump.

Figure 4.2: Conventional Tank Water Heaters by Fuel Type for Canadian Provinces



Source: EnerGuide Data (2004)

4.2 Demand or Instantaneous Water Heaters

Demand or instantaneous water heaters that do not continuously heat and store water are often referred to as tankless systems. A gas burner or electric element automatically ignites when a faucet is turned on and hot water is delivered on demand, thus allowing for a reduction in stand-by heat losses. While gas demand heaters typically have a higher hot water output than electric models, their one overall limitation is the flow rate. Heated water flow rates range from 7 to 15 litres/minute (U.S. DOE, 1995). As a result, demand water heaters are best suited for households with low simultaneous demands. The initial unit cost is higher than either electric or natural gas conventional storage water heaters, but operating costs for the gas demand models are lower. Fuel consumption for gas-powered units can be higher if pilots remain lit, but units are now produced with electronic ignitions that reduce this cost. Efficiency factors for electronic ignition models are cited as 0.84 (Platts, 2004).

4.3 Tankless Coil, Indirect, and Condensing Water Heaters

Tankless coil water heaters use a heat exchanger integrated with a space-heating boiler to heat water instantaneously. This type of heater works well in cold climates where the boiler is used frequently, but is less efficient in warmer climates. While this system avoids the need to have a separate water heating system, this means that the space heating system must be operated in the non-heating season just to heat water.

Indirect water heaters circulate water through a heat exchanger in a boiler. This heated water then flows to an insulated storage tank. Because the boiler does not need to operate frequently, this system is more efficient than the tankless coil.

Condensing residential water heaters are typically installed as combination space and water heating units. In addition to being able to capture over 90% of input energy, these heaters can capture almost all of the heat value of condensing flue gas water vapor to liquid, and their forced draft burners eliminate off-cycle heat transfers to the flue. However this efficiency comes with a substantial initial cost premium (Sachs et al. 2004).

4.4 Heat Pump Water Heaters

Instead of creating heat directly, heat pump water heaters transfer heat. This type of heater uses an electrically driven compressor to remove heat energy from a low-temperature heat source and move it to a higher-temperature heat sink, the water stored in the hot-water tank. The energy required by the heat pump is primarily electrical energy needed to operate the compressor. For any given energy amount, heat pump water heaters are capable of heating two to three times as much water as electric resistance heaters.

Air heat pump water heaters heat water by removing heat from ambient air. These water heaters are in use in the United States, but lack popularity in Canada due to the warm temperatures required for proper function. They can offer a space cooling benefit, since as indoor air is used to heat the water, heat pump water heaters vent cool air into the space. Air heat pump water heaters can provide hot water at 40 to 100 percent of the rate of electric resistance units and 30 to 50 percent of the rate of gas units, but require warm ambient temperatures and a large heat pump or storage tank to provide a constant flow of hot water (Bodzin, 1997). Most of these heaters have a back up heating elements to heat water during cold periods. They heat water more slowly than other types of heaters, and are more expensive to install, but have a shorter pay back period due to increased savings provided hot water energy use is relatively high.

Most geothermal heat pumps can make hot water at any time of the year because heat is drawn from the earth, which is warmer than air temperature in winter. Even in severe weather this type of heater is about 30% more efficient than the most efficient air source heat pump (DOE, 2004). They are more efficient because they are less reliant on electric resistance heaters to supplement heating capacity (Martin and Gettings, 1998). In colder Canadian climates, this type of heater has proven to be effective as a pre-heater. However, due to the ground loops necessary for these types of heat pumps to function, property alterations and high initial costs have made them less practical for existing homes (Martin and Gettings, 1998; OEE, 2003).

4.5 Solar Water Heaters

Direct solar water heaters circulate household water through the collectors while indirect solar heaters circulate a form of antifreeze through them. Solar water heater capacity is dependent upon weather patterns and seasons. Active systems use pumps and controls to move heat and circulate water, while passive systems function without either and can be more reliable and durable. Both types of systems can act as pre-heaters, but they often require electric or gas heaters for backup when they are the main domestic water heater. Solar water heater installation and equipment costs can be higher when compared to other types, but their operating costs are lower (U.S. DOE, 1995).

Merrigan and Parker (1990) found that in Florida, solar hot water systems operated with the highest average electrical system efficiency and with the lowest average daily electrical demand profile. For a domestic water heating system, it is claimed that the use of solar energy with an electricity and diesel backup can result in a savings of 75% in greenhouse gasses compared to a conventional system (Kalogirou, 2004). While the installation cost of solar water heating systems (with electric backup) is high (see Table 4.1), it is argued that the life-cycle costs are such that in single-family dwellings in Toronto with a high hot-water load, the generated societal benefits make solar domestic water heating economically viable (Berbash et al., 1995). Estimates based on experimental and theoretical investigations in Denmark indicate that the performance/cost ratio for small systems can be improved by up to 25% by using a smart solar tank in which the auxiliary energy supply system (electricity), controlled by an electronic control system, heats up the tank from the top (Furbo et al., 2005). However, such systems have not yet been developed.

5. Measuring and Analyzing Domestic Hot Water Consumption

In metered studies, domestic hot water consumption and/or energy required for domestic water heating (or for other purposes) and/or energy use by appliances within the home, are measured under typical household conditions (Wenzel et al., 1997). The measurement and analysis of domestic hot water consumption is usually accomplished using one of two methods – the temperature-based event inference method and the flow trace signature analysis method. In the latter, flow measurements are made as water leaves the hot water tank and selected supporting temperature measurements are made at the main piping branches. Temperature-based event inference methods involve temperature measurements as close as possible to specific end uses, with flow measurements at the hot water tank outlet (Henze et al. 2002). Although flow trace analysis is less intrusive and requires less instrumentation, temperature-based event inference is more accurate and capable of separating out simultaneous events.

According to Henze et al., (2002), existing information about residential hot water use is limited and largely out of date. Not all water heating fuels are represented, and the majority of studies focus on electric storage type heater systems. There is limited consistency between studies, and the occupancy characteristics are often incomplete or uncorrelated with specific sites (Henze et al., 2002). Tiller et al. (2004) describe an online database for domestic hot water use data that could be used to resolve and summarize usage trends for individual end uses.

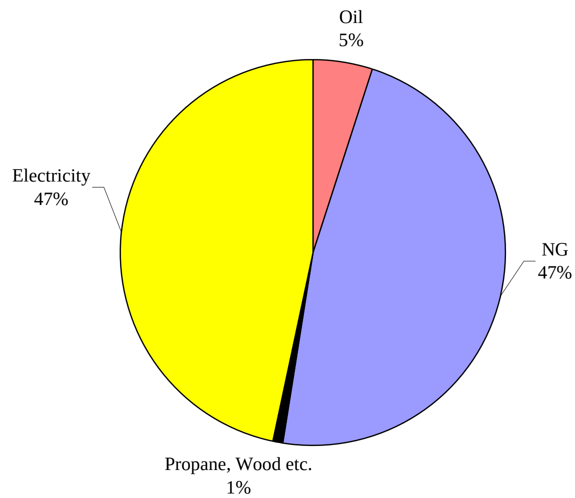
6. Factors Influencing Domestic Hot Water and Energy Consumption

Flow rate, occupancy rate, household composition, installed appliances, and climate influence the volume of domestic hot water consumed. Household hot water consumption patterns vary according to factors such as climate and season, household composition, family income, and cultural background. Factors affecting household energy expenditure that is required to produce domestic hot water include the type of fuel used, inflow temperature, set temperature, hot water heater type, appliance types and efficiency ratings, and any water or heat losses.

6.1 *Fuel Type*

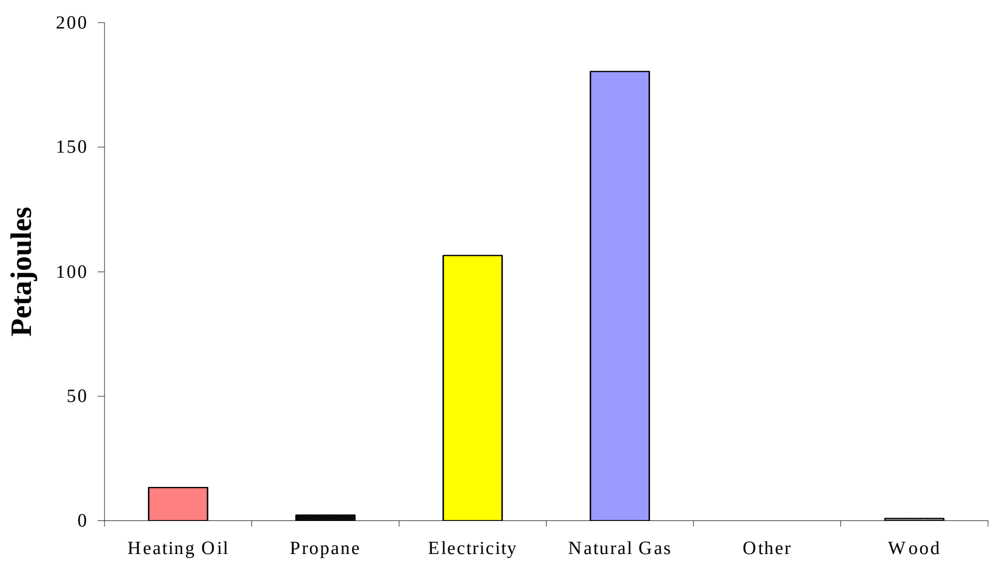
Electricity and natural gas are the most commonly used energy sources for the purpose of water heating in Canadian households (Fig. 6.1). Energy consumption in petajoules is estimated to be higher for natural gas (Fig. 6.2). This may partially be due to higher standby heat losses with natural gas than with electric water heaters, but it may also be due to larger water heating requirements for households with natural gas water heaters.

Figure 6.1: Percentage of Homes Using Each Fuel Source for DWH - 2002



Source: Survey of Household Spending, 2002 (weighted data).

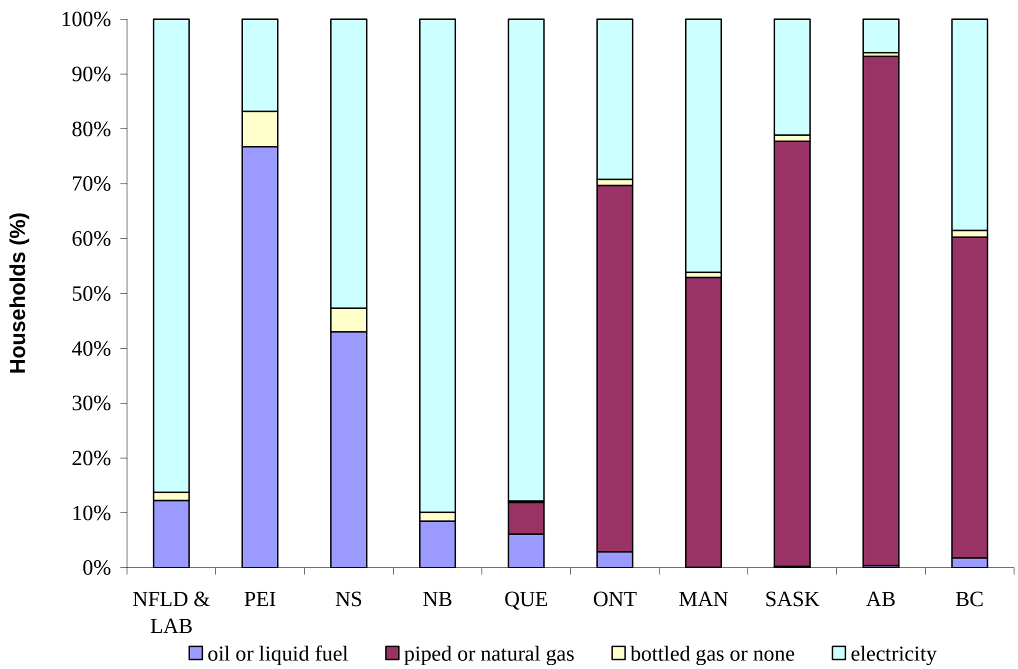
Figure 6.2: DWH Energy Consumption by Energy Source (PJ) - 2002



Source: Natural Resources Canada, *Energy Use Data Handbook, 1990 and 1996 to 2002*, June 2004.

Although DWH fuel choice is influenced by fuel cost and efficiency as well as equipment cost, it is also limited in some regions of Canada by fuel availability. In the Maritimes (apart from Prince Edward Island) and Quebec, the DWH fuel source is primarily electricity, with oil and liquid fuel as the secondary fuel source. From Ontario westward to British Columbia, the primary fuel used is natural gas with electricity as the secondary fuel. Manitoba and British Columbia have a more even mix of electricity and natural gas usage with a minimal amount of oil and liquid fuel use (Fig. 6.3).

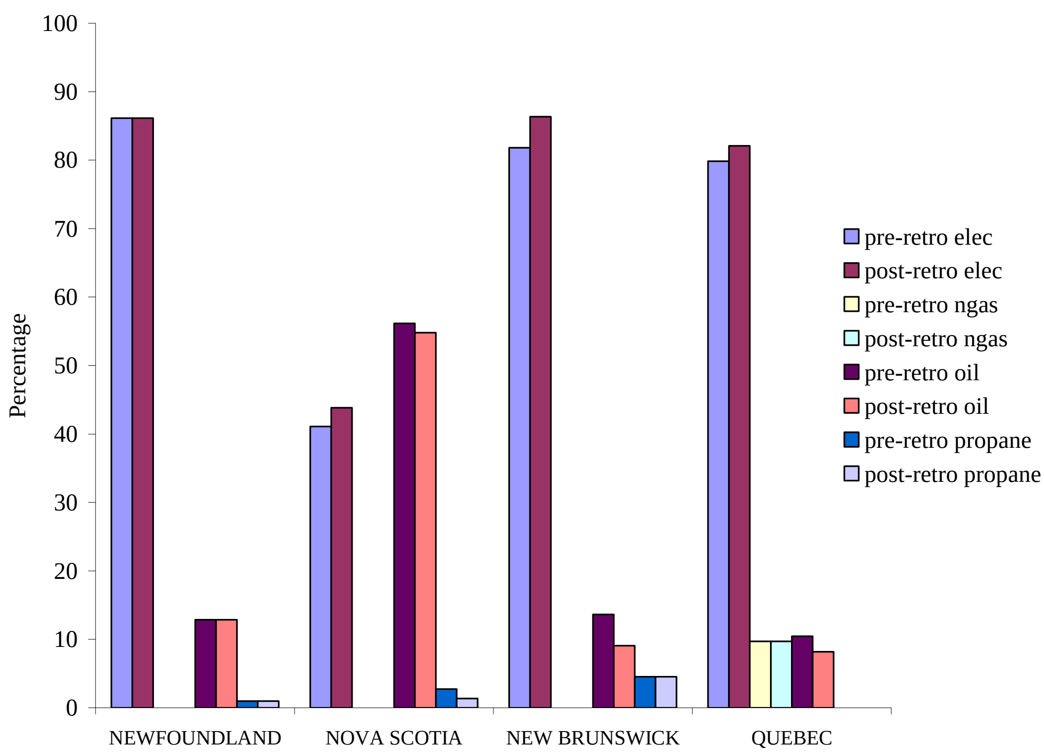
Figure 6.3: Primary fuel source for domestic hot water heating (%) by province – 2002



Source: Statistics Canada, Survey of Household Spending, 2002

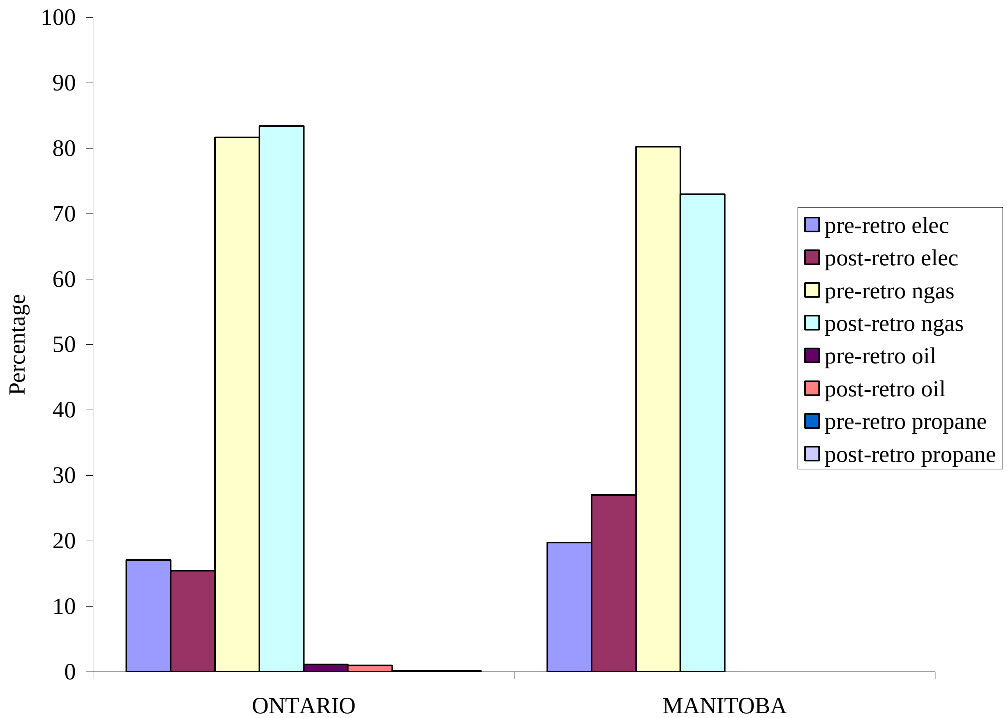
Based on the limited information available in the EnerGuide database concerning houses that underwent retrofits and had energy audits both prior to and after the retrofits were undertaken (6847 of the total 103672 observations in the database), it is possible to examine the extent of any DWH fuel switching that accompanied these residential retrofits. In total, only 22 of the 6847 houses changed the fuel used for DWH, with the types of changes varying across Canadian regions. In the Maritimes and Quebec, the use of oil-fueled DWH units tended to decline, while the use of electric water heaters increased (Fig. 6.4). In Ontario there was a decrease in electric type heaters accompanied by an increase in natural gas fired heaters (Fig. 6.5), while in Manitoba the change was in the opposite direction (Fig. 6.5). Saskatchewan, Alberta, and British Columbia use natural gas as the preferred DWH fuel with little or no switching associated with retrofit activity (Fig. 6.6). More detailed analysis is required to determine if the retrofits involve upgrading the existing DWH system to energy efficient storage tanks or demand type systems.

Figure 6.4: Maritimes and Quebec - Pre and Post Retrofit DWH Fuel Type



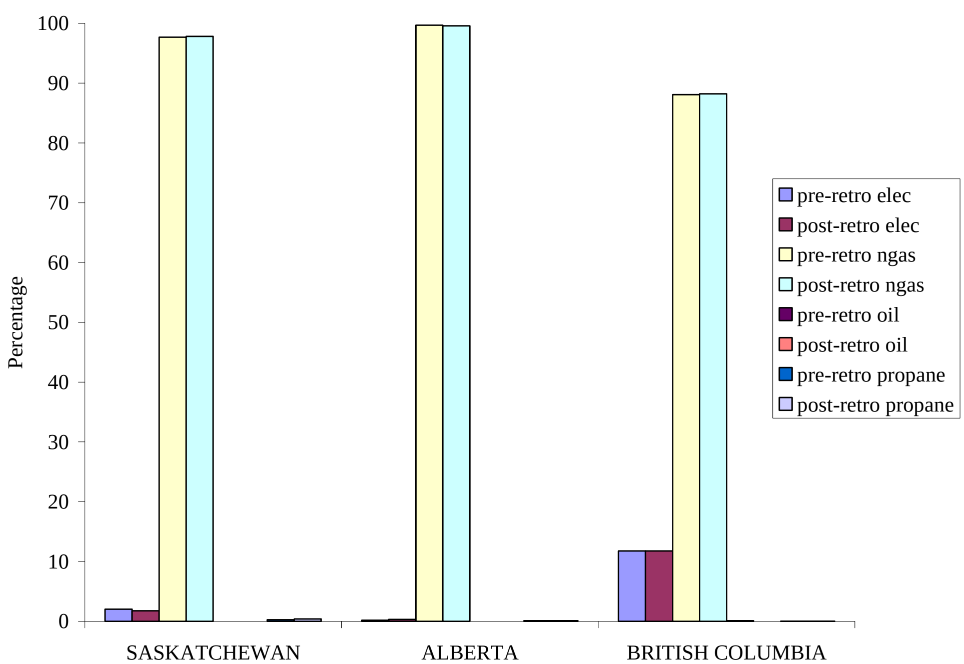
Source: Retrofit Data (6847 observations) from EnerGuide Data (2004)

Figure 6.5: Ontario and Manitoba – Pre and Post Retrofit DHW Fuel Type



Source: Retrofit Data (6847 observations) from EnerGuide Data (2004)

Figure 6.6: Saskatchewan, Alberta, and B.C. - Post Retrofit DHW Fuel Type



Source: Retrofit Data (6847 observations) from EnerGuide Data (2004)

6.*2 Water and Energy Consumption*

Canadian daily residential per capita water use in 1999 was estimated at 343 litres, an increase from 327 litres in 1996, but lower than the 1989 level of 347 litres per person per day (Environment Canada, 2004). The U.S. Residential End Uses of Water Study (REUWS) reported a mean daily per capita indoor water use of 69.3 gallons per day or 262 litres (Mayer et al., 1999). Although this study does not separately identify hot water use, total indoor water use per capita was distributed as shown in Table 6.1.

Table 6.1: Daily Per-Capita Indoor Water Use (Gallons per person per day)

Appliance	Indoor Water Use Gallons/person/day	Indoor Water Use Litres/person/day
Dishwasher	1.0	3.8
Bath	1.2	4.5
Other domestic	1.6	6.1
Leak	9.5	36.0
Faucet	10.9	41.3
Shower	11.6	43.9
Clothes washer	15.0	56.8
Toilet	18.5	70.0
Total Indoor Use	69.3	262.4

Source: Mayer et al (1999)

North American water consumption appears to be considerably higher than in a number of other countries. For example, in Finland, estimates of daily per capita water consumption range from 70 to 110 litres (Simonson, 2004). In South African townhouses, per-capita hot water consumption was found to range between 88.6 litres per day in low-density townhouses to 61.5 litres per day in high-density townhouses (Meyer and Tshimankinda, 1998).

In a study using flow trace analysis of 10 homes in Seattle with average occupancy of 2.6 residents, DeOreo and Mayer (2000) estimated per capita daily consumption of hot water to be 25.1 gallons or 95 litres. Household daily consumption of hot water was estimated at 65.3 gallons or 247 litres. Approximately 40% of overall water use was attributed to hot water use.

Faucets, showers, baths and clothes washers had the highest per capita hot water use (Table 6.2). Those end-uses involving direct consumer behavior or preferences, such as baths or showers, result in more water consumption than appliances with pre-set water consumption patterns, such as dishwashers.

Table 6.2: Household Hot Water Use from Flow Trace Analysis

Category	Per Capita Hot Water Use (litres/day)	Household Hot Water Use (litres/day)	Percent of Total Hot Water Use in Each Category (%)	Percent of Overall Use that is Hot Water (%)
Bath	15.9	41.3	16.7	78.2
Clothes Washer	14.8	38.2	15.5	27.8
Dishwasher	3.4	8.7	3.6	100
Faucet	32.6	84.8	34.3	72.7
Leak	4.5	11.7	4.8	26.8
Shower	23.8	62.1	25.1	73.1
Toilet	0.0	0.0	0	0.0
Other	0.04	0.1	0	35.1
Indoor Total	95.0	247.2	100%	39.6%

Source: DeOreo and Mayer (2000).

In terms of energy use, typical homes in Finland with four occupants and a gross floor area of 140 m^2 are estimated to consume 27 kWh/ m^2/year or 3780 kWh/year for domestic water heating (Simonson, 2004). Estimated average annual energy consumption for 2003 Baseline water heater designs from the regulatory impact analysis of the DOE are given in Table 6.3.

Table 6.3: Energy Consumption for Domestic Water Heaters by Fuel Type

Water Heater Fuel Type	Average Energy Use		Total Average Energy Use
	kWh/yr	MMBtu/yr	Equiv. kWh/yr
Electric	3460		3460
Natural Gas		23.4	6856
LPG		22.8	6680
Oil	75.1	25.4	7517

Source: U.S. DOE (2000).

Most of the applied (measured/metered) research on energy consumption associated with water heating has involved electric heaters. However, the cost of obtaining hot water differs with different fuels and different types of water heating systems. Unless there is no price responsiveness at all, these different costs would be expected to induce different levels of hot water consumption and different energy use requirements. This suggests that simply generalizing from electric water heater results to other types of water heaters may be misleading. Clearly, more research is needed to determine hot water, and hence energy, consumption with other types of water heaters, particularly gas-fired water heaters which are the main type of water heater used in Western Canada.

6.3 *Weekly and Seasonal Variation*

In a study of 30 multi-family buildings in New York,[3] Goldner (1994) found quite distinct seasonal variation in domestic hot water consumption. After adjusting for leaks, hot water consumption was observed to increase 10% from summer to fall, and a further 13% during the winter, before decreasing 1% in the spring. In addition, hot water consumption on a weekend day was approximately 7.5 percent greater than during a weekday. Specifically, weekend day consumption was estimated at 55 gallons (207 liters) per capita per day while weekday consumption averaged 51 gallons (183 liters) per capita per day. Average consumption was 174 litres/capita/day.

In an Australian study, 30 to 48 percent of the day-to-day variance in hot water energy consumption was explained by weather patterns, with an increase in air temperature correlated

[3] In his study, Goldner included buildings whose size ranged from 17 to 103 apartments, with 2.2 occupants per apartment on average, and with either 5 or 6 above ground stories. The study was conducted over 14 months.

with a decrease in energy consumption, particularly during summer (Hart and de Dear, 2004). In Florida, average hot water energy consumption was 30% greater on the coldest winter day than on the mildest day (Bouchelle and Parker, 2000). In both Australia and Florida, the majority of hot water heaters are located in unconditioned spaces, which contributes to the sensitivity to seasonal temperatures. However, in colder climates where water heaters are located in conditioned space, seasonal variation in the temperature of the incoming cold water is expected to have a substantial effect on energy consumption for water heating (Abrams and Shedd, 1996).

Seasonal hot water consumption data for Canada do not appear to be available. However, a CMHC study (1999) of apartment dwellings found that the number of heating degree-days had no effect on overall (hot plus cold) water consumption while average annual consumption of energy per suite and energy per square metre increased as the number of heating degree-days increased. This increase in energy consumption obviously reflects space heating requirements, but may also include additional energy required for water heating in colder periods.

6.4 Occupancy Rate and Occupant Characteristics

Occupancy is one of the strongest determinants of hot water consumption (Parker, 2003). Not surprisingly, as household size increases, consumption of water heating energy increases (U.S. DOE, 2004c). However, indoor water use has been shown to increase as household size increases while per capita use decreases. These efficiencies appear to be associated with the age of the occupants and/or the amount of water needed for cleaning, washing clothes and dishes, and general maintenance (Mayer and DeOreo, 1999).

Occupant characteristics are also important, as they not only affect personal hot water consumption, but also the use of hot water consuming equipment within the home. Age, income, and employment status all affect hot water end-uses, including the number of hot, warm, and cold cycles by clothes washers, the amount of hot water used in hand washing dishes or hot water consumed by dishwashers, and the number, length, and temperature of showers and baths (Lutz et al., 1996). Aydinalp et al.'s (2004) model results suggest that owner occupied residences would consume higher amounts of domestic hot water than renter-occupied dwellings. However, behavioural research suggests that home owners are more likely to be energy savers than those who rent, and that senior populations are more likely to employ energy conservation strategies (Barr et al., 2005). Hot water use in apartment buildings is difficult to characterize and data on consumption patterns are extremely limited. Factors complicating the collection of reliable data for these buildings include the availability of alternatives to the use of domestic hot water, such as coin laundries (Lowenstein and Hiller, 1999).

The Canadian Mortgage and Housing Corporation (1999) found that apartment buildings housing families consumed 44 per cent more water per suite than seniors' buildings. Overall energy consumption for seniors' buildings was, however, only 10 percent lower per suite than family buildings. This observation is explained by the higher demand for space heating among seniors that may offset decreased hot water use. Lutz et al (1996) note that while studies conducted over a decade ago reported lower hot water consumption for seniors, the data were limited and based solely on electric water heaters. Goldner (1994) reported that if children are present in the home, DWH energy consumption increases.

Statistics Canada estimates that the percentage of the Canadian population over the age of 65 will increase to 21 percent by 2026 (Statistics Canada, 2002). In the U.S. the percentage of population over 60 is estimated to increase to 22 percent by 2020 (Liao and Chang, 2002).

Clearly hot water consumption as affected by age of household occupants and the age mix in a given household requires further investigation.

6.5 Household Income

In a model of DWH energy consumption using the Canadian Survey of Household Expenditure data (1993), Aydinalp et al. (2004) reported that energy consumption for water heating increased by 0.0418 GJ/year for every $1000 increase in yearly income. Based on the U.S. Residential Energy Consumption Survey (RECS), average water-heating energy consumption per household ranges from 11.8 Mbtu for households earning less than $10,000 US in 2001 to 19.3 Mbtu for those earning $50,000 US or more in 2001 (U.S. DOE, 2004c). However, in 1993, low-income households across the U.S. were estimated to use in the range of 10.8 to 18.0 Mbtu (3165 to 5275 kWh) to heat water (Martin and Gettings, 1998). Low-income families have exhibited above average hot water energy consumption in other studies (Goldner, 1994). As well, evidence suggests that households that are not required to pay for their hot water expenditures consume above average amounts of hot water (Lutz et al., 1996). Barr et al. (2005) suggest that income may be a weak predictor of energy conservation behaviour.

6.6 Water and Heat Losses

Due to colder temperatures, storage tank water heaters can experience greater heat losses particularly if they are situated in poorly insulated or unconditioned spaces (Parker, 2003). Analysis of energy use for domestic water heating in New Zealand households estimated losses ranging from 34% of total electricity use for electric storage systems to 27% of total gas use for natural gas storage systems (BRANZ, 2004). Simulation studies indicate that compared to copper pipe, use of CPVC pipe results in an estimated 50% energy loss reduction, while the typical hot water wait time with CPVC pipe is about 5% less than for the standard conventional copper system (Baskin et al., 2004).

Hot water energy consumption can also increase if more water than necessary is utilized. This can occur through water purging and unintended use. Water purging occurs when water in the pipe supplying hot water to an outlet is below the acceptable delivery temperature and is purged or run out of the line until the desired hot water temperature is delivered. Unintended use refers to the drawing of hot water when only the use of cold water was intended, such as can occur with single handle faucets or in the case where hot water taps are turned on and off in such a short period of time that hot water is delivered into the piping system but not the outlet by the time the draw is completed. Although the energy consumed in unintended activities is often considered minimal, these activities do result in hot water consumption (Wiehagen and Sikora, 2002b).

6.7 Hot Water Distribution Systems

The piping system transporting hot water to the faucet or hot water using appliance typically consists of a “tree” system where individual outlets are fed from main supply or trunk. Recent simulation research evaluating the relative efficiency of the tree system and a “parallel” piping system, where each outlet is fed via an individual line directly from a manifold, indicates that there are some efficiencies to be gained primarily from installation of demand water heaters, with additional potential gains from modified distribution systems (Baskin et al., 2004; Wiehagen and Sikora, 2002a).

6.8 Appliance Efficiency

The amount of energy or hot water consumed will also depend on the efficiency of the installed appliances. In Table 6.4 the unit energy consumption of specific appliances that use hot water are summarized.

Table 6.4: EF and UEC for Hot Water Consuming Appliances

Appliance	EF	UEC
Clothes Washer[a]	0.82	1434 kWh/yr
Dishwasher[b]	0.29 – 0.35	636 kWh/yr

a. Source: Canada(2004). Annual energy consumption for clothes washers is based on a typical 392 clothes washes per year.
b. Source: Wenzel et al. (1997). Highest EF values are for electric water heaters (98% recovery efficiency); lowest are for gas water heaters (76% recovery efficiency).

7. Modeling Domestic Hot Water Consumption and Energy Use

When discussing hot water *generating* appliances, the term consumption refers to the energy used by the water heating unit in order to heat water and deliver it to the point of demand. In regard to hot water *consuming* appliances, however, the term consumption refers to both the energy and hot water consumed by the unit while in the pursuit of the task it was built to perform. Therefore, measures of hot water and hot water heating consumption patterns are needed when analyzing the energy consumption associated with residential DWH use.

7.1 Appliance Hot Water and Energy Consumption

Even when using data collection methods such as metering and appliance signature monitoring, it is difficult to ascertain how much hot water a particular unit consumes at any given point in time, as these methods are designed to determine when an appliance is in use or how much energy it is consuming. To determine how much hot water a dishwasher or washing machine will use for a particular cycle or load, Lutz et al. (1996) use the average temperature of warm water used in a cycle to calculate the percentages of hot and cold water. Then, the hot water fraction is used to estimate the amount of hot water used per cycle, or load, as well as daily consumption. Specifically,

(7) $$T_{warm} = T_{hot} * (x) + T_{cold} * (1-x)$$

where: T_{warm} = the average temperature of warm water used in a cycle (33.5°C)
T_{hot} = the temperature of hot water used by the unit (48.9°C)
T_{cold} = the temperature of cold water used by the unit (17.7°C)
x = the fraction of water that is hot

The formula in (7) is used to solve for x (=0.51), the fraction of water that is hot (Lutz et al, 1996). Of course, when the appliance performs a cold wash or a hot wash, the fraction of hot water used is 0 and 1, respectively. Once calculated, the estimated hot water fraction can be used to approximate the amount of hot water used by a washing machine during a particular cycle.[4]

(8) $Use_{cycle} = V_{cycle} * f_{hot}$

where: Use_{cycle} = the amount of hot water used per cycle (litres/cycle)
V_{cycle} = the total water used per cycle (litres/cycle)
f_{hot} = the fraction of hot water used per cycle

Since every load of laundry is subject to different temperature cycles, the average hot water used per load will be the sum of the hot water used by each cycle.

(9) $Use_{load} = (f_{hwash} * Use_{hwash}) + (f_{wwash} * Use_{wwash}) + (f_{wrinse} * Use_{wrinse})$

where: Use_{load} = the amount of hot water used per average load (litres/load)
f_{hwash} = the frequency of hot wash cycles from all loads (cycles/load)
Use_{hwash} = the amount of hot water used per hot wash cycle (litres/cycle)
f_{wwash} = the frequency of warm wash cycles from all loads (cycles/load)
Use_{wwash} = the amount of warm water used per warm wash cycle (litres/cycle)
f_{wrinse} = the frequency of warm water rinse cycles from all loads (cycles/load)
Use_{wrinse} = the amount of hot water used per warm rinse cycle (litres/cycle)

Finally, the amount of hot water consumed by a washing machine per day can be calculated using the estimated amount of water used per load and an estimate of the average number of loads a household does per week. The total number of warm, hot, or cold cycles and loads done by a household will depend upon the number of occupants in residence (Lutz et al., 1996).

(10) $Use_{day} = (Loads_{week} * Use_{load}) / 7$

where: Use_{day} = the average amount of hot water used per day by the unit (L/day)
$Loads_{week}$ = the average number of loads per week (load/week)
Use_{load} = the amount of hot water used per average load (L/load)

This same equation is used by Lutz et al. (1996) to provide an estimate of hot water use by dishwashers and hand washing, with the amount of hot water used per load, Use_{load}, calculated as

[4] This calculation is unnecessary for the purpose of determining hot water consumption by dishwashers and hand washing.

the total amount of water used per load multiplied by the fraction of total water that is hot. Current US DOE assumptions are 215 cycles (loads) per year for dishwashers and 392 for clothes washers, but these values vary by household type, household size, and probably a number of other factors (US DOE, 2000b).

As both domestic hot water generating and consuming units use energy in order to function, a measure of unit energy consumption (UEC) is needed for each. In general, UEC is an estimate of the amount of energy a unit consumes during its various modes. This measure includes energy consumed while the unit is "off," since some appliances can still consume energy while not in use. Wenzel et al. (1997) argue that to assess the energy use for water heating in a particular household, and to evaluate the effects of various energy conservation measures, it is necessary to disaggregate total hot water use to reflect these various components. Therefore, as well as equations that determine the UEC for water heaters, Wenzel et al. (1997) provide individual UEC equations for dishwashers, and washing machines. All these equations utilize the unit's EF rating, and can therefore reflect changes made to efficiency standards – for new units, that incorporate different efficiency standards, the UEC estimate is adjusted to reflect the difference in average energy factors. Wenzel et al. (1997) used the following equations to calculate UEC:

Dishwasher (*incorporating Motor, Dryer, Booster Heater, and Hot Water Energy*):

(11) $$UEC_{dish} = Use / EF$$

where: UEC_{dish} = unit energy consumption (kWh/yr)
Use = the total number of dishwasher cycles used by the household in a year (cycles/yr)
EF = energy efficiency factor (cycles/kWh)

Clothes Washing Machine (*incorporating Motor and Hot Water Energy*):

(12) $$UEC_{wash} = (Use * Capacity) / EF$$

where: UEC_{wash} = unit energy consumption (kWh/yr)
Use = the total number of washing machine cycles used by the household in a year (cycles/year)
Capacity = the washing machine's volume (cubic feet)
EF = energy efficiency factor (cubic feet/kWh)

Electric Water Heater:

(13) $$UEC_e = (Use * TempRise * SHW * 365) / [3413 * (EF/100)]$$

where: UEC_e = unit energy consumption (kWh/yr)
Use = household hot water use (gallons/day)
TempRise = the annual average temperature difference between incoming cold water and tank temperature.
SHW = specific heat of water (8.2928 Btu/gallon-F)
3413 = conversion factor (Btu/kWh)
EF = energy efficiency factor from DOE test procedure (%)

Fuel (Oil or Gas) Water Heater:

(14) $$UEC_f = (Use * TempRise * SHW * 365) / (EF/100)$$

where: UEC_f = unit energy consumption (MMBtu/yr)

Rather than use either of these latter two equations to estimate a household's total hot water energy consumption, individual UEC estimates could be aggregated. However, in addition to UEC for dishwashers and clothes washers, unit specific information would be needed for the major hot water end uses – namely through basins, bath faucets and showerheads – and this information may be difficult to obtain. For this reason, a household's hot water energy consumption could be calculated as a residual, after first disaggregating total household energy consumption into major end-uses which may be easier to measure, such as for space heating and appliances, and subtracting the energy required for these uses from the total energy consumed by the household (Aydinalp et al, 2001):

(15) $$Q_{DWH} = TEC - Q_{space} - Q_{applight}$$

where: Q_{DWH} = annual DWH energy consumption (MJ)
TEC = total annual household energy consumption (MJ)

Q_{space} = total household space heating energy consumption (MJ)
$Q_{applight}$ = total household appliance and lighting energy consumption (MJ)

The drawback of this method is that the division of household energy consumption into broad categories may result in a less reliable figure compared to a summation of individual UECs.

7.2 Hot Water Use Models

In 1985 the Electric Power Institute (EPRI) model was developed to estimate hot water demand at specific times of the day using multiple regression analysis (Lutz et al., 1996). The model comprised 16 equations that were used to estimate the amount of hot water consumed, in gallons per hour, at eight separate time intervals during a day, with weekdays and weekend days considered separately. Instead of using a typical household, the EPRI model classified all household demographics into 3 age groups – infants and children (to age 5), children, ages 6 to 13, and adults, ages 14 and older – where each household was assumed to have both a dishwasher and clothes washing machine (Lutz et al., 1996). Additional variables included outside air temperature, inlet water temperature of the water heater, thermostat setting of the water heater, water heater tank size, and dummy variables to reflect differences that may arise in different seasons and if the household includes an unemployed family member who was at home during the day.

Although the original EPRI model allowed for the estimation of domestic hot water consumption, its applicability is limited due to the assumptions it incorporates, such as all households having dishwashers, as well as the small sample size (110 households) on which it was based. It also only covers electric water heaters. In order to obtain predictions for a broader range of households, Lutz et al. (1996) expanded the model, including two new demographic variables and two new appliance variables. The two demographic variables, reflecting senior-only households and households that do not pay for their hot water (no-pay households), were added in order to capture the differences in consumption patterns these two groups seemed to exhibit. Evidence suggests that hot water consumption is higher in households that are not required to pay for the hot water used, while senior-only households consume less (Liao and Chang, 2002; Lutz et al., 1996). The addition of the no clothes washers and no dishwashers variables were designed to facilitate application of the model to households that did not own both these appliances.

The generic form of the modified model, which is not estimated, but rather includes adjustments to an existing equation based on various metering studies, involves linear equations that have the following form:

(16) $$vol = [f(\,seasonals, per, age1, age2, age3, T_{tank}, T_{in}, T_{air}, athome, Tsize, g_1(per, \sqrt{per}) * nodw, g_2(per, \sqrt{per}) * no\ cw] * (1- \alpha_1*\text{senior}) * (1+\alpha_2*\text{nopay})$$

where:

vol = hot water consumption (litres/hour or gallons/day)
seasonals = seasonal variables (=1 in a particular season, =0 otherwise)
per = total number of persons in household
age1 = number of preschool children, age 0-5 yrs
age2 = number of school age children, age 6-13 yrs
age3 = number of adults, age 14-64 yrs
T_{tank} = water heater thermostat setting, °F
T_{in} = water heater inlet water temperature, °F
T_{air} = outside air temperature, °F
Tsize = water heater nominal tank size, gallons
athome = 1 if adults are at home during the day, =0 otherwise
no_dw = 1 if no dishwasher, =0 otherwise
no_cw = 1 if no clothes washer, =0 otherwise
$g_1(per, \sqrt{per})$ and $g_2(per, \sqrt{per})$ = different linear functions of *per* and square root of *per*, as determined by Lutz et al (1996)
senior = 1 if this is a senior-only household, =0 otherwise
nopay = 1 if household does not pay for hot water, =0 otherwise
α_1 and α_2 are coefficients determined by Lutz et al (1996)

This model, known as the hot water draw module, is one of the five major modules that are used in the Life Cycle Cost (LCC) analysis in U.S. DOE (2000). This analysis is used to examine the economic impacts on individual consumers arising from possible revisions in U.S. residential water heating efficiency standards. Specifically, the LCC represents the consumer's cost of purchasing and installing a water heater and operating it for its lifetime (U.S. DOE, 2000). Since there are errors associated with the estimated coefficients that Lutz et al (1996) provided for the equations, in their analysis U.S. DOE (2000) allow for uncertainties in the coefficients as well as in the thermostat setting (T_{tank} in the above model). With this variation, the equations are used with a large sample of households from the U.S. Residential Energy Consumption Survey (RECS) databases to determine estimated hot water use.

7.3 Domestic Water Heater Energy Consumption Models

Domestic water heating energy consumption models are designed to estimate the amount of energy consumed over a particular period of time to produce hot water and to determine the relative efficiency of water heaters for the purposes of establishing manufacturing standards. In the U.S. DOE (2000) engineering analysis of water heaters, three separate models are used to investigate the energy efficiencies resulting from design options and combinations of design options for different types of water heaters: (i) the WATSIM computer simulation model for electric storage water heaters (Hiller et al., 1992), (ii) the TANK computer simulation model for gas-fired storage water heaters (Paul et al., 1993), and (iii) WHAM, a simplified water heater analysis model that calculates average daily energy consumption based on a small number of variables that describe the water heater and its operating conditions(Lutz, et al., 1998). The U.S. DOE (2000) uses WHAM for their analysis of energy consumption for oil-fired water heaters. In addition, as part of the Life Cycle Cost (LCC) analysis that the U.S. DOE (2000) conducts, the outputs from these three different models – for electric, gas, and oil water heaters – are used in WHAM to estimate residential water heater consumption with baseline water heaters, as well as with all design options under consideration, for a large number of households.

7.3.1 WATSIM

According to U.S. DOE (2000), WATSIM is a detailed electric water heater simulation program developed by EPRI. This program provides detailed temperature profiles of the water inside the heater tank during the simulation run. These temperature profiles can be used subsequently to determine the energy-efficiency characteristics of the water heater. WATSIM is proprietary, and cannot be publicly verified. However, U.S. DOE (2000) reports on experiments that demonstrate the accuracy of the WARSIM algorithm at the efficiency levels and types of design options that are appropriate for their analysis.

7.3.2 TANK

According to U.S. DOE (2000), TANK is a detailed gas-fired storage water heater program developed for the Gas Research Institute by the Battelle Memorial Institute. TANK calculates energy flows throughout a water heater, including water draws, flue heat losses, jacket heat losses, fittings heat losses, and combustion chamber heat losses. In contrast to WATSIM, the TANK program directly produces information concerning the energy efficiency characteristics of the water heater, namely its energy factor (EF), Recovery Efficiency (RE), and the stand-by heat loss coefficient (UA).

7.3.3 WHAM

According to U.S. DOE (2000), The Water Heater Analysis Model (WHAM) is a simple energy equation that accounts for a variety of operating conditions and water heater characteristics when calculating energy consumption. The assumptions underlying the energy calculation in WHAM account for a variety of field conditions and types of water heaters. U.S. DOE (2000) reports that based on a comparison of energy calculations from WHAM with those from the much more detailed WATSIM and TANK simulation models, the much simpler WHAM accurately estimates residential water heater energy usage to within 3% to 5%.

WHAM requires only minimal descriptions of the water heater and water heater operating conditions. Specifically, the operating condition information that is required is the daily draw volume, the thermostat setpoint temperature, the inlet water temperature, and the ambient air temperature. The required characteristics of the water heater include its rated input (*Pon*), its stand-by heat loss coefficient (*UA*), and its recovery efficiency (*RE*).

A water heater's *RE* value is the ratio of energy added to the water compared to the energy input to the water heater. It is a measure of how efficiently energy is transferred to the water when the heating element is on or the burner is firing (U.S. DOE, 2000). The *Pon* value is the nominal input power rating assigned to the heater by the manufacturer, expressed in terms of kW for electric heaters and Btu/hr for natural gas or oil fueled units. The *UA* represents the hourly stand-by energy losses exhibited by the water heater and is measured in Btu/hr-°F (U.S. DOE, 2000). It is the amount of energy that is needed to maintain the water in the storage tank at the setpoint temperature while there is no hot water demand.

WHAM is based on a number of simplifying assumptions, including constancy of the water and air temperatures, constancy of water density and the specific heat content of water, and also the assumption that the water temperature in the tank is always at the thermostat setpoint. U.S. DOE (2000) notes that due to their relatively high recovery efficiency, this last assumption is likely to be best approximated with an of oil-fired water heater.

During a 24-hour trial, water is drawn from the water heater, in equal amounts, every hour for the first six hours, totaling 64.3 gallons (243.4 liters) (U.S. DOE, 2000). For the last 18 hours, the water heater is left in stand-by mode and energy losses during this time are measured. Total energy consumption and total mass of water drawn during the trial is then obtained. The temperature of the water entering, leaving, and inside the tank, as well as the ambient temperature of the area surrounding the heater is recorded. Using this information, along with the heater's rated input (*Pon*), as well as the stand-by heat loss coefficient (*UA*) and recovery efficiency (*RE*) that are determined in the course of the test procedure, WHAM calculates the average daily energy consumption of a water heater:

(17) $$Q_{in} = (Q_{out} / RE) * [1 – (\{UA * (T_{tank} – T_{in} \}/ Pon)] + 24 * UA* (T_{tank} – T_{amb})$$

where: Q_{in} = total water heater energy consumption (Btu/day or kWh/day)
Q_{out} = the heat content of the water being drawn from the water heater (Btu/day or kWh/day)
RE = recovery efficiency
UA = stand-by heat loss coefficient (Btu/hr-°F or kWh/°C)
T_{tank} = thermostat setpoint temperature; i.e. the desired hot water delivery temperature (°F or °C)
T_{in} = the inlet water temperature; i.e. the temperature of the water supplied to the water heater (°F or °C)
Pon = manufacturer's rated input power (Btu/hr or kWh/day)
T_{amb} = the temperature of the ambient air surrounding the water heater (°F or °C)

In this calculation, the heat content of the water being drawn from the water heater, Q_{out}, is calculated as:

(18) $$Q_{out} = vol * den * C_p * (T_{tank} – T_{in})$$

where: vol = volume of water that is drawn
den = density of water

C_p = specific heat of water

7.3.4 Use in Life Cycle Cost (LCC) Analysis

As part of the Life Cycle Cost (LCC) analysis that the U.S. DOE (2000) conducts, the outputs from the WATSIM (electricity), TANK (gas) and WHAM (oil) models – specifically the values of *RE*, *UA* and *Pon* for baseline water heaters, as well as for water heaters that incorporate particular design options that are being studied – are subsequently combined with information from individual households (water and air temperatures and average daily hot water use) to estimate residential water heater consumption for these households using these particular water heaters. These latter calculations, for all types of water heaters, use the WHAM model described previously. Although the WATSIM model does not produce values of *RE* and *UA*, these can be determined from the detailed temperature profiles of water inside the water heater tank during the simulation that WATSIM does provide U.S. DOE, 2000). When a water heater's energy factor (*EF*) and recovery efficiency (*RE*) are known, the stand-by heat loss coefficient (*UA*) can be determined as:

(19) $$UA = \{(1/EF) – (1/RE)\} / \{(T_{tank} – T_{amb}) * [(24/Q_{out}) - (1/ \{RE * Pon\})]\}$$

where: UA = stand-by heat loss coefficient (Btu/hr-°F or kWh/°C)
EF = energy efficiency factor

7.4 Stock Saturation & Retirement Curves

As a means to simplify analysis of stock turnover rates, the U.S. DOE (2000) assumes that when a water heater is retired, homeowners replace the old unit with a new one of the same fuel type. On this basis, changes to fuel type market shares result mainly from purchases made for new homes. However, market shares for specific types of models will be affected by all purchases. Sanchez et al. (1998) find that in the U.S. during the period 1976-1995, the relationship between energy growth in existing product stock and in new product stock was 4 to 1, that is, that for every four terawatt hours (TWh) of growth in energy consumption from existing models, there was one TWh of growth from new models.

Before stock saturation estimates can be obtained, a "survival curve" for existing stock must be created. Survival curves for existing appliance stocks are an estimation of the unit's retirement rate, that is, the rate at which a unit is retired and consequently replaced. The average lifetimes of various hot water consuming and producing appliances are shown in Table 7.1.

Table 7.1: Average Product Lifetimes of Specific Residential Appliance Units

Appliance	Estimated Average Product Lifetime (Years) [a] Canada	U.S. DOE Estimated Average Product Lifetime (Years)[b]
Gas Water Heater	12	9 (min=5, max=13)
Oil Water Heater	n/a	9 (min=5, max=13)
Electric Water Heater	15	14 (min=6,max=21)
Dishwasher	13	n/a
Clothes Washer	14	14.1 (min=12, max=16) [c]

[a] Average lifetimes for the Gas & Electric Water heaters, and Clothes Dryers are from Canada (2004). Dishwasher lifetime is from The EnerGuide Appliance Directory, NRCan OEE online
[b.] U.S. DOE (2000)
[c.] U.S. DOE (2000b)

In their analysis of the effects of appliance efficiency standards for the U.S. residential sector, Koomey et al. (1998) use a linear retirement function (survival curve), in which no units are retired in the first two thirds of their average life, but all are replaced by the time four thirds of their average life has elapsed. Specifically,

- If the unit's age < {2/3 * average life} ⇒ 100% survive
- If {2/3 * average life} < unit's age < {4/3 * average life}

  ⇒ 100{2 – age * (1.5/average life)}% survive
- If the unit's age > {4/3 * average life} ⇒ 0% survive.

This function is used to estimate the retirement rate of appliances. By applying this function to projected shipments, the number of appliances purchased in a particular year and still existing at a specified date can be determined. Koomey et al refer to the devices that are still existing in a given year that are affected by efficiency standards as the "Applicable Stock".

Since Koomey et al (1998) are concerned with regional impacts of appliance efficiency standards, it is necessary for them to determine the applicable stock in each geographical area. This is done by disaggregating the national stock using the following equation:

(20) $$AS_i^{G,A} = AS_i^{N,A}\left[\left(F_i^{REPL}\ x\ \frac{Sat_{Exist}^{G}}{Sat_{Exist}^{N}}\ x\ \frac{HH^{G}}{HH^{N}}\right) + \left(F_i^{NEW}\ x\ \frac{Sat_{New}^{G}}{Sat_{New}^{N}}\ x\ \frac{NHP^{G}}{NHP^{N}}\right)\right]$$

where: G = geographical level (provincial, municipal, census division)
A = appliance/end-use (unit) type
i = year
N = national level
$AS_i^{G, A}$ = applicable stock; shipments minus retirements of unit type A for geographical area G in year i
$AS_i^{N, A}$ = applicable stock; shipments minus retirements of unit type A for the national level in year i
F_i^{REPL} = fraction of units that are replacements in year i; a figure calculated using national stock data
F_i^{NEW} = fraction of units that are new in year i; a figure calculated using national stock data
Sat^{G}_{Exist} = number of total existing units[5] for all appliances in geographical area G
Sat^{N}_{Exist} = number of total existing units for all appliances at the national level

Sat^{G}_{New} = number of total new units for all appliances in geographical area G
Sat^{N}_{New} = number of total new units for all appliances at the national level
HH^{G} = total number of households in geographical area G
HH^{N} = total number of households at the national level
NHP^{G} = total number of new housing permits in geographical area G
NHP^{N} = total number of new housing permits at the national level

[5] Koomey et al. (1998) use the 1993 Residential Energy Consumption Survey (RECS) as a source for saturation levels and define old saturations as those units within homes built before 1987 and new saturations as those in homes built after 1986. This is mainly due to the National Appliance Energy Conservation Act of 1987 (NAECA), which enacted minimum efficiency standards for appliances in the U.S.

In Canada, no attempt appears to have been made to explicitly disaggregate national appliance stock data into regional appliance stocks. However, in view of differences across regions in water heater types – and possibly in household stocks of water-using appliances – it may be prudent to consider such a disaggregation in subsequent analysis. An equation such as (20) could be used for this purpose, where, analogously to Koomey et al (1998), the distinction between saturation of existing and new units could be based on dates when efficiency regulations changed.

8. Domestic Water Heating and the Residential End-Use Model (REUM)

8.1 Domestic Water Heating in REUM

Total hot water energy demand in REUM is obtained by summing hot water energy demands of three components – major appliances (dishwashers and clothes dryers), personal use (via showers, baths, and faucets), and base load (standby losses from the water heater). For each of these components, hot water demand is obtained as:

$$(21) \qquad HWED_i = (WHSTOCK * OCCRATE * HHDEMAND_i \ / \ WHPERHH) \ / \ EF$$

where: $HWED_i$ is hot water energy demand for component i
WHSTOCK is the water heating stock
OCCRATE is the occupancy rate (proportion of houses occupied and using hot water)
$HHDEMAND_i$ is a measure of household energy demand for hot water for that component (see below)
WHPERHH is the number of water heaters per household
EF is the water heater efficiency factor
and i represents the component, i = {major appliances, personal use, and standby losses}.

Note that HWED and WHSTOCK may differ across province or region (p), time (t), DWH fuel type (ft), and household type (ht). OCCRATE and HHDEMAND may differ across p, ht and t, while EF differs across ft.

In order to clearly identify the assumptions that are required for the calculations in (21), it is convenient to consider the components of (21) in detail. In some cases these values are determined within REUM so that the equation specifications that follow are not necessarily identical to those in REUM which may, for example, combine several components into a single variable.

In the calculation in (21), the household energy demand for hot water measure varies by component. For the major appliances component, the hot water energy demand measure is the major appliance water heating energy load per household, which is the sum of energy demand for hot water for dishwashers and energy demand for hot water using clothes washers. The per-household energy demand for hot water for dishwashers, $HHDEMAND_{dish}$, is calculated as:

(22) $$HHDEMAND_{dish} = prop_{dish} * loads_{dish} * enload_{dish}$$

where: $prop_{dish}$ is the proportion of households with dishwashers
$loads_{dish}$ is the number of dishwasher loads per year for a household with a dishwasher
$enload_{dish}$ is the average energy consumption for hot water per dishwasher load

The average energy consumption for hot water per dishwasher load, $enload_{dish}$, is the sum of the energy in the hot water that is delivered to the dishwasher and the energy used by the dishwasher to heat the water further:

(23) $$enload_{dish} = hwenergy_{dish} + encons_{dish} * pheat_{dish}$$

where: $hwenergy_{dish}$ is the energy in the hot water delivered to the dishwasher per load
$encons_{dish}$ is the direct unit energy consumption per dishwasher load
$pheat_{dish}$ is the proportion of unit energy consumption by the dishwasher that is used to heat water.

Unfortunately, values for $hwenergy_{dish}$ and for $pheat_{dish}$ may both be unknown. In such cases it may be possible to approximate $enload_{dish}$ as a constant proportion of $encons_{dish}$:

(23a) $$enload_{dish} = \theta_1 encons_{dish}$$

where θ_1 is a proportion. This is the procedure used in REUM.

The per-household energy demand for using clothes washers, $HHDEMAND_{cwash}$, is calculated as:

(24) $$HHDEMAND_{cwash} = prop_{cwash} * loads_{cwash} * hwenergy_{cwash}$$

where: $prop_{cwash}$ is the proportion of households with clothes washers

$loads_{cwash}$ is the number of clothes washing loads per year for households with a clothes washer

$hwenergy_{cwash}$ is the energy in the hot water delivered to the clothes washer per load.

Unfortunately, values for $hwenergy_{cwash}$ may be unknown. In such cases it may be possible to approximate this variable as a constant proportion of $encons_{cwash}$, where $encons_{cwash}$ is the direct unit energy consumption per clothes washer load:

(24a) $$hwenergy_{cwash} = \theta_2 \, encons_{cwash}$$

where θ_2 is a proportion. This is the procedure used in REUM.

For the personal use component, the hot water energy demand measure in (21), $HHDEMAND_{pers}$, is the energy required to provide hot water for personal use by household.

For the base load (standby losses) component, the hot water energy demand measure in (21), $HHDEMAND_{base}$, is water heater output, which is calculated as:

(25) $$HHDEMAND_{base} = energy_{watheat} * WHPERHH$$

where: $energy_{watheat}$ is the unit energy output per water heater. This variable indicates the base amount of energy that a water heater uses per year, that is, the amount of energy used by a water heater that is connected but where hot water is not being drawn from the unit.

The assumptions/information required to determine energy required for hot water are summarized in Table 8.1.

Table 8.1: Assumptions to Determine Energy Required for DWH

Variable	***Description***	***Current REUM Values &Assumptions***
WHSTOCK	Water Heater Stock	Determined in REUM using stocks and sales values
OCCRATE	Percent of houses occupied	Determined in REUM
WHPERHH	Water heaters per house	1.0
EF	Water heater Efficiency Factor	Electricity – 0.84864 Natural Gas – 0.52985 Oil – 0.52369 Propane – 0.5
HHDEMAND-dish	Household energy demand for hot water for dishwashers	
Prop-dish	Proportion of households with dishwashers	
loads-dish	Dishwasher loads per year per household	
Enload-dish	Energy consumption for hot water per dishwasher load	0.88 * Encons-dish (constant proportion)
Hwenergy-dish	Energy in the hot water delivered to the dishwasher per load	n/a
Encons-dish	Direct unit energy consumption (UEC) per dishwasher load	Reported by Manufacturers
Pheat-dish	Proportion of UEC per dishwasher load used to heat water	n/a
HHDEMAND-cwash	Household energy demand for hot water for clothes washers	
Prop-cwash	Proportion of households with clothes washers	
loads-cwash	Clothes washer loads per year per household	
Hwenergy-cwash	Energy in the hot water delivered to the clothes washer per load	0.92 * Encons-cwash (constant proportion)
(Encons-cwash)**	Direct unit energy consumption (UEC) per clothes washer load	Reported by Manufacturers
HHDEMAND-pers	Household energy demand for hot water for personal use	10 GJ per household (constant)
HHDEMAND-base	Household energy demand for baseload hot water (standby losses)	
Energy-watheat	Standby energy loss per water heater per year	3.5 GJ per water heater (constant)

Note: ** indicates a variable not required in model equations specified above, but used in REUM to obtain an approximate measure.
n/a indicates "not available".

8.2 Examination of REUM Assumptions

In this section, values of specific variables and parameters in the domestic water heating component of REUM are considered. The main objective here is to identify the sources of existing assumptions, to describe any changes in these assumptions that might be appropriate, as well as to discuss various issues associated with the use of some of these assumptions.

8.2.1 Water Heater Stock

Water heater stock is determined within REUM using stock information from the *Survey of Household Spending* (Statistics Canada) and sales from *Canadian Gas Facts*. However, more efficient water heaters use less energy. Therefore it would be desirable to know if higher efficiency models are being adopted (especially those incorporating increased insulation, draft induced fans etc.) and their rate of adoption. This information could be obtained from surveys, but is not available in the Survey of Household Spending, although DWH efficiency is recorded in the EnerGuide Data. It appears that the last time that comprehensive survey information on the age of a household's water heater was collected in a random sample was in the 1993 Survey of Household Energy Use (SHEU93).

8.2.2 Occupancy Rates and Average Household Size

In REUM, the occupancy rate refers to the proportion of households that are occupied and assumed to be using a water heater. This variable is determined within REUM. An additional related factor that does not appear to be explicitly incorporated in the water heating component of REUM is average household size. This variable differs across provinces, and more importantly, over time. This variable is important because as household size changes, so too does domestic hot water consumption. Apart from increased requirements for personal use, this also affects energy consumption for hot water for use by major appliances, since it affects both the number of dishwasher and clothes washer loads. In addition, larger household sizes typically have higher hot water use patterns, which can affect standing heat losses. While it might be preferable to include average household size directly in equation (21) as an additional variable, an alternative is to incorporate this variable in each component of hot water energy demand. Thus, for example, household energy demand for hot water for personal use could be calculated as individual demand for hot water for personal use multiplied by household size. Similar calculations could be used for energy use for hot water for major appliances and base load. In this way, the effects of changes in household size across provinces and time would be directly reflected in the calculations in the model.

8.2.3 Water Heaters per House

Within REUM, the number of water heaters per house is assumed to be 1.0. There appears to be no literature or studies that examine this value, although there are some articles that examine aspects of dual-tank systems (Hiller, 1996). In cases where, for example, instantaneous water heaters or solar systems are coupled with conventional tanks, the number of water heaters per house would obviously exceed 1.0. If every house is expected to have at least one water heater and some have more than one water heater, the average number of water heaters per house would exceed one. However, survey information would be required to determine if changes in this value were warranted, and if so, the revised value that should be used. Over time as the EnerGuide database expands, it may be possible to use information from that source to determine whether the assumed number of water heaters per house should be revised.

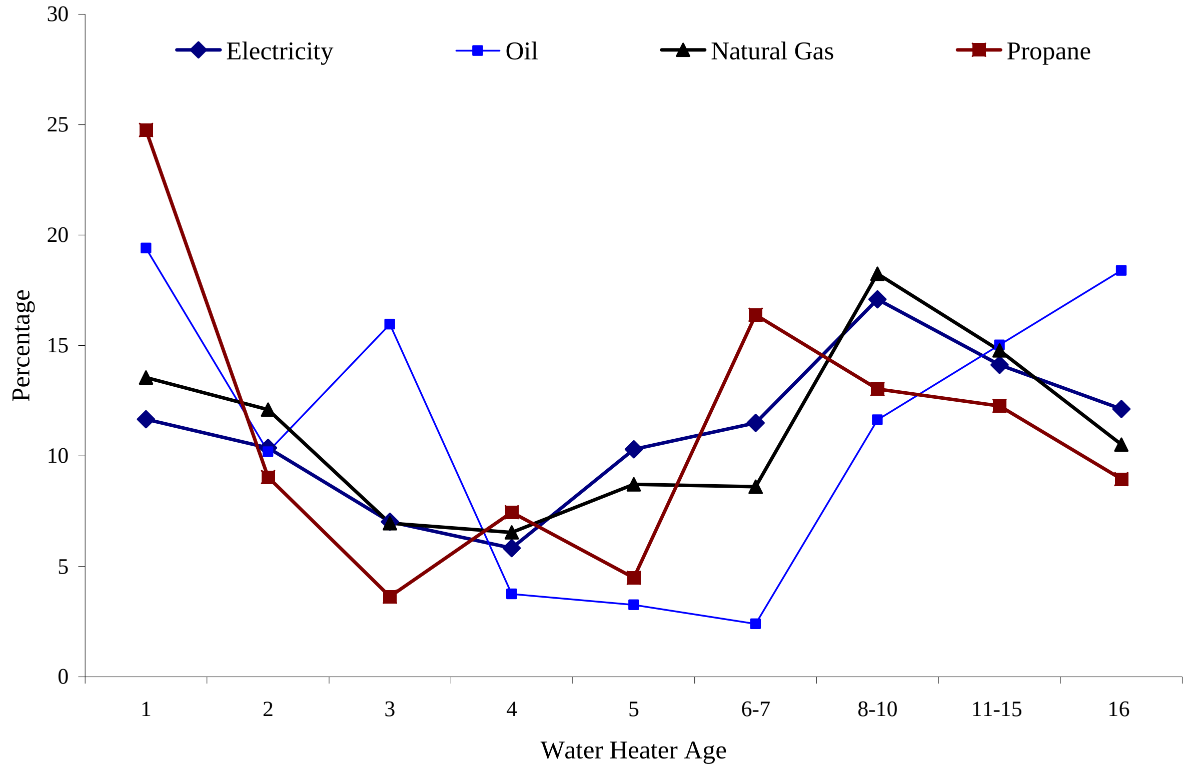
8.2.4 Water Heater Efficiency Factors

Without some reliable indicators of the age of existing Canadian water heater stocks, it is not possible to accurately estimate the efficiency of water heaters in place. It is not known whether the efficiency values used in REUM reflect characteristics of the stock in place, based, for example, on some form of replacement function using stock shipments, residential construction, etc.

Table 8.2 provides a summary of the factors currently used in the REUM, the minimum energy factors in the U.S. and Canada, selected energy factors in place in 2000-01, and in the pre- and post-1990 period. From the values in this table it appears that the EF factors currently in use in the REUM are at the lower end of the efficiency scale.

The last comprehensive survey of water heater age in Canada appears to have been in SHEU93. At that time (over 12 years ago), based on water heaters where the age and fuel type was known, over 26% of electric water heaters, 33% of oil water heaters, 25% of natural gas water heaters, and 21% of propane water heaters were over 10 years old (Fig. 8.1). Clearly most of these would have been replaced by now. SHEU97 survey results and the 2004 EnerGuide data would appear to indicate that water heater replacements predominantly involve replacement with a water heater that uses the same fuel type, although in some cases natural gas-fueled water heaters have replaced electric water heaters, or vice-versa. In addition, in 1993, over 30% of water heaters were less than 3 years old (Fig. 8.1). In view of this information, and the efficiency factors for post 1990 water heaters shown in Table 8.1, it would appear that the EF factors presently in use are at the conservative end of the efficiency scale.

Figure 8.1: SHEU93 Water Heater Age by Fuel Type in 1993



Source: Survey of Household Energy Use, 1993.

Note: Observations with unknown or unspecified water heater fuel type or age have been excluded in the calculations underlying this figure. Values refer to the percentage of water heaters of a particular fuel type that are in a specified age range.

Table 8.2: Water Heater Energy Factor Comparisons

Water Heater Type	REUM Energy Factors (2005) (EF)	Minimum Energy Factors (2004) (EF)	Manufacturer/Utility/ Gov. Agency Energy Factor Ranges (2000-04) (EF)	Historical Energy Factors (EF)
Electric				
conventional	0.84864	0.97 - (0.00132*VG)[1]	0.86 to 0.95[3]	pre-1990 - 0.80 to 0.83[8] post-1990 - 0.83 to 0.89[8]
energy efficient			0.92 to 0.94[6]	
instantaneous		0.93 - (0.00132*VG)[1]		
Natural Gas				
conventional	0.52985	0.67 - (0.0019*VG)[1] 0.67 - (0.0005*V)[2]	0.54 to 0.63[3]	pre-1990 - 0.48 to 0.49[8] post-1990 - 0.48 to 0.56[8]
direct vent			0.53 to 0.59[7]	
power vent			0.53 to 0.65[7]	
instantaneous pilot		0.62 - (0.0019*VG)[1]	0.69[5]	
instantaneous electronic ignition			0.80 to 0.84[5]	
condensing			0.89[4]	
Propane				
conventional	0.52369		0.54 to 0.63[3]	
Oil				
conventional		0.59 - (0.0019*VG)[1] 0.59 - (0.0005*V)[2]		post-1990 - 0.45 to 0.53[8]

[1] U.S. DOE (2001b, 2005)
[2] Canada (2004), NRCan (2003)
[3] U.S. DOE Technology Fact Sheet (2001b)
[4] Sachs et al. (2004)
[5] BC Hydro (2005)
[6] US DOE (2000)
[7] RHEEM-Gas (2005)
[8] Kelso (2003)
V = Water storage capacity of a water heater , in litres, as specified by the manufacturer.
VG = Water storage capacity of a water heater , in gallons, as specified by the manufacturer

8.2.5 Household Energy Demand for Baseload Hot Water (Standby Losses)

Consumption of energy for baseload hot water is currently estimated at 3.5GJ per household in the REUM. As was the case with energy consumption for hot water for personal use, this value is treated as being constant across provinces, water heater fuel type, household type, and time.

In view of the REUM model formulation, where hot water energy usage is based on end-use, that is appliances and personal use, the baseload requirements should refer to all energy use for water heating that is not captured in these specific end uses. Therefore, this would include standby heat losses as well as distribution losses and leakage. In many studies these components are considered jointly, although in some studies they appear to be examined separately. However, in general there is very little information on energy use for this purpose. This lack of knowledge forms the motivation for a project recently proposed by the Lawrence Berkeley National Laboratory (LNBL) (Stoops et al, 2005), which is designed to measure how much water and energy is wasted in hot water distribution systems in California residences.

In terms of information that is currently available, Pratt et al (1993) studied water heater standby consumption in the Pacific Northwest in the U.S. They found that single-family homes with electric space heating equipment consumed more than 4700 kWh/year to heat water for domestic uses. Average standby load for existing homes was found to be 1200 kWh/year, or approximately 26% of total energy consumed for water heating. Homes built as part of a Residential Standards Demonstration Program, which are presumably more energy efficient, averaged 1100 kWh/year (23%) in standby load, while a regional energy forecast for the same area assumes a standby load value of 1300 kWh/year (28%).

In a study of energy end-use in New Zealand houses, an average of 1020 kWh/year was required to replace standing heat losses for domestic hot water (Stoecklein et al, 1998). However, there was considerable variation in this value, with the standard deviation being 450 kWh/year. The average amount of energy used for heating of consumed hot water (that is, excluding the standing heat losses) was 1890 kWh/year. On average standing losses were found to account for 40% of total domestic hot water energy consumed, although with a range from 20% to 70%, this proportion varied quite considerably across houses. A later New Zealand study (Pollard et al, 2002) found standing losses from electric water heaters to be 42% (3.56 kWh/day out of 8.38kWh/day), while for natural gas water heaters, standing losses accounted for 21% of energy used for water heating (3.9 kWh/day out of 18.72 kWh/day). This is the reverse of the pattern typically found in North America, where relatively smaller standby losses are associated with electric water heaters than with natural gas water heaters.

In U.S. DOE (2000), values are presented for the standby heat loss coefficient (UA) for various types of water heaters. As noted earlier, this coefficient measures the rate at which energy must be added to the water heater when it is not heating water for delivery, that is, it indicates the energy input required to maintain water at the setpoint temperature. The values measured in Btu per hour for each degree Fahrenheit for baseline water heaters are 3.64 for electric water heaters, 13.99 for natural gas fueled water heaters, and 14.49 for oil-fueled water heaters. These values can be converted to Watts by multiplying by 0.293, to degrees Celsius by multiplying by 1.8, and then to kWh per year per degree Celsius by multiplying by 24 x 365 /1000. Finally, they can be converted to GJ per degree Celsius by multiplying by 0.0036. In terms of required temperature rise, a Canadian study concerned with residential greywater heat recovery systems (Proskiw, 1998) calculates the temperature rise as being 49°C, based on an inlet temperature of 11°C, which was the average inlet temperature of 8 Canadian cities, and a water heater thermostat setting of 60°C. On this basis, the estimated standby heat losses from water heaters are calculated as shown in Table 8.3.

Table 8.3: Water Heater Standby Energy Losses

Water Heater Type	Standby Heat Loss Coefficient (UA) (Btu/hr - °F)[1]	Standby Energy Loss per year (kWh / yr - °C)	Standby Energy Loss per year for a 49°C temperature rise (GJ / yr)
Electric	3.64	16.82	2.97
Natural Gas	13.99	64.65	11.40
Oil	14.49	66.96	11.81

[1] US DOE (2000)

Particularly for natural gas and oil, these standby energy losses exceed the value of 3.5GJ per household (water heater) that is assumed in REUM. In addition, the variation in these values suggest that different standby energy losses should be assigned to water heaters with different fuel types. It should also be noted that various improvements to water heater technology that were examined in US DOE (2000) could result in reductions in the UA coefficients, and therefore in the standby energy losses per year for each type of water heater.

8.2.6 Household Energy Demand for Hot Water for Personal Use

Personal consumption of energy for hot water through showers, baths and faucet use is currently estimated at 10GJ per household in the REUM. This value is treated as being constant across provinces, water heater fuel type, household type, and time.

According to Wiehagen and Sikora (2002a), a 1985 study that monitored hot water use for 59 residences in Canada found average <u>hot water</u> use <u>per household</u> to be 236 litres per day, with per-capita consumption values ranging from approximately 47 to 86 litres per day. However, based on other studies, these values appear to be underestimates of current hot water consumption levels. Average per-capita domestic water consumption (including both hot and cold water use) in Canada is currently rated as one of the highest in the world at approximately 350 litres/day – up from a reported 327 litres per capita per day in 1996, and 343 litres per capita per day in 1999 (Environment Canada, 2001; 2004). This daily value ranges between 269 litres/capita/day for metered user households and 457 litres/person/day for unmetered user households, with current values being similar to those in 1989 (347 litres), previously the highest use year on record. This information is summarized in Table 8.4.

Table 8.4: Per-Household and Per-Capita Hot Water Use

Source	Location	Water Type	Per Household Measure Litres/day	Per-capita Measure Litres/day
Wiehagen and Sikora (2002a) [Perlman and Mills – 1985]	Canada	Hot	236	47-86
Env Canada (2004)	Canada	All		350
Env Canada (2004) [using proportion from DeOreo et al (2000)]*	Canada	Hot		138.6 (106.5-181)
Goldner (1994)	US	Hot		167 avg ** 274 max **
Henze (2002)	US	Hot Hot - personal	227.4 (2 adults) 98.8	
Abrams et al (1998)	US	Hot	277.2 avg. (128.1-1096.4)	
DeOreo (2000)	US	Hot Hot - personal	246.8 (2.6 res) 131.4	94.9
Env Canada (2004) [using hot water proportion from DeOreo et al (2000) and personal use shares from Henze(2002) and DeOreo et al (2000)]*	Canada	Hot-personal		66.5 (59.6-73.5)

Notes: l/d refers to litres per day
* refers to an implied measure calculated from more than one source.
** excluding leaks

Using the estimate of DeOreo and Mayer (2000) that 39.6% of total water use is hot water, an estimate of current Canadian per capita hot water use would be 350 x 0.396 = 138.6

litres/day (range = 106.5 to 181 litres/capita/day) which is much higher than the 1985 values reported by Wiehagen and Sikora (2002a). These values are generally smaller than metered values from a 1994 U.S. study where average per capita daily hot water consumption was 167 litres, with a maximum of 274 litres, excluding leaks (Goldner, 1994). However, in other U.S. studies, per household hot water use was 227.4 litres per day (Henze et al, 2002), or an average of 277.2 litres per day (Abrams and Shedd, 1998).

The proportion of the metered hot water consumption allocated to personal use ranges from 43% (Henze, 2002) to 53% (DeOreo and Mayer, 2000) assuming that 1/3 of hot water from faucets is for personal use.[6] Using the same assumption for faucet use and assuming a dishwasher is present, corresponding proportions calculated from information in Kelso (2003) range from 42% (one-person household), to 58% (two-person household) and 67% (three-person household). However, these figures appear less reliable since the use values presented by Kelso are an amalgamation of information from other sources, and as the household size increases, the amount of hot water required for personal use increases but the amounts required for other activities do not.

Applying the proportions of hot water that are for personal use from Henze (2002) and DeOreo and Mayer (2000) to estimated current per-capita hot water consumption in Canada of 138.6 litres/day yields values for Canadian personal use hot water consumption ranging from 59.6 to 73.5 litres/day per person, or an average of 66.5 litres/day per person. Using an average household size of 2 (as in Henze, 2002) or 2.6 (DeOreo et al, 2000) these Canadian per-capita personal use hot water consumption values yield household personal use average estimates (of

[6] This figure is derived from detailed information on hot water consumption in Henze (2002), assuming that hot water obtained through the kitchen sink faucets is not for personal use.

133.1 and 173.0, respectively) that appear to be approximately 30% larger than household personal use values calculated in U.S. metered studies (Table 8.4).

Since there does not appear to be any information on energy consumption for water heating purposes by Canadian households, it is necessary to utilize US values. Table 6.3 contains US DOE (2000) estimates of average annual energy consumption according to the water heater fuel type. The analysis in US DOE (2000) uses the 1997 Residential Energy Consumption Survey (RECS) as its underlying data source. Key household characteristics, identified in RECS according to the water heater fuel type, are displayed in Table 8.5 along with the US DOE (2000) energy consumption values previously reported in Table 6.3.

Table 8.5: Household Values Underlying US DOE (2000) Calculations

Water Heater Fuel Type	Average Household Size	Average Hot Water Use Litres/day	Water Heater Energy Consumption by Fuel kWh/year (GJ/yr)
Electricity	2.45	171.5	3460 (12.5GJ)
Natural Gas	2.82	188.9	6856 (24.7GJ)
LPG	2.58	173.0	6680 (24.0GJ)
Oil	2.87	179.0	7517 (27.1 GJ)
U.S. Average	*2.68*	*178.1*	

Source: US DOE (2000). Water heating energy consumption values also appear in Table 6.3.

Based on the values in Table 8.4, it appears that the average hot water use values used by the DOE are much lower than those experienced in metered studies in the U.S., and also much lower than estimated hot water use values in Canada. In particular, the estimate of Canadian hot water use of 138.6 litres per person (or its range from 106.5 litres to 181 litres per person), translates into per household consumption (for an average household size of 2.55 persons (Statistics Canada, 2001 Census)) of 353.4 litres/household (with a range from 271.6 to 461.6 litres per household). Compared to the US average hot water use in Table 8.5, the average value in Canada is almost twice as high, while the lowest value, which refers to metered water consumption, is 1.5 times as large as the US average (the highest value is 2.6 times the US average value). This suggests that the water heater energy consumption values in Table 8.5 need to be scaled up by a factor of between 1.5 and 2.6 to obtain corresponding Canadian values.

Estimates of Canadian per-capita energy consumption for personal use can be obtained by multiplying the proportion of hot water consumption allocated to personal use (ranging from 43% to 53%, with an average of 48%) by US water heater energy consumption (scaled by 1.5, 2, or 2.6) after first deducting standby losses (Table 8.3) that are assumed not to be affected by the increased hot water usage in Canada compared to the US, although it is possible that they could be lower in these circumstances). The results of these calculations are presented in Table 8.6.

Table 8.6: Estimated Household Energy Demand for Hot Water for Personal Use in Canada

Water Heater Fuel Type	Scale Factor Applied to US Hot Water Energy Consumption	Proportion of Hot Water Consumption that is for Personal Use		
		43%	48%	53%
Electricity	None	4.1	4.6	5.0
	1.5	6.9	7.7	8.5
	2	9.4	10.4	11.5
	2.6	12.6	14.1	15.5
Natural Gas	None	5.7	6.4	7.0
	1.5	11.3	12.6	13.9
	2	16.2	18.0	19.9
	2.6	22.6	25.2	27.9
LPG	None	5.4	6.1	6.7
	1.5	10.9	12.1	13.4
	2	15.6	17.4	19.3
	2.6	21.9	24.4	27.0
Oil	None	6.6	7.3	8.1
	1.5	12.7	14.1	15.6
	2	18.0	20.1	22.2
	2.6	25.1	28.0	30.9

Notes: In the absence of other information, the standby energy loss for LPG is assumed to be the same as for natural gas.

As can be seen from the values in this Table with no scale factor applied to the DOE energy consumption amounts, the estimated energy that is required for water heating for personal use is less than the value of 10GJ assumed in REUM regardless of whether personal use is assumed to account for 43%, 48%, or 53% of total household hot water consumption. However, this situation changes once the apparently higher levels of consumption of hot water, and hence of energy required for water heating, in Canada are taken into account through a scaling factor. Using an average value of Canadian water consumption (scaling factor of 2), and where personal use accounts for 48% of household hot water consumption, it is seen from the highlighted cells in Table 8.6 that for electric water heaters, the energy that is required for water heating for personal use almost matches the current REUM assumption of 10GJ. However, the energy that is required for water heating for this purpose for all other types of water heaters is somewhat larger than 10GJ. Even taking a more conservative viewpoint and using a scale factor of 1.5 (corresponding to water use just in metered houses) and with personal use at a smaller 43% of total hot water consumption, there is still considerable variation in energy requirements according to the water heater fuel type. In this case, electric water heaters use less than the assumed 10GJ value for personal use water heating, while all other water heater types use more than 10GJ. Thus, it would seem that the assumption in REUM pertaining to energy required for water heating for personal use should be allowed to vary by fuel, and should be modified somewhat from its currently assumed 10GJ value.

8.2.7 Household Energy Demand for Hot Water for Appliances

Within REUM, the water heating energy requirements are considered for two types of water-using appliances, dishwashers and clothes washers. In each case it is necessary to calculate the amount of energy that is required to heat water for use in the appliance. Dishwashers may intake heated water and also heat it further. Clothes washers also intake heated (as well as cold) water but generally do not heat water within the appliance. However, in view of the apparent difficulty in measuring the energy that is required to heat the water prior to its arrival at the appliance, a convenient simplification that is used in REUM with both these appliances involves determining the water heating energy requirements as a proportion of the direct unit energy consumption of the appliance. For dishwashers the proportion that is used is 0.88, while for clothes washers the proportion that is used in REUM is 0.92.

There appears to be relatively limited publicly available information on this variable especially for more recent models. This has also been complicated by the inclusion of clothes drying with clothes washing when calculating efficiency factors in order to reflect the reduced clothes dryer energy needs associated with the use of horizontal axis clothes washers since in this case the clothes have less water content when they are removed from the clothes washer.

Table 8.7 contains historical information pertaining to the proportion of unit energy consumption that is attributable to hot water energy for both clothes washers and dishwashers. For clothes washers, the proportion of unit energy consumption that is attributable to energy required for water heating varies from 0.93 to 0.85. Therefore the REUM assumption of 0.92 is consistent with these 1990, 1994 and 1998 values. For dishwashers, the proportion of unit energy consumption that is attributable to energy required for water heating varies from 0.72 to 0.74. While noting that the dishwasher values reported in Table 8.7 refer to data from 1990 and 1994, the 0.88 value for this proportion that is assumed in REUM appears to be considerably higher than the values found in empirical studies.

Table 8.7: Clothes Washer and Dishwasher Hot Water Energy Consumption

Appliance	Energy Factor EF/MEF [3]	Hot Water Energy Consumption (kWh/yr)	Motor Energy Consumption (kWh/yr)	Water Heating Energy %
Clothes Washer 1990 [1]	0.86 (100% RE) 0.85 (98% RE) 0.67 (76% RE)	1045 1066 1375	103	91 91 93
Dishwasher 1990 [1]	0.36 (100% RE) 0.35 (98% RE) 0.29 (76% RE)	458 467 603	179	72 72 73
Clothes Washer 1994 [2] Clothes Washer 1994 [2]	1.18 1.18	708 548	99 99	88 85
Dishwasher 1994 [2]	0.46	584	211	74
Clothes Washer 1998 [3]		544	75	88

(1) Wenzel et al (1997). These calculations assume 380 cycles/year for clothes washers and 229 cycles/year for dishwashers, and include hot water. The 98% recovery efficiency corresponds to the typical electric water heater while 76% RE corresponds to the typical gas water heater. Hot water load is calculated at a 90°F temperature rise. EF is calculated for a clothes washer capacity of 2.60 cubic feet.
(2) Energy Star (2004) http://www.energystar.bov/index.cfm?c=clotheswash.pr_crit_clothes_washers Note two sources of data for clothes washers are from DOE test procedures and P&G data
(3) US DOE (2000b).

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