Simulation of energy use in residential water heating systems

by

Carolyn Dianarose Schneyer
B.A., Vassar College, 1998

A Thesis Submitted in Partial Fulfillment
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Supervisory Committee

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Dr. Andrew Rowe, (Department of Mechanical Engineering)
Supervisor

Dr. Peter Wild, (Department of Mechanical Engineering)
Departmental Member

Abstract

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Current federal and provincial efficiency standards for residential water heating are based solely on the tested efficiency of individual water heating devices. Additional energy expended or saved as the water cycles through the home is not taken into account. This research, co-funded by British Columbia’s Ministry of Energy, Mines and Petroleum Resources (MEMPR), is a first step toward the Province’s goal of developing a new energy efficiency standard for water heating systems in new construction. This groundbreaking new standard would employ a “systems” approach, establishing guidelines for new construction based on the total energy used for water heating within the building envelope

The research team has developed a Simulink computer model which, using a one-minute time-step, simulates 24-hour cycles of water heating in a single-family home. The objectives of this thesis are to use that model to simulate a variety of water heating technology combinations, and to devise methods of utilizing the resulting data to evaluate water heating systems as a whole and to quantify each system’s relative energy impact.

A metric has been developed to evaluate the efficiency of the system: the *system energy factor* (SEF) is the ratio of energy used directly to heat water over the amount of energy drawn from conventional fuel sources. The CO_2 impact of that energy draw is also considered.

Data is generated for cities in three different climates around BC: Kamloops, Victoria and Williams Lake. Electric and gas-fired tank water heaters of various sizes and efficiencies are simulated, along with less traditional energy-saving technologies such as solar-assisted pre-heat and waste water heat recovery components. A total of 7,488 six-day simulations are run, each representing a unique combination of technology, load size, location and season.

The resulting data is presented from a variety of angles, including the relative impacts of water heater rating, additional technology type, location and season on the SEF of the system. The interplay between SEF and carbon dioxide production is also examined. These two factors are proposed as the basis for devising performance tiers by which to rank water heating systems. Two proposals are made regarding how these tiers might be organized based on the data presented here, though any tiers will have to be re-evaluated pending data on a wider range of technology combinations.

A brief financial analysis is also offered, exploring the potential payback period for various technology combinations in each location. Given current equipment and energy costs, the financial savings garnered by the increase in energy efficiency are not, in most cases, found to be sufficient to justify the expense to the homeowner from a purely fiscal perspective. Additional changes would need to take place to ensure the financial viability of these technologies before large-scale adoption of systems-based standards could be employed.

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Nomenclature

ρ	Density of water, (assumed to be 998 kg/m^3)
BC	The Province of British Columbia
B_{AVE}	Average daily water heating load for baths, litres/day
B_D	Daily water heating load for baths on a weekday, litres/day
B_E	Daily water heating load for baths on a weekend, litres/day
C_{AVE}	Average daily water heating load for clothes washers, litres/day
C_D	Daily water heating load for clothes washers on a weekday, litres/day
C_E	Daily water heating load for clothes washers on a weekend, litres/day
C_p	Specific heat of water, Btu/lb using ºF or kWh/kg using ºC
CaGBC	Canada Green Building Council
CPVC	Chlorinated polyvinyl chloride
CSA	Canadian Standards Association
DWHR	Drain water heat recovery; also called WWHR
DWV	Drain, waste and vent pipes
EF	Water heater energy factor
GFX	Gravity-film heat exchanger
I_{CO_2}	CO$_2$ intensity of a conventional energy source, kgCO$_2$/kWh for electricity or kgCO$_2$/GJ for gas
LEED	Leadership in Energy and Environmental Design
$Load_{AVE}$	Average daily household water heating load, litres/day
$Load_D$	Daily household water heating load on a weekday, litres/day
$Load_E$	Daily household water heating load on a weekend, litres/day
M	Mass of water drawn, lbs or kg
$\dot{m}$	Mass flow rate of delivered domestic hot water, kg/s
n	ith day of year
N	Number of bedrooms and/or residents in a home
NRCan	Natural Resources Canada
PE	Polyethylene
PEX	Cross-linked polyethylene
Q_{dm}	Water heater’s daily energy consumption, Btu or kWh

Q_{DELVD}	Daily delivered energy in a domestic water heating system, kWh
Q_{DW}	Daily recovered energy from drain water heat recovery unit in a domestic water heating system, kWh
Q_{LOSS}	Daily storage tank thermal loss in a domestic water heating system, kWh
$Q_{RESIDUAL}$	Daily residual energy in a domestic water heating system, kWh
Q_{THE}	Total heating energy generated during one day in a domestic water heating system, kWh
Q_{WH}	Daily heating energy generated by main hot water storage tank in a domestic water heating system, kWh
RE	Recovery efficiency of a water heater
REUWS	*Residential End Uses of Water Study*
RSI	SI equivalent value of tank insulation
SDHW	Solar domestic hot water system
SEF	System Energy Factor: ratio of a system’s daily delivered energy over the amount of energy drawn from conventional fuel sources during that day
T_c	Cold inlet water temperature, ºC
T_{inlet}	Inlet water temperature (ºF or ºC)
T_{tank}	Water heater thermostat setpoint temperature (ºF or ºC)
T_s	Delivered domestic hot water temperature, ºC
TMY	Typical mean year
TRNSYS	Transient Energy System Simulation Tool
$\mathbf{v_i}$	Instantaneous volume flow rate of delivered hot water to the ith plumbing fixture, m^3/s
WHAM	Water heater analysis model developed by Lawrence Berkeley National Laboratory
WWHR	Waste water heat recovery; also called DWHR

Acknowledgments

First and foremost I would like to thank Dr. Andrew Rowe, whose guidance, patience and unyielding confidence kept me on track even when my own confidence waned. Truly, I could not have asked for a better supervisor. Many thanks also to my collaborator, Brian Li, whose contributions made much of this research possible. Sue Walton and Peggy White of IESVic provided kinship and support above and beyond the call of duty. Funding was provided by the UVic/MEMPR Partnership. Andrew Pape-Salmon and Katherine Muncaster at the BC Ministry of Energy, Mines and Petroleum Resources provided guidance and inspiration. Thanks also to Susan Fiddler of the UVic Co-op Program for support in my work with MEMPR.

And, finally, thanks to Leah Schneyer-VanZile for mirth and perspective, and to Hank VanZile, for so much more. Bacon.

Dedication

For my family.

Chapter 1

Introduction

1.1 Residential water heating standards

In Canada, water heating accounts for 18% of energy use in the residential sector [1]. The existing standards for residential water heating establish energy factor (EF) ratings for individual water heating appliances; current Canadian federal regulations for water heating are based either on that EF or on a water heater's maximum standby losses [2]. Additional energy expended or saved as the water cycles through the home, however, is not taken into account. Storage, distribution, heat recovery, incorporation of renewable energy and other factors external to the water heater itself may all have significant impact on the overall efficiency and energy impact of the system, yet none are officially accounted for under the current rating structure. This not only gives an inaccurate representation of the water heating efficiency of a given home, but does little to increase incentive for innovation or implementation of energy saving measures external to the water heater.

1.2 A systems-based approach

The Province of British Columbia (BC) has its own minimum performance standards for water heating, more stringent in some cases than the federal regulations, but still based upon the performance of the water heater itself. BC's Ministry of Energy, Mines and Petroleum Resources (MEMPR), however, wishes to explore the possibility of expanding its means of evaluating water heating to include not just the water heater but the other technologies involved in reducing the energy impact of heating water as well [3].

The Ministry’s goal is to develop a new energy efficiency standard for hot water systems in new construction under BC’s Energy Efficiency Act. This new standard would employ a “systems” approach, quantifying the total energy used for water heating within the building envelope. The objectives of establishing this standard include improving the efficiency of water heating systems, minimizing energy losses in the distribution of hot water through a building, and integrating measures such as solar-thermal heating and heat recovery into the design of water heating systems. A systems approach would give credit for innovations such as:

- pre-heating water with solar thermal energy,
- incorporation of heat recovery from waste water using gravity film exchanger technology,
- elimination of storage tanks,
- incorporation of a heat pump water heaters,
- changes in pipe configuration such as: reduction of length, location within a heated space, or insulating piping,
- use of combined space and water heating devices, and/or
- water conservation devices at the tap.

Quantifying the energy impact of these measures would inform further work by the Canadian Standards Association (CSA), a not-for-profit association responsible for establishing standards by which to test and classify products. CSA may then develop a standard by which to evaluate the energy efficiency of a hot water system design. This may involve establishing a menu combining various water heater types with other energy-saving measures, and designating standardized tiers of efficiency for each technology combination.

Once established, a systems-based standard, and the performance tiers therein, could be used by industry to develop new technologies and system designs, by utilities to develop demand-side management programs and by governments to set energy efficiency policies regulating water heating in new construction. A similar approach has been used for the design of lighting systems in commercial establishments under the ASHRAE 90.1 standard for lighting power density, allowing for the use of daylighting, better fixtures or more efficient equipment as a means of meeting the standard [4].

The formal establishment of performance tiers can also provide a market incentive for builders to incorporate energy efficient water heating technologies into new construction, even outside of any regulation or external requirement. Without a standard in place, a builder has little financial incentive to incorporate an energy efficient water heating system into design and construction. Any potential increase in construction expense can only be justified if the buyer will be willing to shoulder the burden of that expense. The eventual homeowner may benefit financially from the increased efficiency, but without a standard or rating system the builder has no way to quantify that savings to a potential buyer, and therefore may not be able to meet any increase in construction costs with a comparable increase in asking price. One such rating system that has been successful in quantifying energy savings to both builders and consumers is the Leadership in Energy and Environmental Design or LEED® system, developed by the U.S. Green Building Council and adopted by the Canada Green Building Council in 2004 [5].

1.3 Thesis scope, objective and outline

This research represents a first step toward a systems-based standard for energy use in water heating. The objective of this thesis is to evaluate the relative energy efficiencies of a variety of water heating systems and technology combinations, which may then be used to establish system performance tiers. The scope of this research does not include every possible energy saving measure that may be employed in residential water heating, but begins by simulating both electric and gas-fired storage tank water heaters of varying efficiencies and combining them with energy saving technologies such as solar-assisted preheat and waste water heat recovery components. The evaluation methods developed in this study should beget further research using more complex combinations of technology. Ultimately, work stemming from this study may inform testing and decision-making by the CSA.

The creation and validation of the simulation tool is described in detail in the 2011 Master's thesis of Brian Li [6]. The work described in the following chapters uses that model to simulate a variety of water heating systems, using a range of hot water loads in two different seasons and in three different locations around the Province of British Columbia. The results are used to evaluate water heating systems as a whole and to quantify each system's relative energy, cost, and emissions impact.

A brief outline of what follows is included here. Chapter 2 provides background information on domestic water heating and on the technologies being simulated, as well as details on current energy efficiency standards for domestic water heating. Chapter 3 reviews relevant literature, including previous water heating simulations and studies of energy use in domestic water heating. A brief description of the simulation model and its key outputs are presented in Chapter 4. Chapter 5 provides an in-depth look at the hot water load profiles used in the simulation and the methods used to derive them. Results of the simulations are presented in Chapter 6, broken down by a variety of factors. Chapter 7 uses the data to provide a financial analysis and synthesizes the most salient points from Chapter 6. Potential sets of tiers are proposed, and the possibility of translating the work to jurisdictions outside the Province is discussed. Finally, in Chapter 8, conclusions are presented and recommendations for future work are made.

Chapter 2

Background

This chapter presents background information about residential plumbing and water heating technologies relevant to this study.

2.1 Residential plumbing systems

The primary components of a residential plumbing system are supply pipes for both hot and cold water, and drain, waste and vent (DWV) pipes which manage water outgoing from the building (Figure 1).

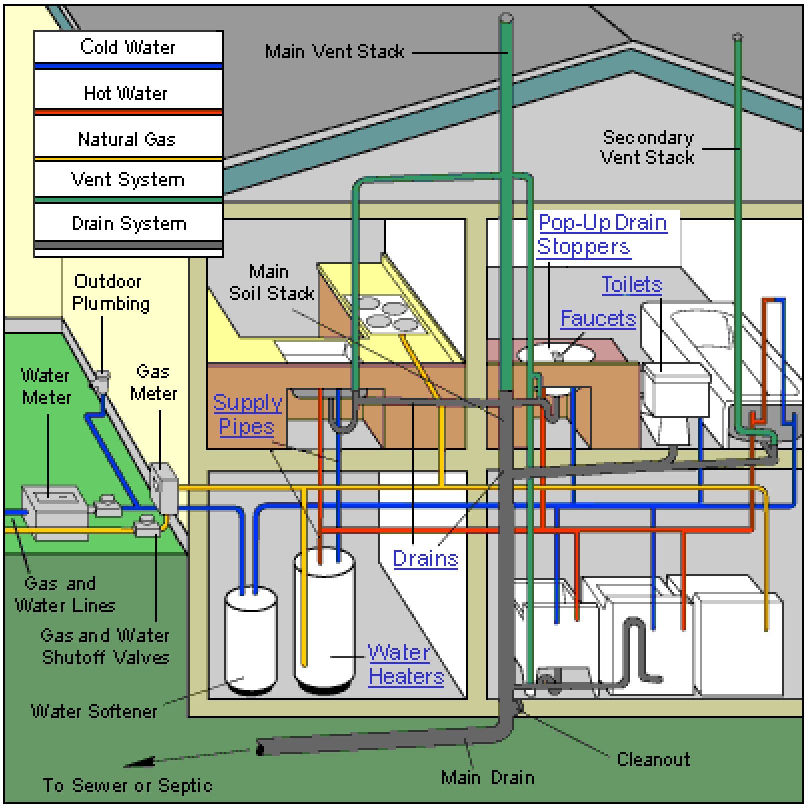

Figure 1: Residential plumbing system with gas-fired tank water heater [7].

In a detached residential building, a water heater is connected directly to the external water line, which supplies cold water to the home from the water company or municipality. One line of cold water branches off to become an inlet to the water heater while the rest goes on to supply cold water to the home. A hot water outlet line runs out of the heater to feed the hot water taps in the home. The hot and cold supply pipes and their respective branches usually run parallel to one another. The water lines are under constant pressure; water flows out at a tap or fixture when the tap is opened and pressure is released.

The DWV system uses both gravity and pressure to carry waste water away from fixtures. U-shaped traps below the drains hold a measured amount of standing water, which keep sewer gases from backing up into the home. A vent pipe extends out above the roof of the building, allowing air to enter the drain pipes and maintain an equalized pressure inside them, which keeps the waste water from flowing back past the traps to the fixtures.

While pipes in older buildings may be made from galvanized steel, iron or even lead, modern pipes are generally constructed either from copper or cross-linked polyethylene (PEX). Copper piping is often considered ideal for supply lines as it is resistant to corrosive elements, high temperatures and high pressure and generally maintains its structural integrity with age. It is also biostatic, so bacterial growth is inhibited. PEX piping, which is generally less expensive than copper, is most commonly used in DWV systems, though it may often be used as supply piping as well. PEX is also quite resistant to temperature extremes and maintains a smooth surface over time. Resistance to corrosion is particularly important in DWV systems because surface irregularities inside a pipe can impede the downward flow of waste water and sewage. Other pipe materials such as polyethylene (PE) or chlorinated polyvinyl chloride (CPVC) may also be used depending on local plumbing codes [8-10].

2.2 Water heaters and alternative technologies

2.2.1 Storage tank water heaters

Traditional water heaters (Figure 2) take in cold water, heat it to a preset temperature (typically ~60˚C in Canada), and hold it in a glass-lined, steel storage tank to be distributed when a hot water tap is opened. As the hot water exits through an outlet near the top of the tank, more cold water flows into the tank to be heated and stand ready yet again. The cold water enters the tank through a dip tube, which usually empties at the bottom of the tank near the heat source. A thermostat senses any drop in the temperature of the tank and activates the heating component: a burner in the case of gas or oil-fired water heaters, and electrical heating elements in the case of electric water heaters.[1] Foam insulation in the walls of the tank helps to keep the water from cooling as it stands in wait, and an anode rod, often made from magnesium, attracts oxidizing ions to prevent the tank from corrosion [8,11].

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[1] Oil-fired storage tank water heaters also exist; however, because they make up less than 1% of tank water heaters currently sold in Canada [12], they have not been considered here.

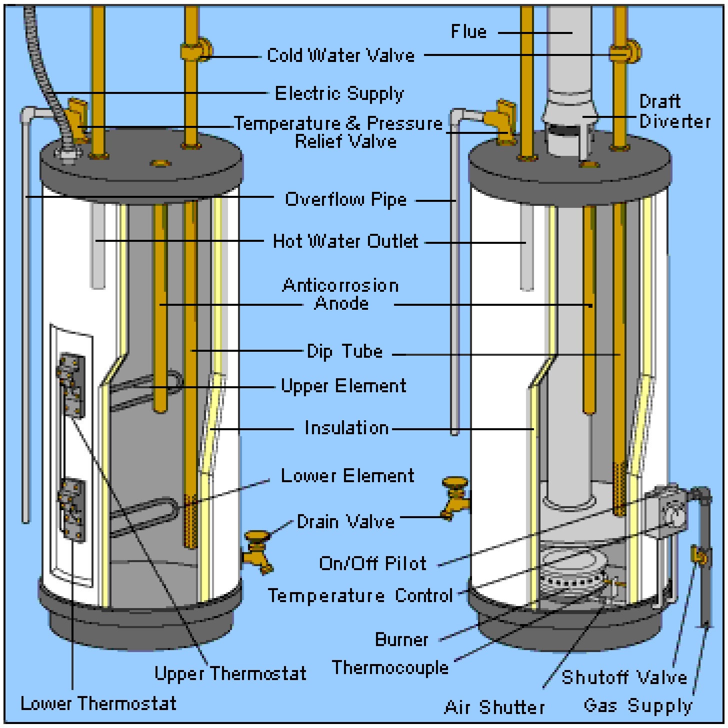

Figure 2: Storage tank water heaters; electric at left, gas at right [7].

Storage tank heaters make up the vast majority of residential water heaters sold in North America, more than 95% of the market in both Canada and the US. Though they are the standard, they unfortunately tend to be inferior to alternative technologies when it comes to energy efficiency. This is due to the inevitable heat loss that occurs as the hot water sits waiting to be used. To keep the water at a constant, high temperature requires repeated heating over time and additional energy expenditure by the heating component. Numerical details regarding energy standards in tank water heaters will be explored in section 2.3 [11,13].

2.2.2 Solar-assisted water heating

The incorporation of a solar domestic hot water (SDHW) system is one potential strategy for reducing the amount of electricity or fuel required to heat water in a home.

SDHW systems generally consist of three main components: a solar collector which converts solar radiation into heat energy, a heat exchanger module which transfers the heat from the collector to the water, and a storage tank to hold the water once it has been heated. In most cases, an auxiliary water heater is also needed to compensate for any shortfall between the demand and the amount of water that can be heated via solar energy. Other components such as pumps or mixers may also be included depending on the system.

A variety of solar collector technologies are available and may be chosen based on what is most appropriate for a given climate. Unglazed collectors are efficient with warm ambient temperatures, while glazed collectors are better for moderate to cool climates, and evacuated tube collectors for even colder climates. A glazed flat-plate collector (Figure 3) was chosen for this simulation because it is both the simplest variety and the type most commonly used in Canada.

Collectors are mounted on a south-facing slope or roof and connected to a storage tank. A heat transfer fluid – potable water in the case of a direct system or another fluid such as propylene glycol in the case of an indirect system – passes through the collector and is heated by the solar radiation. The heated fluid is circulated to a heat exchanger which transfers the energy to the water in the storage tank.

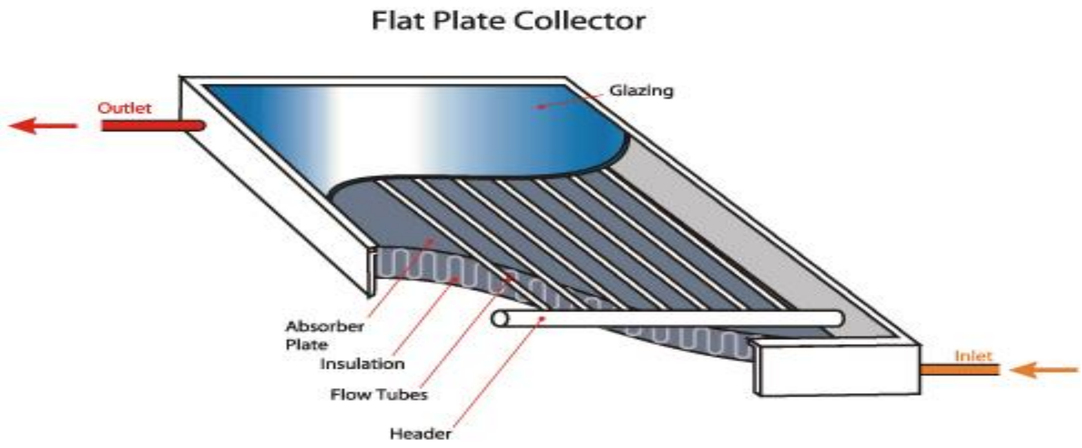

Figure 3: Cutaway view of a glazed flat-plate collector [14].

Solar-heated water is stored in an insulated tank. This tank may be larger than a storage tank used by a conventional water heater, because solar heat is available for use only during the day and sufficient hot water must be available to meet both evening and morning demand. An auxiliary heat source may be included as part of the storage tank, or added on as a separate component [15-19].

2.2.3 Waste water heat recovery

Waste water heat recovery (WWHR) or drain water heat recovery is a method of harvesting the heat from already-warmed waste water – also called greywater - as it flows down the drain. A heat exchanger (Figure 4) made of copper piping, often called a gravity-film heat exchanger (GFX), is coiled tightly around the drain pipe. Cold water from the external water line flows through the coil before entering the water heater. As warm waste water flows down the drain some of its heat is transferred to the cold water in the coil, which then enters the water heater preheated. Water heating systems get the most benefit from GFX technology when it is used in situations where warm water is flowing down the drain simultaneously with more warm water being demanded at the tap, such as in a shower [20-21].

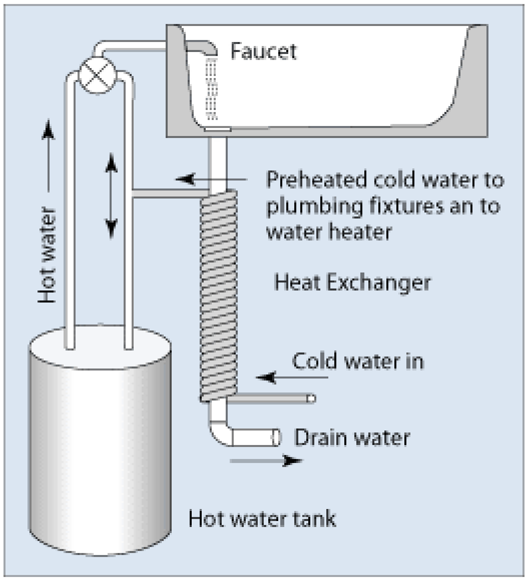

Figure 4: Waste water heat recovery uses a heat exchanger to preheat cold water before it enters the water heater [20].

2.3 Energy efficiency standards in water heating

As noted in section 1.1, one criterion for evaluating the efficiency of a water heater is its energy factor (EF), defined by the CSA Standard C745-03 as “the ratio of the energy supplied in heating water daily to the total daily energy consumption of the water heater” [22]. The formula for calculating EF is also included the CSA standard, and is broken down into straightforward terms in a 2000 publication by the US Department of Energy (DOE) [23]:

$$EF = \frac{M \bullet C_p \bullet \left(T_{tank} - T_{inlet}\right)}{Q_{dm}} \tag{1}$$

where:

EF = energy factor
M = mass of water drawn (lbs or kg)
C_p = specific heat of water (Btu/lb using ºF or kWh/kg using ºC)

T_{tank} = water heater thermostat setpoint temperature (ºF or ºC)
T_{inlet} = inlet water temperature (ºF or ºC)
Q_{dm} = water heater's daily energy consumption (Btu or kWh)

The Province of British Columbia instituted new efficiency standards for storage tank water heaters, effective 1 September 2010. Current Canadian federal regulations correspond to an EF ≥ 0.59 – 0.0005*tank volume for oil-fired storage water heaters and EF ≥ 0.67 – 0.0005*tank volume for gas-fired storage water heaters. The new BC standard is stricter than this with EF ≥ 0.70 – 0.0005*tank volume for both oil and gas-fired heaters [2, 24]. The federal standard, however, is currently under review and is likely to become more stringent in coming years. Proposed increases to minimum performance levels would give residential gas-fired heaters a minimum EF of 0.75 – 0.0005*tank volume possibly as early as 2013 and an EF of 0.80 – i.e. a complete switch to tankless water heaters - as early as 2016. Oil-fired water heaters would increase to an EF ≥ 0.68 – 0.0005*tank volume possibly as early as 2015 [25].

For electric water heaters the situation is somewhat less straightforward. US DOE estimates typical EFs for electric storage tank water heaters in the range of 0.90–0.95. Canadian regulations, however, are based not on EF but instead on a maximum standby loss calculation which varies by tank size.[2] For electric storage tanks with a top inlet, the new BC standard is stricter than the federal regulation; for those with a bottom inlet, it is commensurate with the federal regulation. (Table 1) [2, 11, 26].

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[2] NRCan's move away from EF as a regulatory factor for electric tank water heaters was based largely on a 2003 study by Healy, et. al demonstrating variability in EF test results between labs [27, 28]

Table 1: A comparison between Canadian federal regulations for electric storage tank water heaters and those enacted by the Province of British Columbia in 2010 [2, 26].

Inlet	Tank Size	Federal Regulated Standby Loss (watts)	2010 BC Regulated Standby Loss (watts)
Top	50 to 270 litres	≤ 35 + (0.20*tank vol)	≤ 25 + (0.20*tank vol)
Top	>270 to 454 litres	≤ (0.472*tank vol) – 38.5	≤ (0.472*tank vol) – 48.5
Bottom	50 to 270 litres	≤ 40 + (0.20*tank vol)	≤ 40 + (0.20*tank vol)
Bottom	>270 to 454 litres	≤ (0.472*tank vol) – 33.5	≤ (0.472*tank vol) – 33.5

While equipment specifications are important in determining energy consumption, actual system configurations, use patterns and loads are also important. The following chapter will review system studies relevant to this thesis while domestic hot water loads will be discussed in detail in Chapter 5.

Chapter 3

Related Studies

The following is an overview of other recent work attempting to quantify energy consumption in residential water heating. Most of the works considered use numerical computer models, which inform the development of the model created here. Although the goals of each study are similar in a general sense, there is variation in the focus and methodology used in each model. The final study is a real-world test of various water heating technologies, the goals of which are closely aligned with those of the simulations performed for this research.

3.1 WHAM

The water heater analysis model (WHAM) is a tool developed by James Lutz and colleagues at the Lawrence Berkeley National Laboratory in Berkeley, California in 1999 [29, 30]. WHAM calculates average daily energy use by water heaters in residential scenarios. It does not consider details of individual water use events, but rather assumes broadly defined use patterns for each 24-hour trial: for the first six hours, water is drawn every hour, in equal amounts; for the last eighteen hours, the water heater is left in standby mode and energy losses are measured. Losses incurred after the heated water leaves the tank are not considered.

WHAM is primarily useful for estimating the relative energy use associated with different models of water heater under similar conditions. Four variables are used to simulate operating conditions: daily draw volume, setpoint of water heater thermostat, inlet water temperature and ambient air around water heater. The values assigned to these variables are shown in Table 2.

Table 2: Values of operating condition variables used in WHAM.

Daily Draw Volume, gallons (litres)	Thermostat Set Point, °F (°C)	Inlet Water Temp, °F (°C)	Ambient Air Around Tank, °F (°C)
3 (11)	110 (43)	40 (4)	40 (4)
30 (114)	135 (57)	58 (14)	67.5 (19.7)
64.3 (243)	180 (82)	80 (26)	90 (32)
75 (284)			
150 (568)			

For each draw volume, 26 simulations are performed using different combinations of the other three variables. Extremely high or extremely low variable values are included for illustrative purposes only.

The baseline gas water heater model simulated is a bottom-fired, 40 gal (151 L) unit with a heat input of 40,000 Btu/hr (11.72 kW), and EF of .54 (the minimum allowed at the time) and a recovery efficiency (RE: a ratio of the energy added to the water as compared to the energy input to the water heater) of .76. Other sizes used are 30 gal (114 L) and 100 gal (378 L). The baseline electric water heater simulated is a 50 gal (189 L) tank with a rated input of 4.5 kW, an EF of .86 (also the legal minimum at the time of the study; as noted in Chapter 2, EF is no longer used as a benchmark for electric water heaters in Canada) and an RE of .98. Other tank sizes are 30 gal (114 L) and 80 gal (303 L).

The WHAM study does not list in detail the results derived from various simulations (only sample calculations are shown), but instead aims to validate the model by offering comparisons between the WHAM results and those from other, more detailed simulation models, including a gas-fired water heater simulation model (GWHSM; [31] as cited by

Lutz et al.), an electric water heater simulation model (EWHSM; [32] as cited by Lutz et al.) known more commonly as WATSIM and a simplified water heater simulation model (SWHSM; [33] as cited by Lutz et al.). To that end, the results of WHAM and GWHSM agree to within 3-5% of one another, agreement between WHAM and EWHSM is within 3%, and agreement between WHAM and SWHSM is within 2%.

3.2 Wiehagen and Sikora

A 2002 study by Wiehagen and Sikora of the US National Association of Home Builders Research Center (NAHBRC) [34] models water heating systems in residential homes to determine the potential energy savings between them. The modeling is done using TRNSYS (Transient Energy System Simulation Tool) software. Much of the emphasis in this study is on piping and the distance the water must travel to reach the faucet. Four different systems are considered, all of them powered by electric water heaters, and each building upon the modifications of the last to be incrementally more efficient: the base case system uses a 65 gal (246 L) tank water heater located in a utility room, the second replaces the tank heater with a demand heater, the third moves that heater to a more centrally located place, and the fourth replaces the tree distribution piping system with a parallel piping system. Two types of load sets are profiled: a low use home (ranging 15-41 gal or 57-155 L per day) and a high use home (ranging 66-86 gal or 250-326 L per day). One year's worth of activity is simulated.

In this simulation, replacing the tank heater with the demand heater results in an annual energy savings of 10% for the high use home and 24% for the low use home; moving the heater to a central location increases the savings to 13% over the base case in the high use home and 29% in the low use home, and changing to a parallel piping system increases the savings further to 17% in the high use home and 35% in the low use home. Though the total energy expenditure simulated in each scenario is not specifically spelled out, as this is not the study's focus, one can extrapolate that the base case high use home expends roughly 5412 kWh/year or 14.8 kWh/day and the low use home roughly 2334 kWh/year or 6.4 kWh/day. Wiehagen and Sikora list the addition of solar hot water preheat and a drain waste heat collector as further recommended variations. A follow-up study [35] was published the following year, in which the simulated trials are tested in a laboratory setting.

3.3 Wendt, Baskin and Durfee

Wendt, Baskin & Durfee [36] with the Oak Ridge National Laboratory in Tennessee conduct a numerical simulation using LabVIEW software, evaluating hot water distribution systems in both new and existing homes. Two load patterns are tested, one simulating each draw as a "cold start" and another grouping the draws as "clustered uses," wherein some water remains hot in the pipes between draws. More than 250 scenarios are studied, including five different building archetypes for new construction and two for existing buildings. Variables in the hot water distribution systems for new construction include piping materials and insulation, location of the water heater, pipe configuration (parallel as opposed to standard trunk and branch piping), and the addition of demand-actuated or continuous recirculating systems.

Like the Wiehagen and Sikora study, this study focuses heavily on piping. Also emphasized is the amount of water that is discarded by the user while waiting for hot water to reach the tap. Energy use is measured mostly in direct correlation with the wasted water, that is, energy wasted by virtue of the (previously hot) water being wasted.

3.4 WATSUN

WATSUN [37] is an open-source tool developed by Ontario's University of Waterloo for the purpose of simulating active solar assisted domestic water heating systems. Simulations are performed on an hourly basis based on operating conditions defined by the user, including weather data. The solar collector, solar heat exchanger and connecting pipes are each modeled separately.

WATSUN was used to validate the solar component of the model used for this research, and is discussed in further detail in the Master's thesis of Brian Li [6].

3.5 SaskEnergy water heating trials

SaskEnergy, the natural gas utility for the Province of Saskatchewan, conducted a set of trials between 2008 and 2010 to examine the performance and costs of various technologies intended to reduce energy use in water heating [38]. Eleven households of various sizes participated in the trials. Natural gas consumption by the water heater was monitored in each household for at least three months before the new technology was installed and for a year after installation. Among the technologies tested were instantaneous water heaters, condensing water heaters, solar domestic hot water (SDHW) systems, drain water heat recovery (DWHR) units, and water heater blankets.

Based on the annual energy savings generated in each household, *simple payback* for each technology combination was calculated, using a natural gas price of \$0.2948/m^3 (~\$8.4/GJ) and an extremely escalated price of \$1.00/m^3. At the lower fuel price, none of the technologies reached *simple payback* in less than 30 years – well beyond the expected lifetimes of the technologies - with all the SDHW options and several of the DWHR options stretching upwards of 100 years. It was concluded that for any of the technologies to be attractive from a financial standpoint, either the price of fuel would have to increase significantly or the cost of the technologies would have to decrease.

Because the goals of the SaskEnergy study are so closely aligned with the goals of this simulation, some of the analysis methods utilized by SaskEnergy inform those used here. The simulations discussed earlier in this chapter similarly inform the structure of the computer model developed for this research. This structure is outlined in Chapter 4.

Chapter 4

Model

The following is an overview of the computer model used in this research and the key outputs generated by it.[3]

4.1 Parameters and components

4.1.1 Basic structure

This model was built using MatLab and Simulink technical computing software. Variables for a given run are defined using an Excel spreadsheet, and the results output to Excel as well. These platforms were chosen over others used in some of the simulations discussed in Chapter 3, such as TRNSYS or LabVIEW, because of the versatility they offer and because their ubiquitousness increases the potential for an easy transition of the model to a wider group of users, such as staff at MEMPR.

The model simulates water heating in a detached, single-family home using a one-minute time-step, beginning at midnight and ending at 23:59 after a set number of days. The start and end date are specified by the user. The model iterates to simulate a variety of distinct water heating systems for the specified time period, each utilising a distinct combination of variables which are pre-defined by the user. The variables defining each distinct system include water heater model and fuel source, solar pre-heat component sizes and the presence of a waste water heat recovery component. These variables and the parameters used to define them are discussed in sections 4.1.3 – 4.1.5. The user also

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[3] An exhaustive set of information on the model's architecture and system components, the calculation of metrics, and validation of the model has already been documented in the Master's thesis of Brian Li [6]. For further details on these subjects, please refer to that work.

selects from a range of twelve potential load profiles, which will be discussed at length in Chapter 5.

One important distinction that is made in this model is the difference between water heating energy demanded at the fixture and that which is actually delivered to the fixture. Even when a water heating system is sized appropriately for a home, unmet loads may occasionally occur, and it is useful to build in the capacity to see when water heating loads are not fully met and the size of the unmet load. A high-resolution model with a short time-scale provides the capacity to do so. Although it is not a crucial characteristic of the simulations presented in this research, the ability to quantify unmet loads may prove useful in future studies.

An important factor defined by the user is the location to be simulated. The current model includes three location options in British Columbia: Victoria, Kamloops and Williams Lake. The weather data used to represent these cities originates from WATSUN's typical mean year (TMY) weather database which reflects the average weather conditions over a 20 year period [37]. These cities were selected because they represent three relatively different climates within the Province. Ideally, a more northern community such as Dawson Creek would have been included, but unfortunately a complete set of comparable weather data for this area could not be found. Inlet water temperatures are assumed to be 10ºC, 14ºC and 12ºC in Victoria, Kamloops and Williams Lake respectively in the summer, and 4ºC uniformly in the winter.

In this initial version of the model, the spatial parameters of the home and configuration of the pipes are assumed to be the same for all systems. Assumptions regarding pipe sizes and properties are listed in Table 3:

Table 3: Assumptions regarding pipes in the model

Pipe outer diameter:	25 mm
Pipe inner diameter:	15 mm
Convection coefficient of air:	10 W/m^{2}K
Thickness of pipe insulation:	15 mm
Thermal conductivity of pipe insulation:	0.02W/M-K
Indoor pipe length:	10 m
Outdoor pipe length:	20 m

In addition to these assumptions, the temperature field distribution of the water inside the pipe is assumed to be constant, i.e. the temperature of the water is the same at all points inside the pipe. While this does not necessarily provide the most accurate representation of water temperature within a pipe, it helps to limit the parameters of this initial model. In future versions of the model, adding variables for size of home and length, configuration and parameters of pipes, as well as adding a more robust representation of temperature distribution within the pipes, would probably provide additional insight.

4.1.2 Energy flow modeling

The daily energy flow as simulated within this model is depicted in Figure 5:

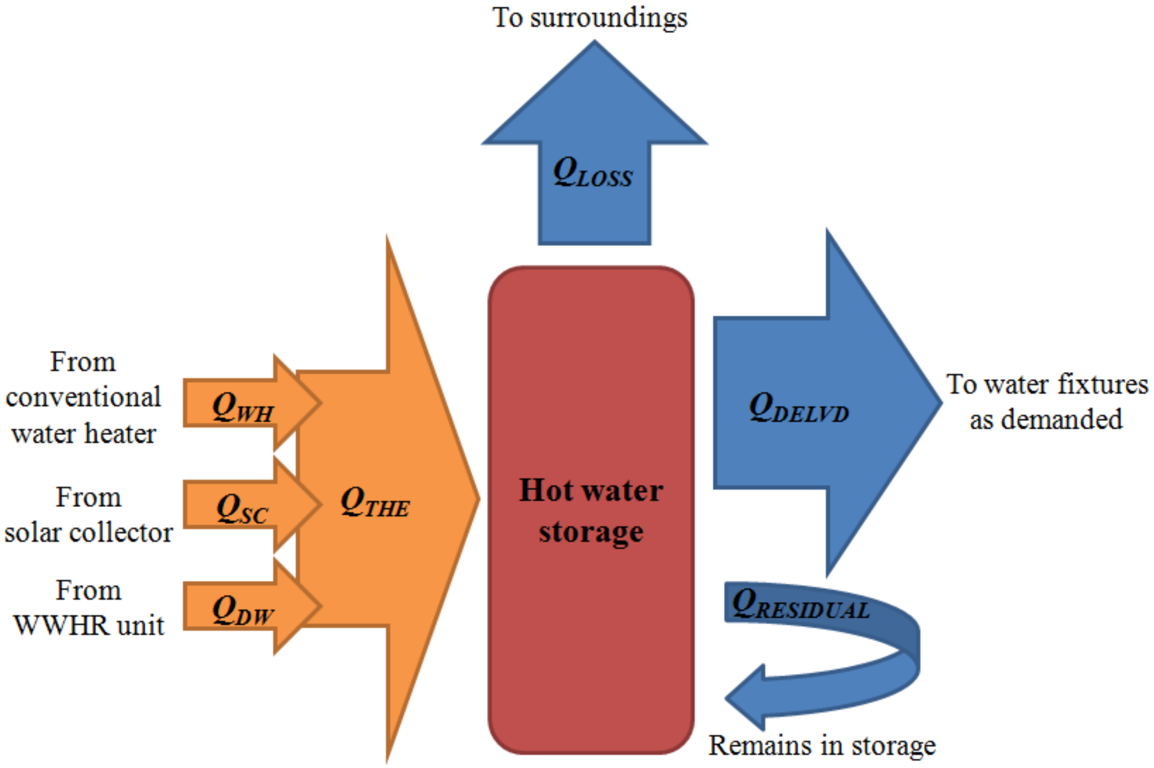

Figure 5: A graphic representation of daily energy flow within the water heating model.

The *total heating energy* or Q_{THE} (kWh) is the sum of energy flowing into the storage tank (Equation 2). In the current model, this is made up of energy from the conventional water heater, Q_{WH}, drawn from gas or electricity; energy from the solar collector (if a solar preheat component is present), Q_{SC}; and energy recovered via waste water heat recovery (again, if a component is present), Q_{DW}, all measured in kWh.[4]

$$Q_{THE} = Q_{WH} + Q_{SC} + Q_{DW} \tag{2}$$

The *daily delivered energy*, Q_{DELVD} (kWh), is the thermal energy delivered by the water

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[4] Although energy from natural gas is typically measured in GJ, all conventional energy expenditures in this study are measured in kWh so that comparisons between electric and gas-based water heating systems may more easily be drawn.

heating system to the fixtures in a 24-hour period. The value of daily delivered energy depends upon the daily hot water usage profile, the cold water inlet temperature and the actual delivered hot water temperature. It is shown as:

$$Q_{DELVD} = \int \left(\dot{m} C_p\right)_s (T_s - T_c)\, dt \tag{3}$$

where ($T_s – T_c$) is the temperature difference between the actual delivered hot water and the cold inlet water, and $\dot{m}$ is the mass flow of the delivered hot water, defined as:

$$\dot{m} = \rho * \sum_{i=1}^{n} \dot{V}_i \tag{4}$$

where ρ is the density of water (998 kg/m^3), and $\sum_{i=1}^{n} \dot{V}_i$ is the instantaneous total volumetric flow rate of hot water delivered to ‘*n*’ plumbing fixtures.

Energy flowing out of the tank also includes that which is lost to the surrounding area in a 24-hour period, Q_{LOSS} (kWh). Losses may arise as *standby losses*, occurring as the storage tank sits idle, or as *pipe losses*, lost as the heated water sits in or moves through the pipes to its destination fixture.

It is possible for the temperature inside a storage tank to be higher at the end of the day than at the beginning, particularly if a large of amount of solar energy has been accumulated. This excess energy, accumulated but not delivered to fixtures, is called *residual energy* or $Q_{RESIDUAL}$ (kWh). Thus from an energy balance standpoint, the total heating energy can also be represented as:

$$Q_{THE} = Q_{DELVD} + Q_{LOSS} + Q_{RESIDUAL} \tag{5}$$

If the total inflow of energy to the storage tank is smaller than the outflow, then the tank temperature decreases and an unmet load may occur.

4.1.3 Water heater component

Tank water heater models included in the simulation are fueled either by natural gas or by electricity. These two fuel sources were selected because the vast majority of residential-scale tank water heaters sold in Canada fall into one of these two categories. According to a 2009 report by Caneta, electric water heaters represent about 60% of annual sales and gas-fired water heaters about 40%. Oil-fired water heaters represent less than 1% of residential water heater sales, and were therefore not included in the scope of this model [11].

Tank water heaters were selected from NRCan's database of existing models [39, 40]. 151 L (40 gal) and 189 L (50 gal) water heaters were chosen, as they are among the most common sizes used in single-family homes [11]. For both gas and electric simulations, several different models of tank water heater were selected in each of these sizes. The models selected represent a range of performance levels.

For gas-fired water heaters, the minimum EF currently regulated in BC is .62 for 151 L tanks and .61 for 189 L tanks, and the Energy Star qualifying EF is .67 for both sizes [24], hence a selection of water heaters falling within these ranges were chosen.

For electric water heaters, Canadian regulations are based on standby loss, as discussed in section 2.3, though American regulations still use EF. For sake of comparison with the gas-fired models, the electric models chosen are listed by their roughly equivalent EF, as stated by the manufacturer. For both sizes, the minimum regulated performance is equivalent to about .91 EF and the Energy Star level is about .95 EF [26], so a selection of water heaters within this range were chosen.

In total, seven gas-fired water heaters (three 151 L and four 189 L) and six electric water heaters (three in each size) were simulated. Complete specs for all water heater models used in this simulation are listed in Appendix A.

4.1.4 Solar pre-heat component

The solar collector chosen to be simulated is a glazed liquid flat-plate collector manufactured by Thermo Dynamics Ltd., a Nova Scotia-based company. Industry practice recommends one solar collector panel for households with daily hot water consumption of less than 250 litres per day, and two solar panels for households with daily hot water consumption greater than 250 litres per day [41]. Because, as will be discussed in Chapter 5, some of the load profiles in this simulation fall below 250 litres per day while others are more than double that amount, both one and two-panel as well as three-panel solar collectors were simulated. Each panel has a collection surface area of 2.783 m^2. The panels are assumed to be arrayed in a parallel arrangement, each operating under the same working conditions. The solar panels are assumed to be installed at a fixed slope of 49º with a surface azimuth angle of 0º.

4.1.5 WWHR component

The waste water heat recover component simulated here is based on model G3-40 manufactured by GFX. The parameters of this model were found to be optimal for the water flow rate generated in this model, based on the parameters outlined by Zaloum et al. [21].

4.2 Metrics

4.2.1 System energy factor

In order to quantify the relative energy efficiency of a complete water heating system, it is necessary to define an indicative metric. The metric that has been formulated to be the primary means of evaluating a water heating system is a modified version of the water heater EF, shown previously in Equation 1. This metric is known as the *system energy factor* (SEF), and is defined in Equation 6:

$$SEF \equiv \frac{Q_{DELVD}}{Q_{WH}} \qquad \left(\frac{kWh}{kWh}\right) \tag{6}$$

Like the EF, the SEF is a ratio of the daily hot water energy to the energy drawn from conventional fuel sources during that day; in this case, the ratio of daily delivered energy to the energy supplied by the conventional water heater. Yet because here Q_{WH} may only be a fraction of the total energy supplied to heat the water, the SEF quantifies the fuel efficiency of the system as a whole. In a *base case* system, where the conventional water heater is the sole energy source, this ratio will be less than one as some of the input energy will be lost to the surroundings. With the addition of alternative water heating technologies, however, there is energy input from other sources, thus Q_{WH} decreases as portions of the demand are met by these other sources, and the SEF increases accordingly.

4.2.2 CO_2 emmissions

Because reduction of GHG emissions is one of the goals of increasing energy efficiency, it is useful to quantify the amount of CO_2 emissions generated by a given system. Thus CO_2 emissions are a secondary metric for system evaluation. The quantity of CO_2 emitted in kg/day is calculated by Equation 7:

$$CO_2 = I_{CO_2} * Q_{WH} \tag{7}$$

where I_{CO_2} is the *CO_2 intensity* of a conventional energy source. The CO_2 intensity varies with the fuel source. When the system's conventional energy is electricity, the assumed value for CO_2 intensity in BC is 0.036 $kgCO_2$/kWh [42]. If the system's conventional energy is natural gas, the standard value for CO_2 intensity is 49.7 $kgCO_2$/GJ [42].

Chapter 5

Load

Domestic hot water consumption can be a difficult thing to quantify. Hot water use can vary dramatically from one household to the next. In constructing load scenarios for this research, the goal was to create several profiles representing different types of use. Hot water load profiles represent two-person and five-person households, each with variations for low, medium and high water usage. Because patterns and volumes of water use can differ significantly between weekdays and weekends, scenarios are created to simulate both. Twelve load scenarios are created in total. The following is an overview of related studies, followed by a discussion of the methods employed in constructing the load scenarios.

5.1 Related work

One of the few consistent things about load data is the broad variation measured from one study to the next. A wide range of studies and surveys have been performed on this topic, with an equally wide range of results.[5] Here real-world surveys have been considered, as well as studies which attempt to generate realistic household load profiles for the purpose of simulation not unlike those presented here. Studies relevant to this work are concerned not only with the total or average hot water consumption in a household, but with more specific usage patterns, including flow rate, volume, duration and frequency of different incident types.

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[5] Tiller et al. [43] have proposed a web-enabled database system to provide a repository for domestic water heating data, but that database does not yet appear to be functioning in its intended capacity.

5.1.1 Real-world surveys

Aguilar et al. [30] have compiled a review of literature and numerical models concerning domestic water heating, with particular focus on Canadian data. Many of the studies cited below are also included in their survey.

One of the most well-respected and well-utilised studies addressing domestic water usage patterns is the *Residential End Uses of Water Study (REUWS)* [44], a 310-page tome prepared by Mayer et al. and published in 1999 by the American Water Works Association Research Foundation (AWWARF). This study, described by James Lutz of Lawrence Berkeley National Laboratory as the “best description of residential end uses of water in North America at this time (2004),” [45] aims to provide specific data on the end uses of water in residential settings across the continent. It includes data collected from 1,188 households in twelve diverse locations (eleven across the US - including western cities such as Seattle, WA and Eugene OR - and one covering Waterloo and Cambridge, ON), totaling 28,015 complete days of data.[6] Data collection was divided into two, roughly two-week intervals for each household, spaced to capture both summer and winter use. Water flow was monitored at ten-second intervals, providing sufficient resolution for the flow to be disaggregated into individual water events using flow trace analysis software. Almost one million individual water use events were captured.

The *REUWS* establishes a number of water use patterns which are germane to this study. One such finding is a set of 24-hour usage curves, identifying the times of day each type of water outlet is most commonly used (Figure 6).

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[6] Before the *REUWS*, the largest metered study of residential hot water use covering wide regions in North America was a 1985 study by Ladd & Harrison [46], which included 110 single-family homes from eleven different utility companies across the US.

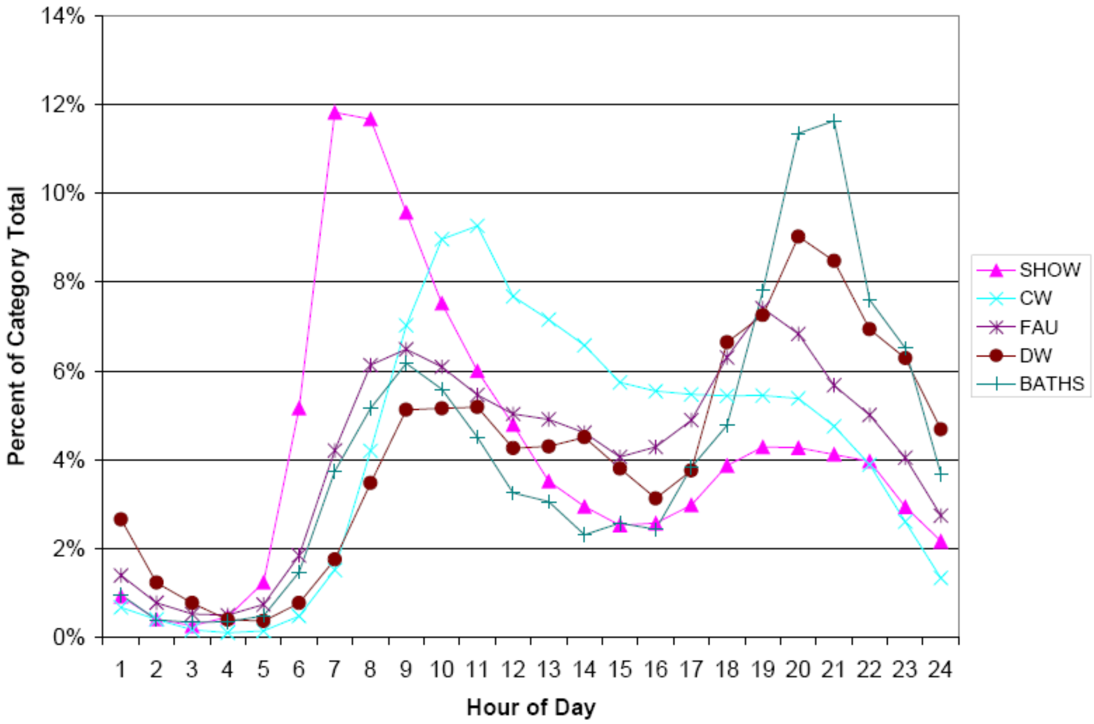

Figure 6: Hourly percent use by category, based on data collected in the *REUWS*, as presented by DeOreo and Mayer [47].

This figure is similar to many long-established curves identifying the typical ebb and flow of residential water use in a 24-hour period,[7] but builds upon them by breaking down the data by end-use. The patterns documented in Figure 6 were utilized to establish time-of-day usage patterns in the load scenarios for this study.

Another useful set of information calculated in the *REUWS* is the per-event water usage, including mean volume, mean duration and mean flow rate per event, for several different outlet types. Mean shower volume across all 12 study sites, for example, was 17.2 gal/event (65.1 L/event), mean shower duration was 8.2 minutes, and mean shower flow rate was 2.22 gpm (8.4 l/min). These, too, were taken into consideration when generating load scenarios.

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[7] See ASHRAE Standard 90.2 [48].

One disadvantage of the *REUWS*, however, is that it does not differentiate between cold and hot water draws. All volume and flow rates taken from the report are therefore understood to be some combination of hot and cold water, the proportions of which must be calculated.

The other available studies done in locations germane to this work have considerably smaller sample sizes. One such study is follow-up to the *REUWS* by DeOreo and Mayer [47]. This paper analyses hot water usage data recorded in 14 Seattle, Washington homes, tracing flow from both the main line (cold water) feed and the hot water feed.

Tiller et al. [49] measure hot water use in four homes of different sizes located in Omaha, Nebraska. Due to both the location and size of the study, this report is considered less relevant to this work.

For data specific to Canada, Environment Canada has published municipal water use data up through 1999, which notes daily residential water use – including both hot and cold water – as 343 L/day-capita. Augilar et al. [30], using proportion data laid out by DeOreo and Mayer [47], have interpolated this to a range of between 107 and 181 L/day-capita of hot water, with an average of 139 L/day-capita of hot water.

Wiehagen and Sikora [34] also note a 1985 study by Perlman and Mills [50] which measured hot water consumption over four years for 59 residences in Canada. That study found average household hot water consumption to be 236 L/day and per capita hot water consumption to be 47-86 l/day-capita. Augilar et al., however, believe these numbers to be somewhat outdated since they are considerably lower than those reported by Environment Canada [30].

The available data pertaining to hot water end use specifically in British Columbia is limited. The provincial power utility, BC Hydro, published a *2006 Residential End-Use Study* [51] which presents data on frequency of use collected via a written survey of participants rather than through actual measurement. For that reason, only an estimated frequency of hot water use could be reported. In the 2006 survey, respondents self-reported the number of baths and showers per week in their households, as well as the number of clothes washer and dishwasher loads per week in households which include those appliances.

Older studies measuring or compiling hot water end-uses in single-family residences include Ladd and Harrison in 1985 [46]; Weihl and Kempton in 1985 [52]; Kempton in 1986 [53]; Becker and Stogsdill in 1990 [54]; DeOreo et al. in 1996 [55]; Lowenstein and Hiller in 1996 [56] and 1998 [57]; and Hiller in 1998 [58]. Older surveys which are concerned with total household hot water consumption include Goldner in 1994 [59] and Abrams and Shedd in 1998 [60].

5.1.2 Simulations

In Wiehagen and Sikora's study [34], two types of load sets were profiled: a low use home (ranging 15-41 gal/day or 57-155 L/day) and a high use home (ranging 66-86 gal/day or 250-326 L/day). This data was taken from year-long study of five homes in Cleveland, Ohio.

Two theoretical, extreme examples of total, daily hot water use are illustrated by Lutz et al. [61]: a high-use, six-person household using a total of 776.5 L/day of hot water and a low-use, one-person household using a total of 32.2 L/day. Both are realistic scenarios, though neither represents an example of typical use.

In Lutz's 2005 paper focused on calculating water and energy losses in residential water heating [62], he uses data reported by KEMA-XENERGY et al. [63] concerning natural gas used for water heating in almost 22,000 California homes. Lutz calculates that a California residence uses an average of 199 L/day of hot water.

Finally, and perhaps most critical to the calculation of the load scenarios in this study, is Hendron and Burch's 2007 paper, "Development of Standardized Domestic Hot Water Event Schedules for Residential Buildings" [64]. Based on a comprehensive survey of recent hot water studies, Hendron and Burch have developed a set of formulas for calculating average daily hot water usage in residential buildings, varying as linear functions of the number of bedrooms in the home (*N*), which serves as a surrogate for the number of occupants. These functions are shown in Table 4.

Table 4: Hendron and Burch [64] have defined benchmark water temperature and volume as follows:

End Use	End-Use Water Temperature	Water Usage (gal/day)
Clothes Washer	120°F (50°C) (Hot)	7.5 + 2.5 x *N* (Hot only)
Dishwasher	120°F (50°C) (Hot)	2.5 + 0.833 x *N* (Hot only)
Shower	105°F (40°C) (Mixed)	14.0 + 4.67 x *N* (Hot + Cold)
Bath	105°F (40°C) (Mixed)	3.5 + 1.17 x *N* (Hot + Cold)
Sinks	105°F (40°C) (Mixed)	12.5 + 4.16 x *N* (Hot + Cold)

These equations were used as a starting point for creating load scenarios, to calculate both the total expected load in a household and the expected distribution of that load across a variety of end uses.

5.2 Load data used in simulation

5.2.1 Calculation of benchmark targets

The functions derived by Hendron and Burch in Table 4 are used to establish baseline expectations for total average hot water use per day for both two-person and five-person households. First, each of the equations in Table 4 are used with both *N*=2 and *N*=5, and the results converted from gallons to litres.

Table 5: Average daily hot water use is calculated as follows based on the equations in Table 4:

	***N*=2 (litre/day)**	***N*=5 (litre/day)**	**% of Total**
Clothes Washer	47.3	75.7	18.8%
Dishwasher	15.8	25.2	6.2%
Shower	88.4	141.4	35.0%
Bath	22.1	35.4	8.8%
Sinks	78.8	126.1	31.2%
Total	**252.4**	**403.8**	

The calculated values in Table 5 represent average daily loads, which incorporate both weekday and weekend data. For all loads:

$$Load_{AVE} = \frac{5Load_D + 2Load_E}{7} \tag{8}$$

where $\mathrm{Load_D}$ and $\mathrm{Load_E}$ represent the loads for weekdays and weekends, respectively. Separate load values for weekdays and weekends were therefore interpolated based on the proportions laid out by Hendron & Burch: For baths, weekend loads are 300% of weekday loads, and for all other load types weekend loads are 115% of weekday loads. So for baths:

$$B_E = 3B_D \tag{9}$$

and using the proportions laid out in Equation 8,

$$B_{AVE} = \frac{5B_D + 2(3B_D)}{7} = \frac{11B_D}{7} = 1.57B_D \tag{10}$$

Therefore to calculate $\mathrm{B_D}$ and $\mathrm{B_E}$ in terms of $\mathrm{B_{AVE}}$:

$$B_D = \frac{B_{AVE}}{1.57} \tag{11}$$

$$B_E = 3B_D = 3\left(\frac{B_{AVE}}{1.57}\right) = 1.91B_{AVE} \tag{12}$$

Likewise, for all other load types, clothes washers, for example:

$$C_E = 1.15C_D \tag{13}$$

$$C_{AVE} = \frac{5C_D + 2(1.15C_D)}{7} = \frac{7.3C_D}{7} = 1.04C_D \tag{14}$$

Therefore,

$$C_D = \frac{C_{AVE}}{1.04} \tag{15}$$

$$C_E = 1.15C_D = 1.15\left(\frac{C_{AVE}}{1.04}\right) = 1.03C_{AVE} \tag{16}$$

Using Equations 11, 12, 15 and 16, the following load data was calculated for weekdays and weekends:

Table 6: Using equations derived from Hendron & Burch [64], values were calculated for weekday and weekend loads.

	***N*=2 (litre/day)**		***N*=5 (litre/day)**	
	Weekday	Weekend	Weekday	Weekend
Clothes Washer	45.1	52.2	72.6	83.5
Dishwasher	15.1	17.4	24.2	27.8
Shower	84.7	97.4	136	156
Bath	14.1	42.2	22.5	67.6
Sinks	75.6	86.9	120.9	139.0
Total	**235**	**296**	**376**	**474**

The totals calculated in Table 6 for each household size served as the baseline for mid-range usage. Because the task at hand was to simulate not only typical usage for each household size but low and high-range usage as well, the numbers were adjusted accordingly. For households with low usage, the expected total volumetric load was decreased by 25%, and for those with high usage it was increased by 25%. This is consistent with the range of high, medium and low usage calculated by Aguilar et al. using data from Environment Canada, as mentioned in Section 5.1.1. The resulting daily volumetric targets for each of twelve load scenarios can be seen in Table 7.

Table 7: Volumetric targets were calculated for each of twelve load scenarios

	***N*=2 (litre/day)**		***N*=5 (litre/day)**	
	Weekday	Weekend	Weekday	Weekend
Low Usage	176	222	282	355
Medium Usage	235	296	376	474
High Usage	294	370	470	592

Based on the loads listed above, on a weekly basis hot water use ranges from 61 L/day-capita for a low-use, 5 person home, to 158 L/day-capita for a high-use, 2 person home. This is well within the range of use in Canadian households compiled from several studies by Aguilar et al. [30], which ranges from 47 L/day-capita to 181 L/day-capita, as discussed in Section 4.1.1. These targets are thus deemed to be reasonable representations of hot water loads in Canadian households, and therefore appropriate for this simulation.

5.2.2 Generation of incidents and load scenarios

The load scenarios are created using Microsoft Excel. Each scenario has its own workbook, containing separate worksheets for each of the six load types: bath, shower, dishwasher, clothes washer, kitchen sink and bathroom sink.[8] A series of individual hot water incidents is constructed in each worksheet, representing the total hot water usage for that load type in a 24-hour period. Data points included in each incident are: time of day, volumetric flow rate (L/min), duration of flow (min), water temperature (°C) and

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[8] For simplicity, all of the homes being simulated include only one bathroom.

length of water store (in the sink basin, bathtub, etc.) before flowing down the drain (min). A sample load scenario can be found in Appendix B.

The distribution of the hot water incidents across a 24-hour period is based roughly on the usage patterns illustrated in Figure 6. For simplicity, the water temperatures are set roughly equivalent to those used by Hendron and Burch, as seen in Table 4: 50°C for dishwashers and clothes washers and 40°C for baths, showers and sinks.

A variety of "per incident" data was compiled from different sources, to provide a starting point for simulating the individual hot water events. Each of these sources has been discussed in previous sections. Because this information can vary so dramatically, in cases where multiple sources existed there was always a certain amount of variation to be found. Table 8 represents the cross-section of that available data which is the most recent and/or geographically relevant to British Columbia. Because the sources differ, the table does have some discrepancies with regard to significant figures.

Table 8: Water usage data was assembled from a variety of external studies [34, 44, 52, 61, 62].

	Volume per Incident (litres)	Duration per incident (min)	Flow Rate (litres/min)	Frequency
Bath	75.5	4	18.9	4.6/week
Shower	65.1	8.2	8.4	11.4/week
Dishwasher[9]	113.6	15	5.4	3.6/week
Clothes Washer	154.8	11.7	13.2	4.3/week
Kitchen Sink	Variable	Variable	2.8	5/day
Bathroom Sink	1.9	1	1.9	12/day

While the data collected on flow rate and duration was directly transferrable to the construction of individual hot water events, the data on incident frequency served only as

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[9] A dishwasher has two or three draws per incident, depending on the model, of roughly five minutes each [61]. The numbers shown here represent one complete incident consisting of three separate draws. In the load scenarios modeled, each draw is listed as separate event.

a rough guideline. This is in part because it may not be the most reliable data. Much of it is data self-reported by users rather than actually measured, which carries some inherent uncertainty. Additionally, the frequency of an event is largely dependent upon household size, but in many cases only data on average frequency is available, often without any reference to household size.

Perhaps even more salient is the fact that, as Hendron & Burch note, while daily or weekly usage for various load types are useful as averages over time, they do not suffice when it comes to specifying the load for a given day. It is one thing, for instance, to note that a three-person household runs an average of .324 baths per day or 0.59 dishwasher loads per day, but when simulating a typical day it is not practical to calculate the water usage for a fraction of a bath or dishwasher load.

To compensate for this incongruity, assumptions were made about each load scenario, and the flow rate and/or duration of specific events within it were adjusted slightly within realistic parameters so that the total hot water usage for a given day matched the target. Low usage households, for example, were assumed to have neither a dishwasher[10] nor a hot water-engaging clothes washer; medium usage households were assumed to have a clothes washer utilizing hot water once during the day, but no dishwasher; high usage households were assumed to have both a clothes washer and a dishwasher utilizing hot water. Additionally, two-person households included baths only in weekend scenarios, rather than both on weekends and weekdays.

The method of portioning load data was validated by looking at a typical “week” – five weekday scenario days plus two weekend scenario days - for the high usage group and

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[10] In scenarios with no dishwasher, duration of kitchen sink use in the post-dinner hours was increased by four minutes over that in scenarios which did include dishwashers, to account for manual dish washing.

checking that the average per day percentage of each load type was roughly equivalent to the proportions laid out by Hendron & Burch. Since only the High usage group included all six load types, it was taken as representative.

Table 9: Percentage of total volumetric load by event type

	Target (See Table 5)	***N*=2 High-Use Scenario**		***N*=5 High-Use Scenario**	
			Difference		Difference
Bath	8.8%	7.2%	-1.5%	14.2%	+5.4%
Shower	35.0%	37.7%	+2.7%	34.6%	-0.4%
Dishwasher	6.2%	12.6%	+6.4%	8.4%	+2.2%
Clothes Washer	18.8%	16.8%	-2.0%	19.5%	+0.8%
Sinks[11]	31.2%	25.6%	-5.6%	23.3%	-7.9%

The results of this comparison show that the total load for both household sizes deviates by less than 10% from the target proportions derived from Hendron and Burch’s equations. For a two-person household the largest deviation was that of dishwashers which, on a weekly basis, make up 12.6% of the load for a two-person household as opposed to 6.2% target. This is an understandable discrepancy: because there are only one weekday and one weekend scenario for each user type, the ”week” of data assumes that the dishwasher is run every day, which is not necessarily realistic for a two-person home, even a high-use one. This demonstrates a shortcoming of the load generation method, though not one significant enough to invalidate the work.

For a five-person household, the most significant deviations are in baths, which make up 14.2% of the load as opposed to 8.8% target, and sinks, which in compensation are 23.3% of the load in this scenario as opposed to 31.2% target. This can be explained when one considers that the make-up of a five-person household is likely to include

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[11] Because Hendron and Burch group all sinks into one category, the kitchen and bathroom sink loads in this study were combined for this comparison.

children. A household with small children might very well run more baths than is proportionally “typical” based solely on size. Specific demographic assumptions such as these, however, are not included the Hendron & Burch equations.

These deviations were concluded to be within reasonable range of the target load values, thus the load scenarios were deemed acceptable for simulation.

The previous two chapters have focused on the details of the computer model and its inputs and functions, summarizing the model’s technological and mathematical components, the metrics used to evaluate results, and the care taken to simulate appropriate hot water loads. In the following chapter the focus shifts from groundwork to results, as the data produced by this model is presented in detail.

Chapter 6

Simulation Results

In this chapter, the results of a total of 7,488 full simulation runs are presented, each run representing a unique combination of water heating technology, load, location and season.

6.1 Refinement of period selection

As with any dynamic simulation where storage is possible, the impact of initial conditions can have a large impact on the state of the system after a short period of time. Initial conditions are less important when the transient period has passed and a steady-state condition is reached.

The impacts of initial conditions and simulation duration in this model became evident when reviewing the first sets of test data, where a 24-hour time period was used. Many of the test runs yielded SEFs greater than 3.00, and some even greater than 4.00. Such results, while within the realm of possibility, are not representative of average conditions. One possible explanation for these occurrences was a set of unrealistic initial conditions for the temperature of the hot water tank (a common problem in any time-series simulation).

Another way performance can be misrepresented is because of the definitions used for metrics, such as how residual energy is taken into account. As an example, a system may absorb a large amount of solar energy in a day, but an equivalent reduction in conventional energy use may not occur. In a real-world, multi-day scenario, the residual energy generated in a high-solar day would roll over as stored energy for the following day. The solution to this problem is to simulate a span of several days rather than just one. This eliminates the potential for either initial condition or residual energy problems, thus yielding more representative results.

Figure 7 shows results for Kamloops where one, three, and six-day simulation periods have been used. All three runs depicted here simulate the same technologies (base case electric water heaters – with SEFs shown between 0.50 and 1.00 – and those same water heaters with the addition of a solar component) in the same location and season (Kamloops in August). Only the period of simulation differs between runs.

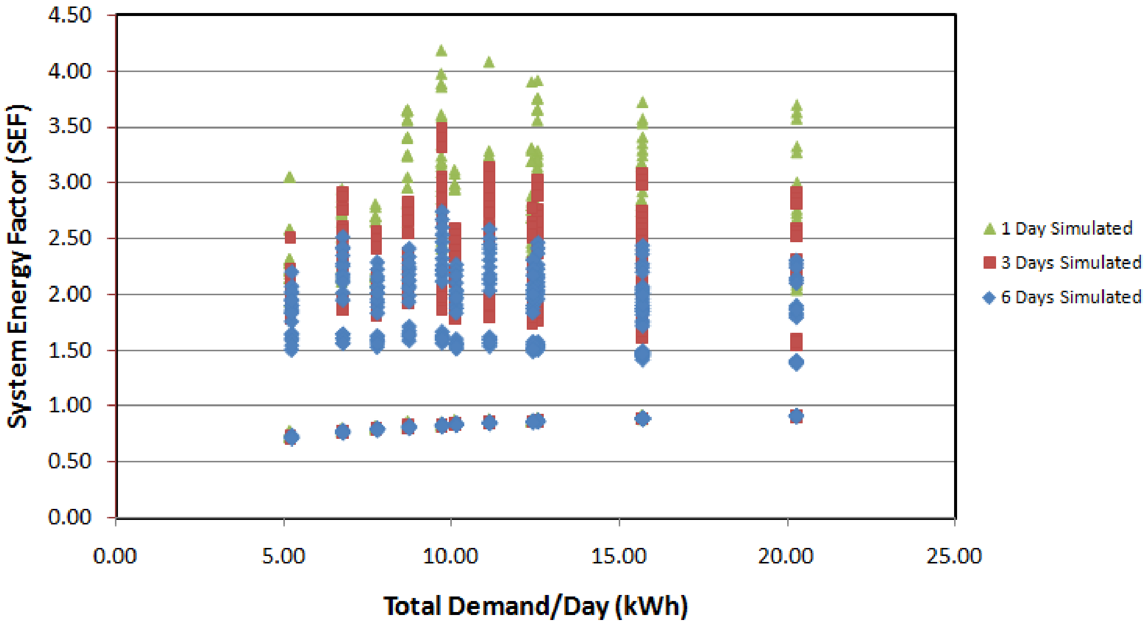

Figure 7: Simulated System Energy Factor results derived by testing three different simulation periods. Results are for conditions at Kamloops in August.

Simulations of a one-day period produce erratic and unrealistically high SEFs. The range of SEFs evens out considerably when the period is increased to three days. As the simulation period increases the SEF results become grouped more tightly together: the set of single-day simulations has a standard deviation of 0.96, while the three and six-day sets have standard deviations of 0.73 and 0.55 respectively. Moreover, the overall SEF trend becomes lower as the period increases, with a maximum of less than 3.00 for the six-day sets. The analyses that follow are all based upon simulations with a six-day period.

6.2 Base case

Base case configurations are considered to be those that use only standard water heating systems i.e. electric or gas-fired hot water tanks.

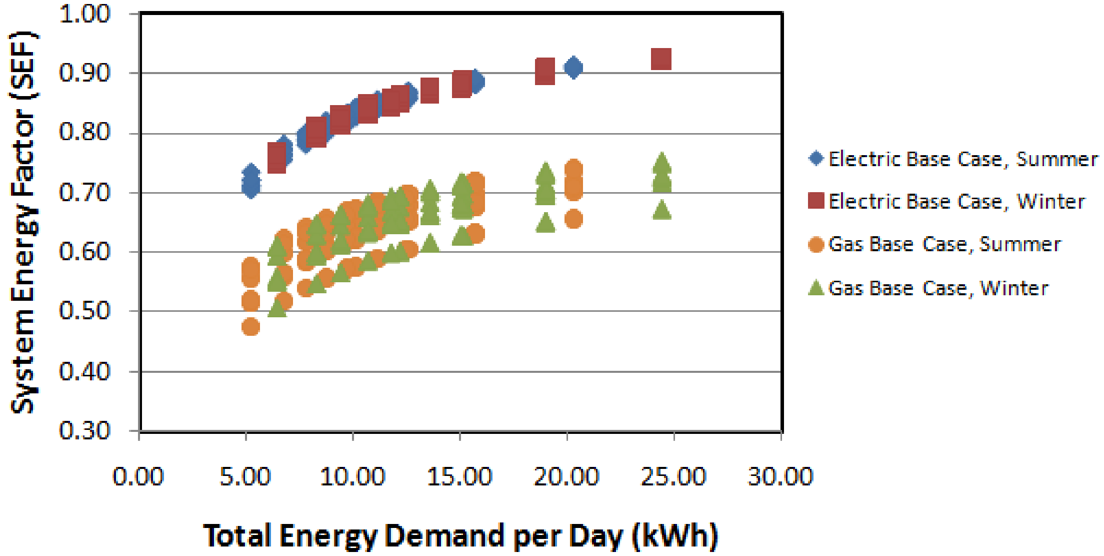

Figure 8: SEF values for all base cases simulated.

As seen in Figure 8, the base case scenarios for homes with electric water heaters yield fairly narrow ranges of SEF values across all the simulated regions. For homes with electric water heaters, the base cases range between 0.70 and 0.91 in the summer and between 0.75 and 0.93 in the winter. For homes with gas water heaters the ranges are larger though the values are predictably lower: 0.46 to 0.74 in the summer and 0.51 to 0.75 in the winter. The fact that the SEFs are slightly higher in the winter can be attributed to the fact that the energy demand to heat a given volume of water is higher in the winter than it is in the summer due to the difference in inlet water temperature.

Another point to note is that the SEF actually increases as load increases. This is because of the distribution of energy losses in the system. Within a given system, losses between the largest load and the smallest vary by less than 0.5 kWh/day. This is because most of the loss occurs as the tank sits idle. When the load is small, however, those losses make up a much greater percentage of the total energy consumed, thereby driving the SEF slightly lower.[12]

While it is true that SEF increases as loads get larger, this certainly should not be taken to mean that the impact of larger loads is positive overall. The negative impact of larger loads can most easily be seen by examining the amount of CO_2 produced. As Figure 9 demonstrates, CO_2 production increases dramatically with load size, particularly for systems using gas water heaters.

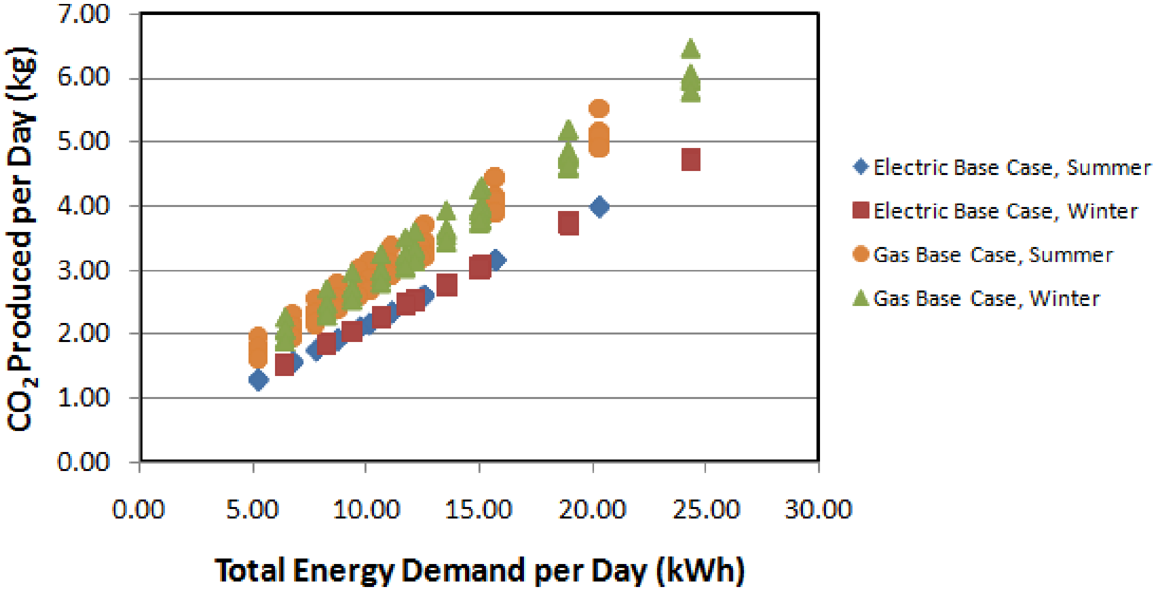

Figure 9: CO_2 production by load size, using the same simulation runs and X-axis scale as Figure 8.

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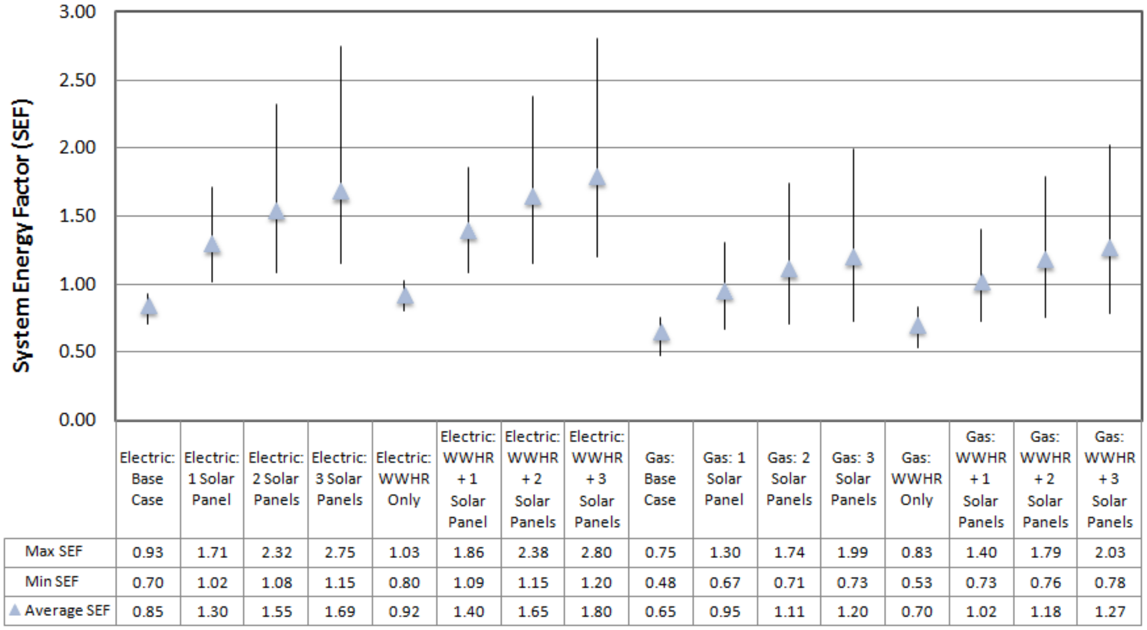
[12] As an example, for two runs with the same system configuration (Kamloops, winter, 189 L gas heaters with EF .67, 2 solar panels, no WWHR) but disparate load sizes (the smallest 6.43 kWh/day and the largest 24.38 kWh/day) results are as follows: For the small load, Q_{tdhe} = 7.95 kWh/day and Q_{loss} = 2.65 kWh/day, therefore loss as a percentage of total is 33%. For the large load, Q_{tdhe} = 24.82 kWh/day and Q_{loss} = 2.27 kWh/day, therefore loss as a percentage of total is only 9%. SEFs for these runs are 0.89 and 0.92 respectively.

Reduced CO_2 production is one of the primary goals of energy efficiency, and demand-side management, while outside of the scope of this research, is a common strategy for reducing the carbon footprint of a system. Since the SEF calculation does not include the impact of CO_2, it is clear that that metric must be considered separately when evaluating a water heating system.

6.3 Aggregate SEF data by technology type

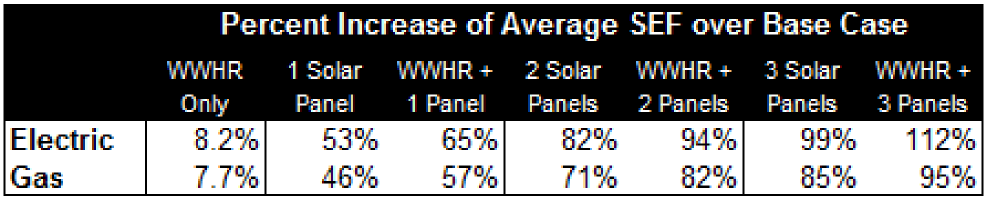


	Electric: Base Case	Electric: 1 Solar Panel	Electric: 2 Solar Panels	Electric: 3 Solar Panels	Electric: WWHR Only	Electric: WWHR + 1 Solar Panel	Electric: WWHR + 2 Solar Panels	Electric: WWHR + 3 Solar Panels	Gas: Base Case	Gas: 1 Solar Panel	Gas: 2 Solar Panels	Gas: 3 Solar Panels	Gas: WWHR Only	Gas: WWHR + 1 Solar Panels	Gas: WWHR + 2 Solar Panels	Gas: WWHR + 3 Solar Panels
Max SEF	0.93	1.71	2.32	2.75	1.03	1.86	2.38	2.80	0.75	1.30	1.74	1.99	0.83	1.40	1.79	2.03
Min SEF	0.70	1.02	1.08	1.15	0.80	1.09	1.15	1.20	0.48	0.67	0.71	0.73	0.53	0.73	0.76	0.78
▲ Average SEF	0.85	1.30	1.55	1.69	0.92	1.40	1.65	1.80	0.65	0.95	1.11	1.20	0.70	1.02	1.18	1.27

Figure 10: Distribution of SEF across all regions and seasons, broken down by fuel source and added technology type.

Figure 10 shows the aggregate data of all simulations run, while Table 10 summarizes the average percent increase over base case yielded by each technology combination. For the same system configuration, average SEFs of gas-based systems are 23% to 29% lower than those of electric-based systems. For both gas and electric systems, the addition of waste water heat recovery increases the average SEF only minimally over the base case (an increase of 0.05 or 7.7% for gas and 0.07 or 8.2% for electric). The increase in SEF caused by the addition of a solar preheat component is significantly larger.

Table 10: Average percent increase in SEF produced by the inclusion of each technology.



	Percent Increase of Average SEF over Base Case						
	WWHR Only	1 Solar Panel	WWHR + 1 Panel	2 Solar Panels	WWHR + 2 Panels	3 Solar Panels	WWHR + 3 Panels
Electric	8.2%	53%	65%	82%	94%	99%	112%
Gas	7.7%	46%	57%	71%	82%	85%	95%

For electric systems, a solar preheat component with one solar panel increases the average SEF by 0.45 or 53% over base case. Two solar panels increase the average further to 82% over base case, and three panels to 99% over. The combination of solar preheat and WWHR yields an average SEF that is slightly higher than the mathematical sum of its parts. Systems in this category with one, two or three solar panels yield average SEFs that are respectively 65%, 94% and 112% higher than the base case.

For gas systems, the impact of solar preheat is also significant. A solar preheat component with one solar panel increases the average SEF by 0.30 or 46% over gas base case. Two solar panels increase the average further to 71% over base case, and three panels to 85% over base case. Systems with WWHR in addition to one, two or three solar panels yield average SEFs that are respectively 57%, 82% and 95% over base case.

In all cases, the average SEF of "WWHR plus solar" systems is roughly 11-12% higher than the corresponding solar-only systems; greater than the roughly 8% boost that waste water heat recovery alone provides over the base case. This suggests there is some additional benefit, albeit small, to combining the technologies.

Figure 11 through Figure 14 illustrate the SEF values generated for each technology type within a given season. Only data for Kamloops is shown, but the general trends are the same across all regions so this data may be taken as representative. The data has been broken down in this way to demonstrate, as much as possible, how the SEF values for individual simulation runs tend to group.

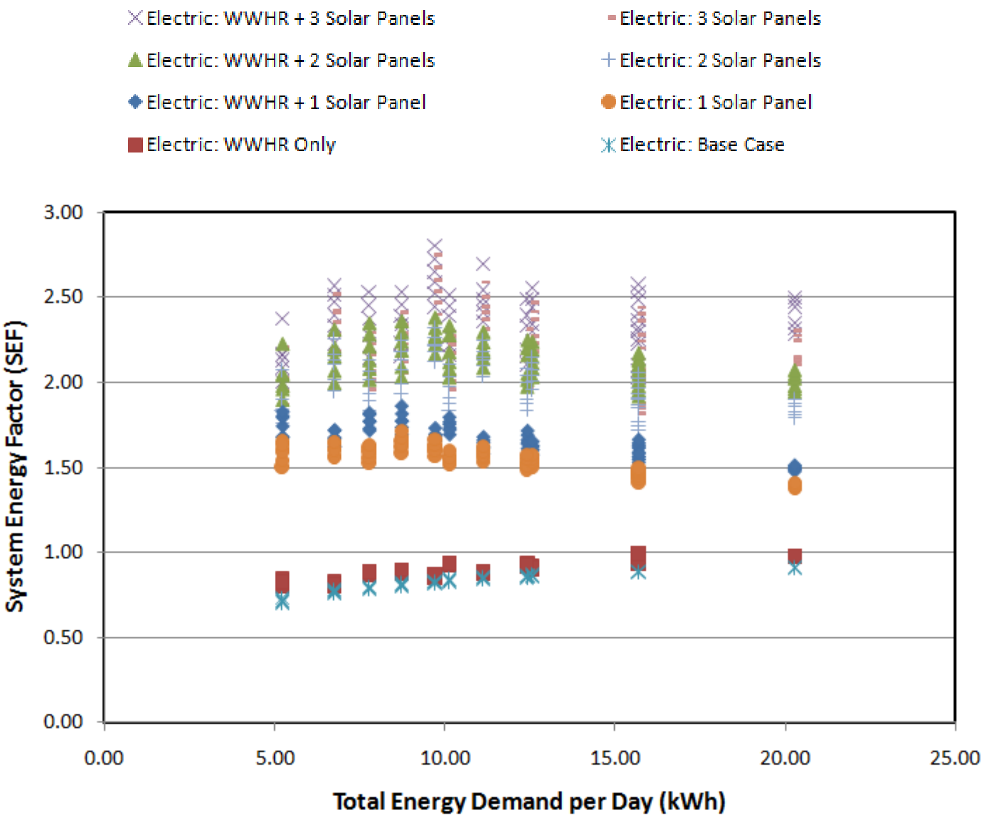


Figure 11: Grouping of SEF values for individual simulations of electric water heating systems in summer time in Kamloops.

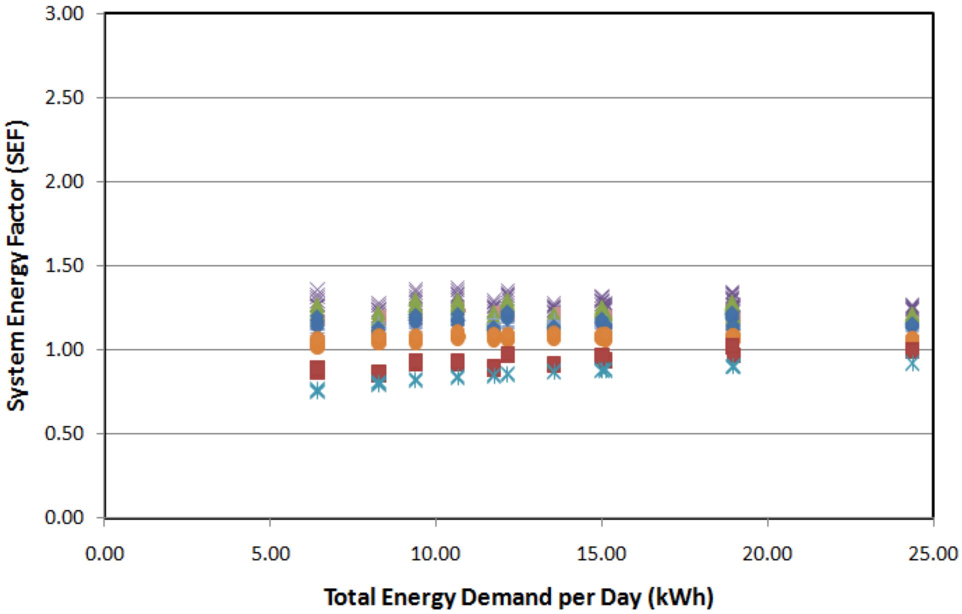


Figure 12: Grouping of SEF values for individual simulations of electric water heating systems in winter time in Kamloops. The scale used is the same as in Figure 11 to allow for a more accurate visual comparison.

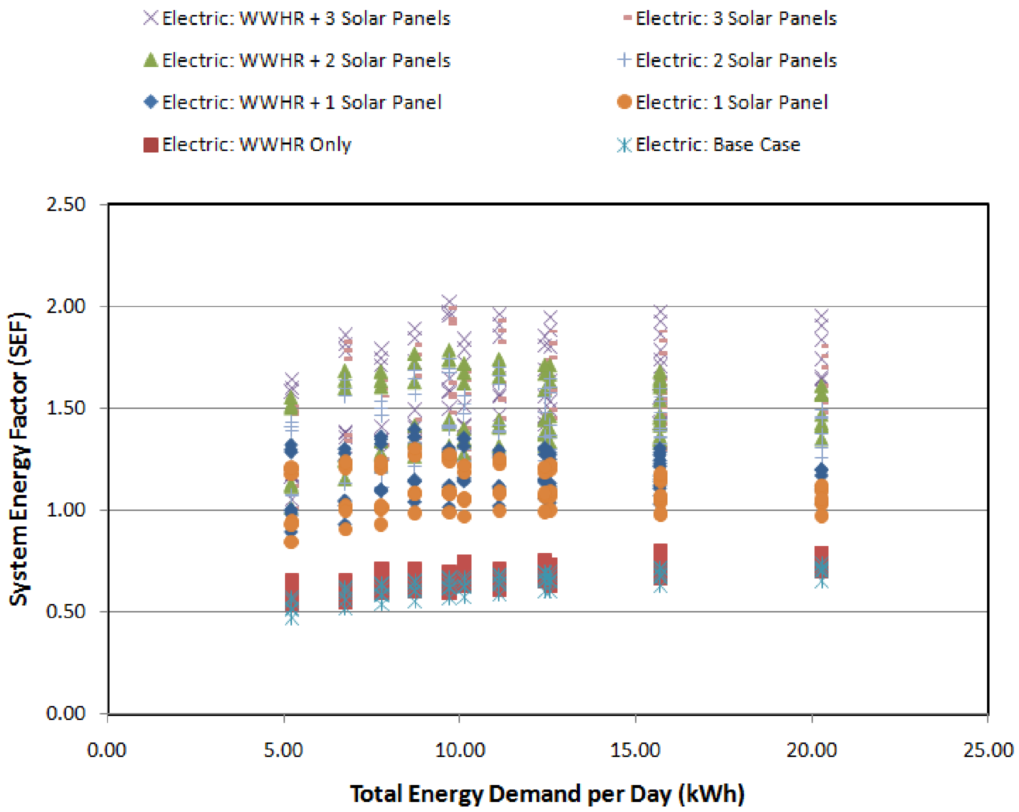


Figure 13: Grouping of SEF values for individual simulations of gas water heating systems in summer time in Kamloops.

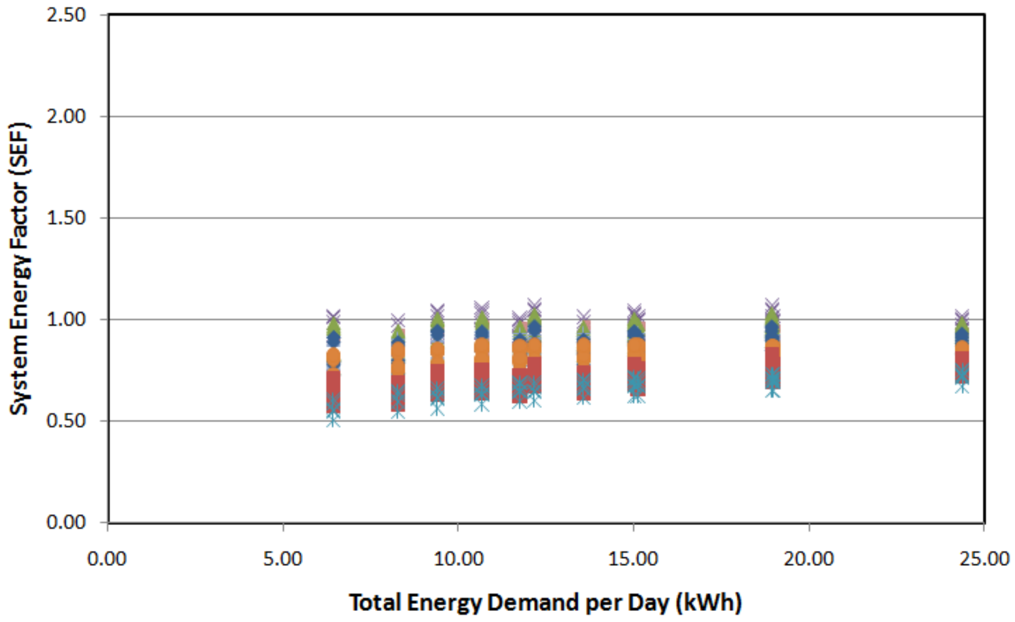


Figure 14: Grouping of SEF values for individual simulations of gas water heating systems in winter time in Kamloops. The scale used is the same as in Figure 13 to allow for a more accurate visual comparison.

The first and most salient observation to be made from these figures is the dramatic difference that the season has on the impact of a solar component. In summer, the addition of even a one-panel solar component can increase the SEF by as much 88% over base case for systems with electric water heaters, while a three-panel component can increase the SEF of those systems to more than 200% over base case (Figure 11). Likewise for systems with gas-fired water heaters, a one-panel solar component can increase the SEF by as much as 76% and a three-panel component by as much as 169% (Figure 13). In winter, however, the impact is very different. For electric systems, a one-panel solar component increases the SEF by only 20%, and a three-panel component increases the SEF only marginally more to 37% over base case (Figure 12). For gas-based systems the impact is even smaller: a 17% increase for one panel and only a 32% increase over base case for three panels (Figure 14).

Also notable is the shift in demand between summer and winter, previously mentioned in the examination of Figure 8. Winter loads are higher than summer because of the lower inlet water temperature, which increases the daily load by about 20%.

6.4 Impact of water heater

Because current water heating standards focus solely on the EF of the water heater, it is useful to examine the impact of differently rated water heaters on the SEF of a system. Figure 15 through Figure 18 and Table 11 and Table 12, below, illustrate the extent to which the water heater EF effects the system SEF.

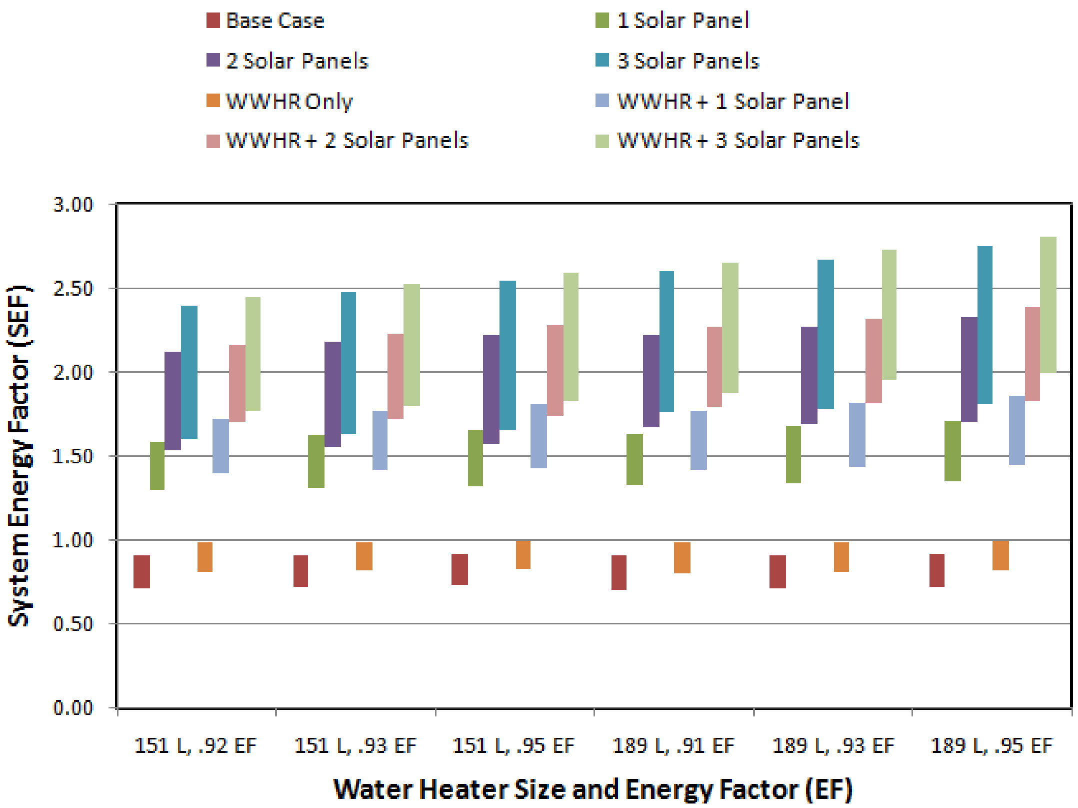


Figure 15: Ranges of SEF values for electric water heaters in summer, broken down by water heater tank size and EF as well as by additional technology type.

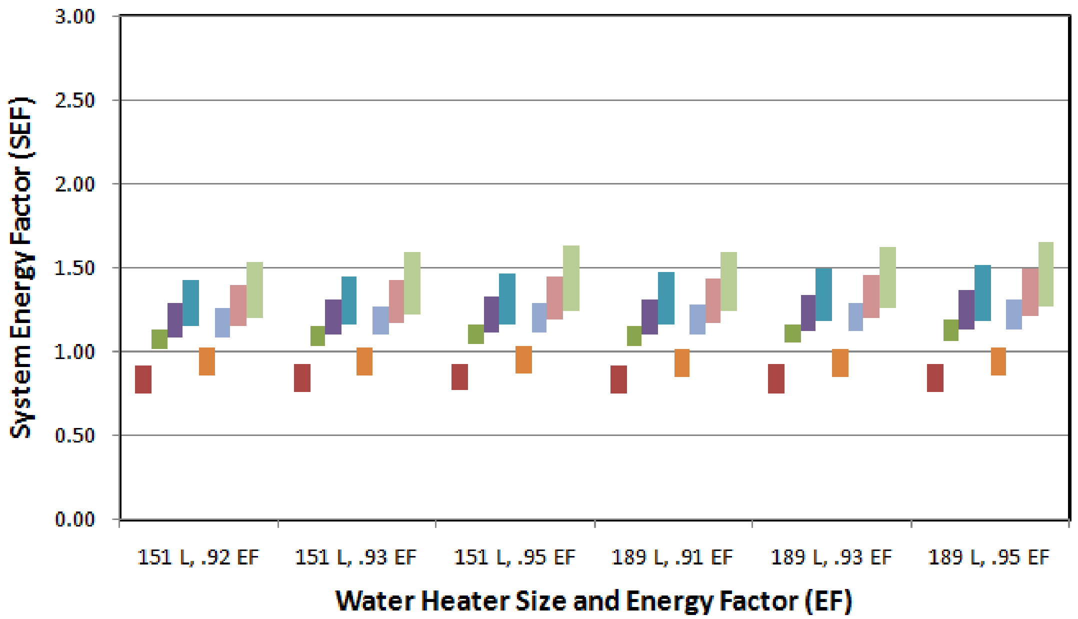
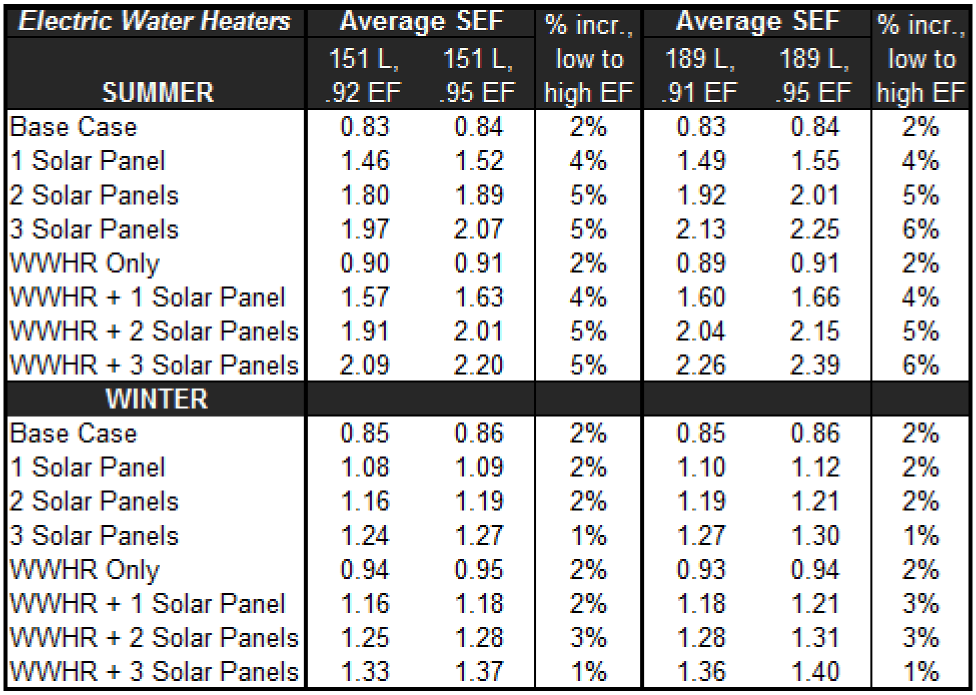


Figure 16: Ranges of SEF values for electric water heaters in winter, broken down by water heater tank size and EF as well as by additional technology type. The scale used is the same as in Figure 15 to allow for a more accurate visual comparison.

Table 11: Comparison of average SEF values for systems containing the lowest-rated and highest-rated electric water heaters. Percent increase of SEF between the lowest-rated heaters and the highest-rated is calculated.



Electric Water Heaters	Average SEF		% incr.,	Average SEF		% incr.,
SUMMER	151 L, .92 EF	151 L, .95 EF	low to high EF	189 L, .91 EF	189 L, .95 EF	low to high EF
Base Case	0.83	0.84	2%	0.83	0.84	2%
1 Solar Panel	1.46	1.52	4%	1.49	1.55	4%
2 Solar Panels	1.80	1.89	5%	1.92	2.01	5%
3 Solar Panels	1.97	2.07	5%	2.13	2.25	6%
WWHR Only	0.90	0.91	2%	0.89	0.91	2%
WWHR + 1 Solar Panel	1.57	1.63	4%	1.60	1.66	4%
WWHR + 2 Solar Panels	1.91	2.01	5%	2.04	2.15	5%
WWHR + 3 Solar Panels	2.09	2.20	5%	2.26	2.39	6%
WINTER						
Base Case	0.85	0.86	2%	0.85	0.86	2%
1 Solar Panel	1.08	1.09	2%	1.10	1.12	2%
2 Solar Panels	1.16	1.19	2%	1.19	1.21	2%
3 Solar Panels	1.24	1.27	1%	1.27	1.30	1%
WWHR Only	0.94	0.95	2%	0.93	0.94	2%
WWHR + 1 Solar Panel	1.16	1.18	2%	1.18	1.21	3%
WWHR + 2 Solar Panels	1.25	1.28	3%	1.28	1.31	3%
WWHR + 3 Solar Panels	1.33	1.37	1%	1.36	1.40	1%

Figure 15 and Figure 16 show the SEF ranges for systems with electric water heaters in summer and winter, respectively. For both base case systems and WWHR only systems, there is almost no variation in the SEF range from one water heater to another, regardless of season. In summer, higher-rated water heaters do provide a notable increase in SEF range for systems containing a solar component though, as shown in Table 11, that change is only as high as 5% to 6% even for systems containing three solar panels. In winter, the water heaters with higher EFs yield only negligibly higher SEF ranges, and the average SEF is increased by only 3% or less. In fact, for systems with three solar panels, the change to a higher-rated water heater yields only a 1% increase in average SEF.

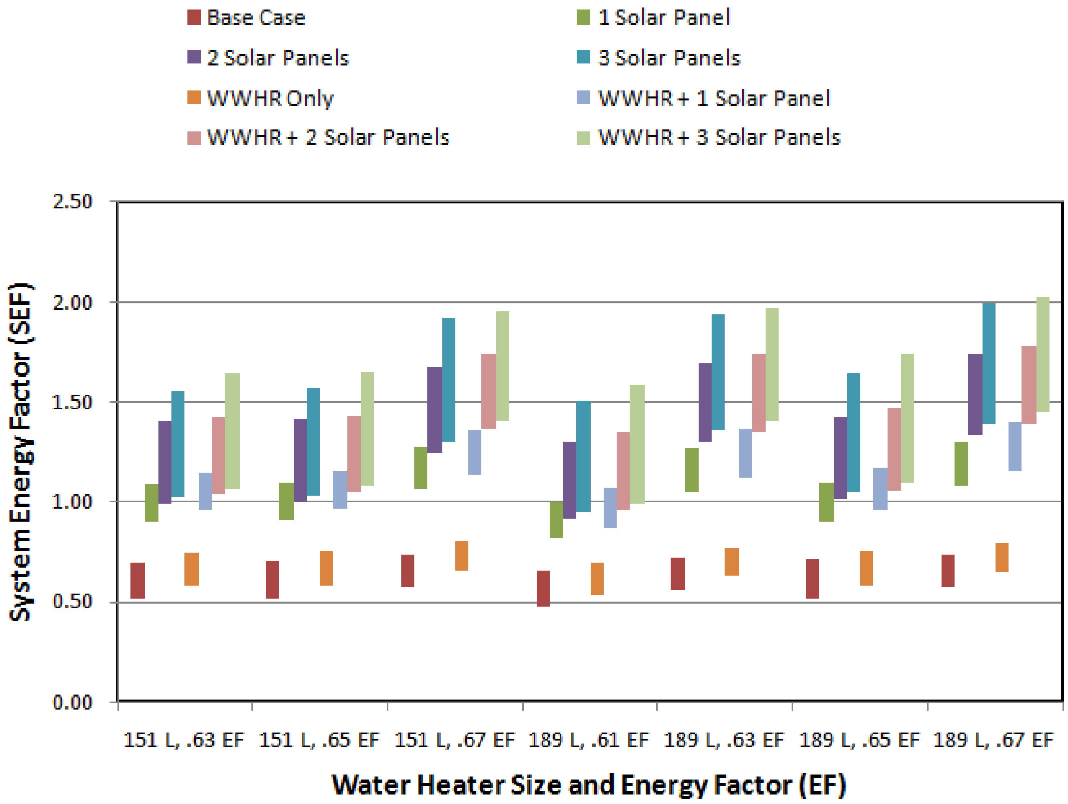


Figure 17: Ranges of SEF values for gas water heaters in summer, broken down by water heater tank size and EF as well as by additional technology type.

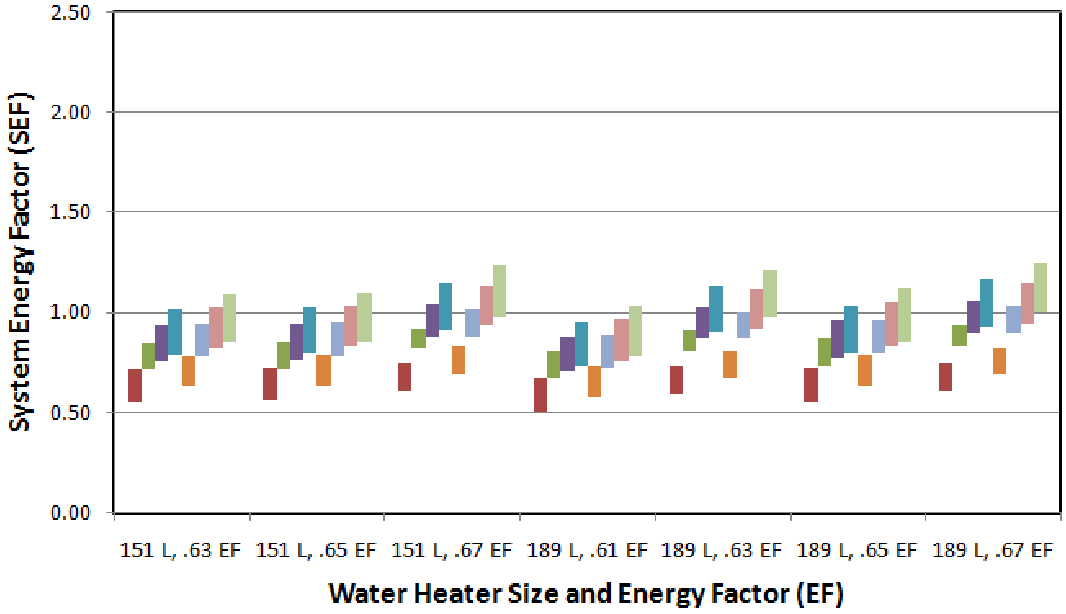
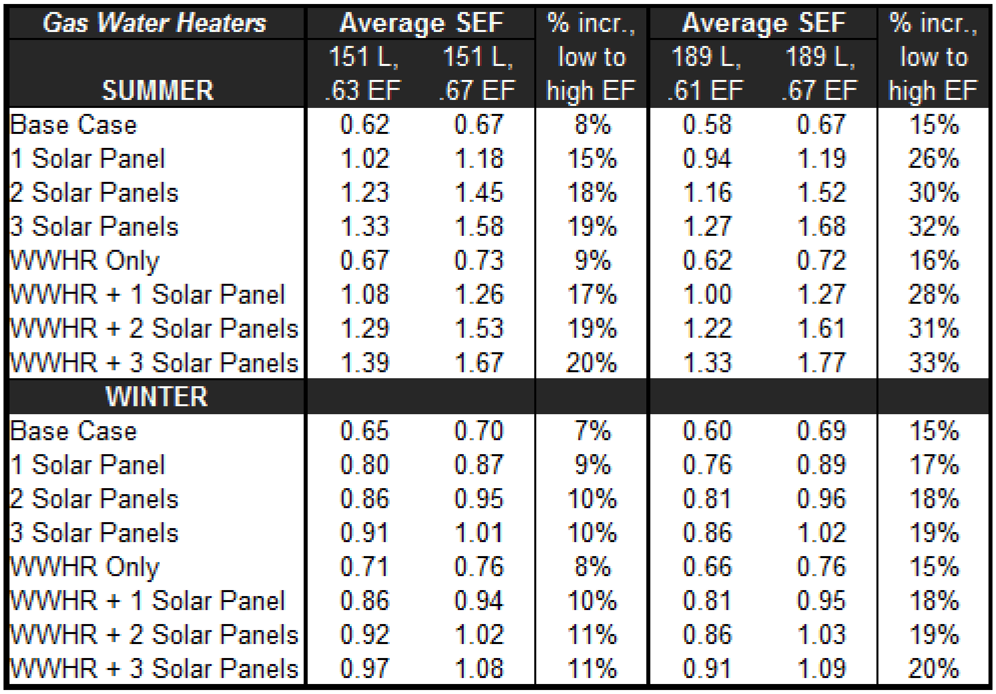


Figure 18: Ranges of SEF values for gas water heaters in winter, broken down by water heater tank size and EF as well as by additional technology type. The scale used is the same as in Figure 17 to allow for a more accurate visual comparison.

Table 12: Comparison of average SEF values for systems containing the lowest-rated and highest-rated gas water heaters. As in Table 11, percent increase of SEF between the lowest-rated heaters and the highest-rated is calculated.



Gas Water Heaters	Average SEF		% incr., low to high EF	Average SEF		% incr., low to high EF
SUMMER	151 L, .63 EF	151 L, .67 EF		189 L, .61 EF	189 L, .67 EF	
Base Case	0.62	0.67	8%	0.58	0.67	15%
1 Solar Panel	1.02	1.18	15%	0.94	1.19	26%
2 Solar Panels	1.23	1.45	18%	1.16	1.52	30%
3 Solar Panels	1.33	1.58	19%	1.27	1.68	32%
WWHR Only	0.67	0.73	9%	0.62	0.72	16%
WWHR + 1 Solar Panel	1.08	1.26	17%	1.00	1.27	28%
WWHR + 2 Solar Panels	1.29	1.53	19%	1.22	1.61	31%
WWHR + 3 Solar Panels	1.39	1.67	20%	1.33	1.77	33%
WINTER						
Base Case	0.65	0.70	7%	0.60	0.69	15%
1 Solar Panel	0.80	0.87	9%	0.76	0.89	17%
2 Solar Panels	0.86	0.95	10%	0.81	0.96	18%
3 Solar Panels	0.91	1.01	10%	0.86	1.02	19%
WWHR Only	0.71	0.76	8%	0.66	0.76	15%
WWHR + 1 Solar Panel	0.86	0.94	10%	0.81	0.95	18%
WWHR + 2 Solar Panels	0.92	1.02	11%	0.86	1.03	19%
WWHR + 3 Solar Panels	0.97	1.08	11%	0.91	1.09	20%

For systems with gas water heaters, the impact of the water heater rating is somewhat more significant. It should be noted that because the SEF values are so much lower to begin with for gas-based systems than for electric, a relatively small increase in average SEF will appear bigger as a percentage increase for a gas-based system than for an electric one.[13] Nonetheless, there is still a marked difference between the SEF increase due to water heater EF in a gas system versus that of an electric system.

In both summer and winter, the average SEF for base case and WWHR only scenarios increases by 7% to 9% for 151 L water heaters and by 15%-16% for 189 L water heaters. (This jump is larger in the 189 L models because a wider range of EFs is available and therefore four different models are being studied instead of three.) The impact for

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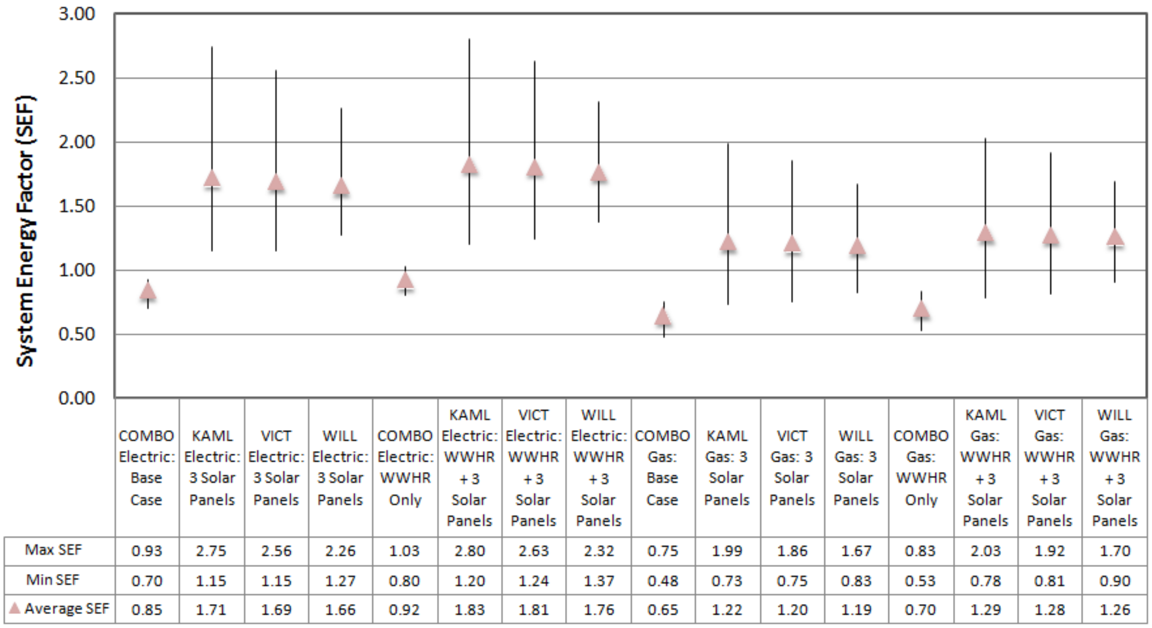
[13] As an example, an SEF increase of 0.10 represents a 5% increase in an electric, 151 L system with 3 solar panels (increase from 1.97 to 2.07), whereas an increase of that same size represents a 16% increase in a gas, 189 L system with WWHR (increase from 0.62 to 0.72).

systems with a solar component is higher; for 151 L water heaters the average SEF grows by as much as 20% in summer and 11% in winter, and for 189 L heaters as much as 33% in summer and 20% in winter.

One inconsistency to note is that the SEF ranges for the 189 L, .63-rated model actually come out higher than those for the supposedly more efficient .65-rated model, as seen in Figure 17 and Figure 18. This is likely due to the specifications particular to the .63 EF model that was chosen, as detailed in Appendix A. As can be seen in the Appendix, the RSI value, pipe diameter and insulation thickness of this particular model are similar to those of the highest-rated 189 L model, and it is likely that one or all of those factors contributed to its unexpectedly high performance in the simulation. Determining how such an anomaly might be avoided in the future bears investigation in future work.

6.5 Impact of region

It is also useful to examine what impact the simulated location may have on the overall performance of a system. Figure 19, below, offers a snapshot of how SEF varies between locations.



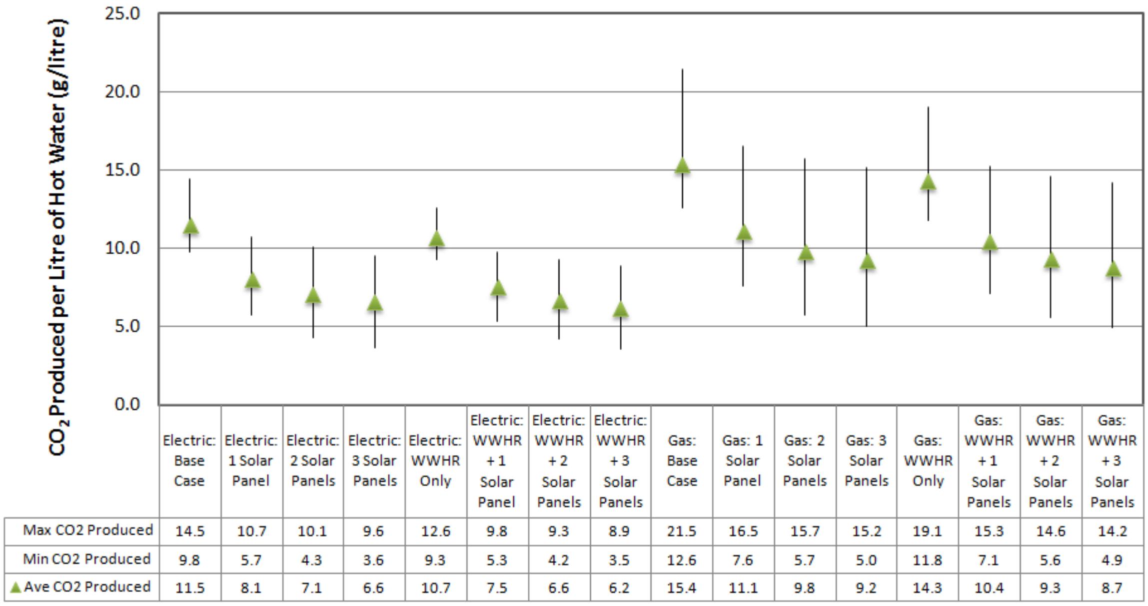
	COMBO Electric: Base Case	KAML Electric: 3 Solar Panels	VICT Electric: 3 Solar Panels	WILL Electric: 3 Solar Panels	COMBO Electric: WWHR Only	KAML Electric: WWHR + 3 Solar Panels	VICT Electric: WWHR + 3 Solar Panels	WILL Electric: WWHR + 3 Solar Panels	COMBO Gas: Base Case	KAML Gas: 3 Solar Panels	VICT Gas: 3 Solar Panels	WILL Gas: 3 Solar Panels	COMBO Gas: WWHR Only	KAML Gas: WWHR + 3 Solar Panels	VICT Gas: WWHR + 3 Solar Panels	WILL Gas: WWHR + 3 Solar Panels
Max SEF	0.93	2.75	2.56	2.26	1.03	2.80	2.63	2.32	0.75	1.99	1.86	1.67	0.83	2.03	1.92	1.70
Min SEF	0.70	1.15	1.15	1.27	0.80	1.20	1.24	1.37	0.48	0.73	0.75	0.83	0.53	0.78	0.81	0.90
▲ Average SEF	0.85	1.71	1.69	1.66	0.92	1.83	1.81	1.76	0.65	1.22	1.20	1.19	0.70	1.29	1.28	1.26

Figure 19: Impact of location on the SEF of a system. Base case and WWHR only systems are compared to those which include 3 solar panels, in all three regions.

Although the range of potential SEFs is greater in Kamloops than in either Victoria or Williams Lake, the average SEF for a given technology combination is quite similar across all regions. This is useful to note because it demonstrates that the impact of a given technology is relatively consistent regardless of the location, at least in the regions simulated here. It may be reasonable, therefore, to set similar SEF-based standards across a variety of regions in the Province.

6.6 CO_2 production

As stated earlier in this chapter, SEF should not be the sole means for evaluating a system; the rate of CO_2 production must also be considered. Figure 20, below, shows the range of CO_2 production for each technology type.



	Electric: Base Case	Electric: 1 Solar Panel	Electric: 2 Solar Panels	Electric: 3 Solar Panels	Electric: WWHR Only	Electric: WWHR + 1 Solar Panel	Electric: WWHR + 2 Solar Panels	Electric: WWHR + 3 Solar Panels	Gas: Base Case	Gas: 1 Solar Panel	Gas: 2 Solar Panels	Gas: 3 Solar Panels	Gas: WWHR Only	Gas: WWHR + 1 Solar Panels	Gas: WWHR + 2 Solar Panels	Gas: WWHR + 3 Solar Panels
Max CO2 Produced	14.5	10.7	10.1	9.6	12.6	9.8	9.3	8.9	21.5	16.5	15.7	15.2	19.1	15.3	14.6	14.2
Min CO2 Produced	9.8	5.7	4.3	3.6	9.3	5.3	4.2	3.5	12.6	7.6	5.7	5.0	11.8	7.1	5.6	4.9
▲ Ave CO2 Produced	11.5	8.1	7.1	6.6	10.7	7.5	6.6	6.2	15.4	11.1	9.8	9.2	14.3	10.4	9.3	8.7

Figure 20: Ranges of CO_2 production rates for each fuel and technology combination.

Predictably, for the same technology combinations the CO_2 levels are higher in gas-based systems than in electric, an increase of between 34% and 41%. Also predictably, the addition of alternative technologies causes a drop in CO_2 production. The addition of a WWHR component causes a ~7% average drop in CO_2 production for all cases. The introduction of a solar component reduces CO_2 production substantially, but the incremental impact of doubling or even tripling the size of that solar component is quite small by comparison, resulting in a diminishing return on investment for each additional panel.

For electric-based systems, a one-panel solar preheat component decreases the average CO_2 production to 30% below base case, while two and three-panel component decrease it to 38% and 43% below base case, respectively. Results for electric systems containing both solar preheat and waste water heat recovery are only slightly lower: 34% below base case for single-panel systems, and 42% and 46% for two and three-panel systems respectively.

While gas-based systems have a higher CO_2 production rate to begin with, the impact of alternative technologies is 2% to 3% poorer in these systems than in their electric counterparts. Here, a one-panel solar preheat component decreases the average CO_2 production to 28% below base case, while two and three-panel component decrease it to 36% and 40% below base case, respectively. Similarly, the impact of a combination waste water heat recovery and solar preheat system is a drop to 32% below base case for a one-panel system and 40% and 43% for two and three-panel systems respectively.

6.6.1 CO_2 and SEF

Because CO_2 production rate must be considered alongside SEF in determining how to evaluate a given system, it is useful to examine the interplay between the two metrics, as in Figure 21, below.

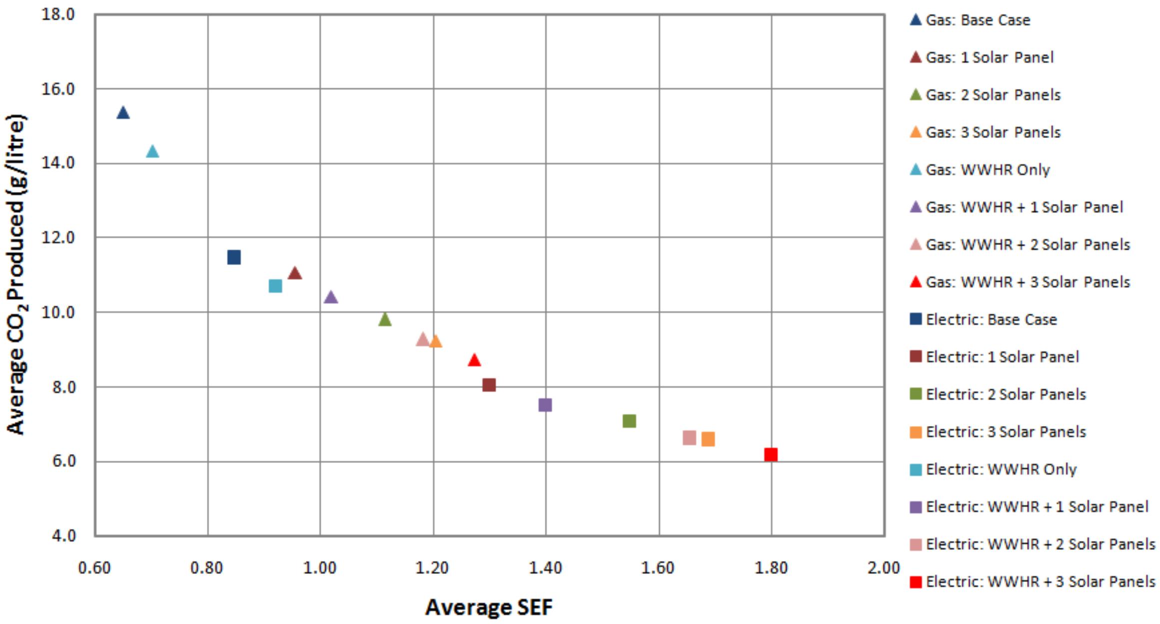


Figure 21: CO_2 production as a function of SEF. One point is shown for each fuel and technology combination, representing the average of all data simulated within that category.

Figure 21 presents a very simplified representation of the results, condensing the data for each combination of fuel and technology into one average value. The trend this illustrates is the significant disadvantage of gas versus electric water heaters overall. Gas base case and WWHR only systems average significantly lower in SEF and higher in CO_2 production than any other technology combinations. On the other end of the spectrum, two and three-panel electric-based systems – both with and without WWHR - stand out as the most desirable systems, with both the highest average SEFs and lowest average CO_2 production.

In the mid-performance ranges, groupings emerge among systems of different fuel and technology types. The data points for electric non-solar systems and gas single-panel systems, for instance, are grouped quite closely together, with the points for electric WWHR only and gas 1 solar panel almost equivalent to one another. Likewise, the average value for the most desirable gas-based systems (WWHR plus 3 solar panels) is quite close to that of the single-panel electric systems. These trends can prove useful in establishing ranking systems among the technologies, as will be explored in Chapter 7.

This simplified encapsulation of data, while quite visually clear, does leave out one technological component over which a homeowner or builder may exert control: the choice of water heater. Although this was shown in section 6.4 to have little impact on the SEF of electric-based systems, the impact of water heater choice on gas-based systems was shown in that section to be more significant, and its potential to impact CO_2 production has not yet been explored. Figure 22, therefore, shows the same information as its predecessor, with data for each water heater broken out into its own point.

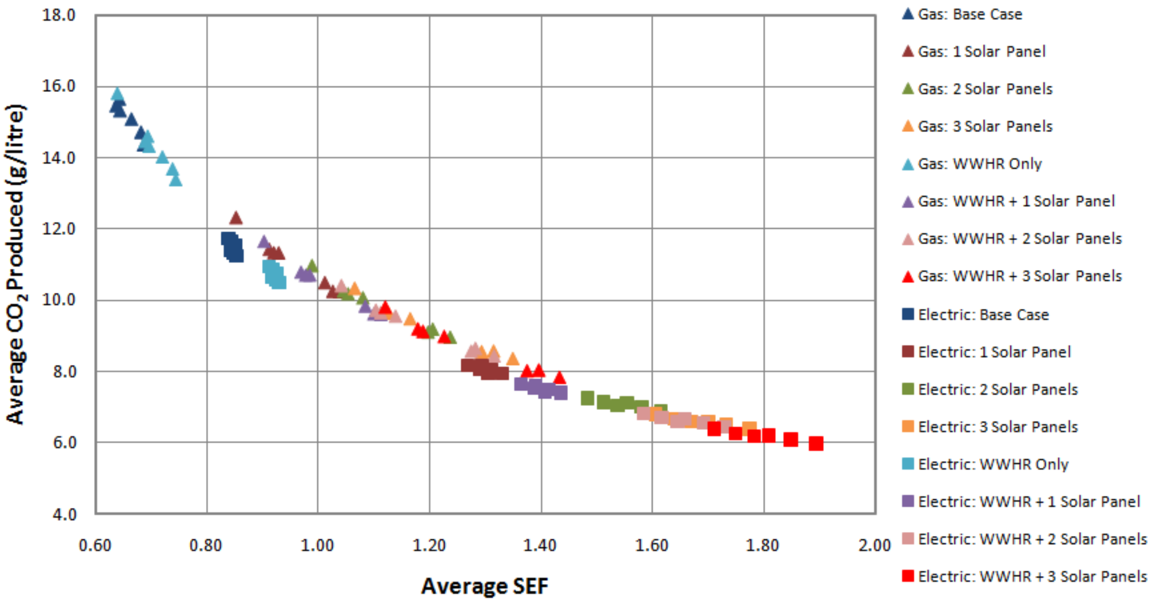


Figure 22: CO$_2$ production as a function of SEF, as in Figure 21, above. Here, average data for each water heater type is broken out into its own plot point.

Here, the trends noted in the more condensed Figure 21 continue, but it can be seen that the impact of water heater choice does, in some cases, prove noteworthy. The overall effect is two distinct and very similar curves, the electric-based curve slightly lower and markedly farther to the right on the graph than its gas-based counterpart, representing its more desirable performance both in SEF and in CO$_2$ production. As the performance of the system improves, so too does the gap in performance between the highest-rated and lowest-rated water heaters. This is most pronounced in the gas-based systems, where distinct gaps can be seen in between the plot points representing the water heaters with high EFs and those with lower EFs. These distinctions, too, may become significant in distilling the results into a ranking system.

Possible options for ranking systems, as well as the financial implications of system installation and several salient points derived from the data presented here, will be explored in the following chapter.

Chapter 7

Analysis and Discussion

This chapter presents a discussion of the results presented in Chapter 6. It explores the financial implications of the water heating systems simulated, examining potential savings, payback periods and cost of CO_2 reduction. Several salient points arising from the data presented in the previous chapter are discussed, and a proposal is made for two possible sets of tiers by which water-heating systems may be ranked. Finally, possibilities are examined for applying what has been learned from this research to other jurisdictions.

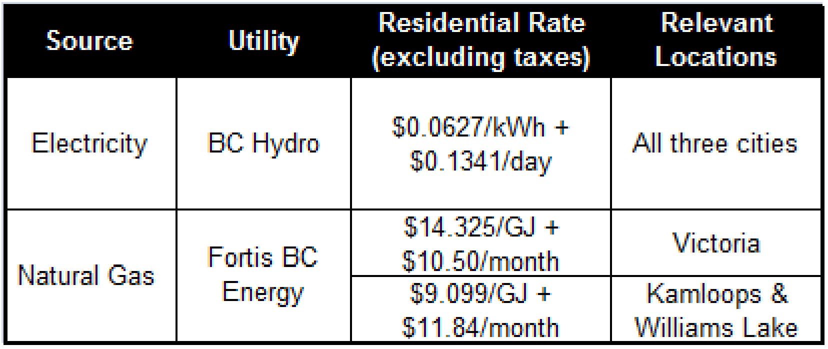
7.1 Financial analysis

While it is not the primary focus of this research, an evaluation of water heating technologies is incomplete without consideration of the financial impact of those components. What follows is a brief look at that potential impact.

7.1.1 Savings, costs and payback

Monetary savings for the homeowner is based upon the avoided cost of conventional energy saved due to the use of more efficient water heating technologies. Table 13, below, lists residential rates for electricity and natural gas in the locations simulated. All rates are current as of July 2011.

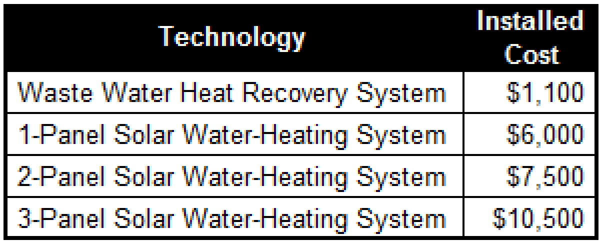
Table 13: Residential rates for electricity [65] and natural gas [66, 67] in the locations simulated.



Source	Utility	Residential Rate (excluding taxes)	Relevant Locations
Electricity	BC Hydro	\$0.0627/kWh + \$0.1341/day	All three cities
Natural Gas	Fortis BC Energy	\$14.325/GJ + \$10.50/month	Victoria
		\$9.099/GJ + \$11.84/month	Kamloops & Williams Lake

These savings must be weighed against the added cost incurred by the inclusion of the energy-saving technologies. While costs will vary from one supplier to the next, an approximation of typical installed costs may be found in Table 14.

Table 14: Approximate installed cost of energy-saving water-heating technologies [38, 68].



Technology	Installed Cost
Waste Water Heat Recovery System	\$1,100
1-Panel Solar Water-Heating System	\$6,000
2-Panel Solar Water-Heating System	\$7,500
3-Panel Solar Water-Heating System	\$10,500

As discussed in section 6.4, for electric-based systems the effect of the water heater rating has only a small effect of the overall performance of the system. For this reason, it is not useful to evaluate the financial impact of each electric water heater separately. Figure 23 shows the average incremental annual savings achieved due to the inclusion of energy-saving technologies in electric-based systems, juxtaposed with the incremental capital costs required.

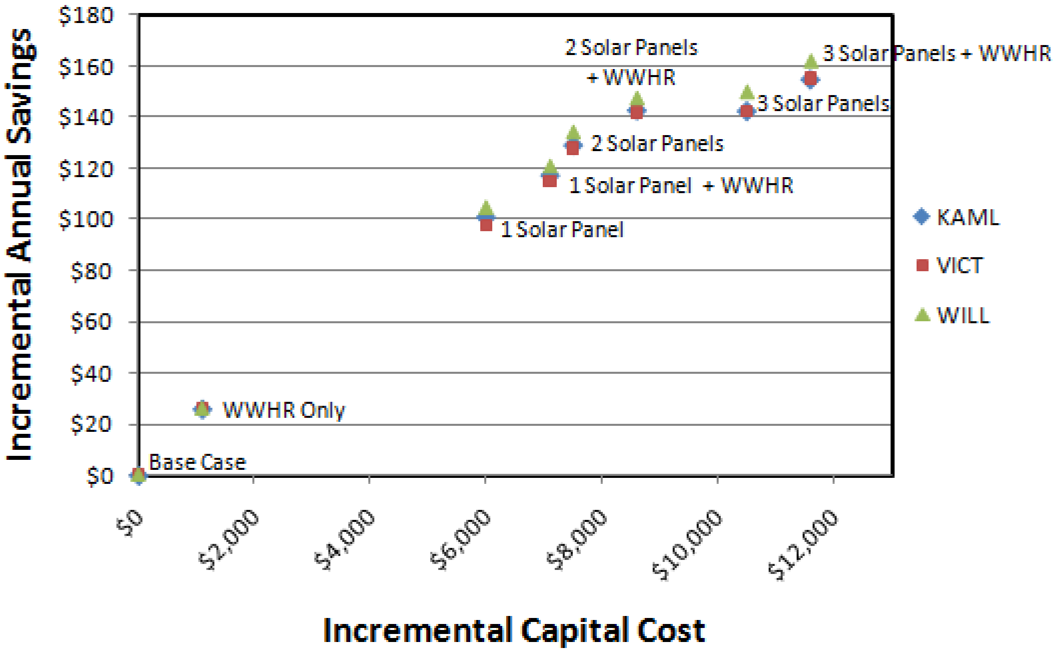


Figure 23: Average incremental annual savings vs. incremental capital cost for electric-based water heating systems.

The relationship between annual savings and capital cost progresses almost linearly until a third solar panel is added. The savings of the 3-panel options remains flat, with little to no increase over the 2-panel + WWHR option, despite the increase in capital cost, showing the 3-panel options to be the least cost-effective of those simulated. Despite the linear progression, however, the difference in scale between annual savings and capital cost is so large as to still render most of these options untenable, as will be discussed shortly.

Because the EF of a gas water heater does affect the performance of the overall system, the individual water heaters simulated have been broken out for this analysis. Approximate incremental capital costs of gas water heaters, which increase with the EF rating, are shown in Table 15.

Table 15: Approximate incremental capital cost of gas water heaters, as interpolated from [12].

Energy Factor	Incremental Capital Cost over Base Case	
	151 L	189 L
EF 0.61	N/A	Base Case
EF 0.63	Base Case	$65
EF 0.65	$62	$135
EF 0.67	$123	$201

Aside from the comparatively small addition of the incremental water heater cost, the capital cost of each technology remains the same as in Table 14. Because the plot points for each technology type fall into the same distinct columns as in Figure 23, they have not been explicitly labeled in Figure 24-Figure 26, below. The same scale has been used for each of the three figures to better illustrate the difference in savings between Victoria and the other two cities.

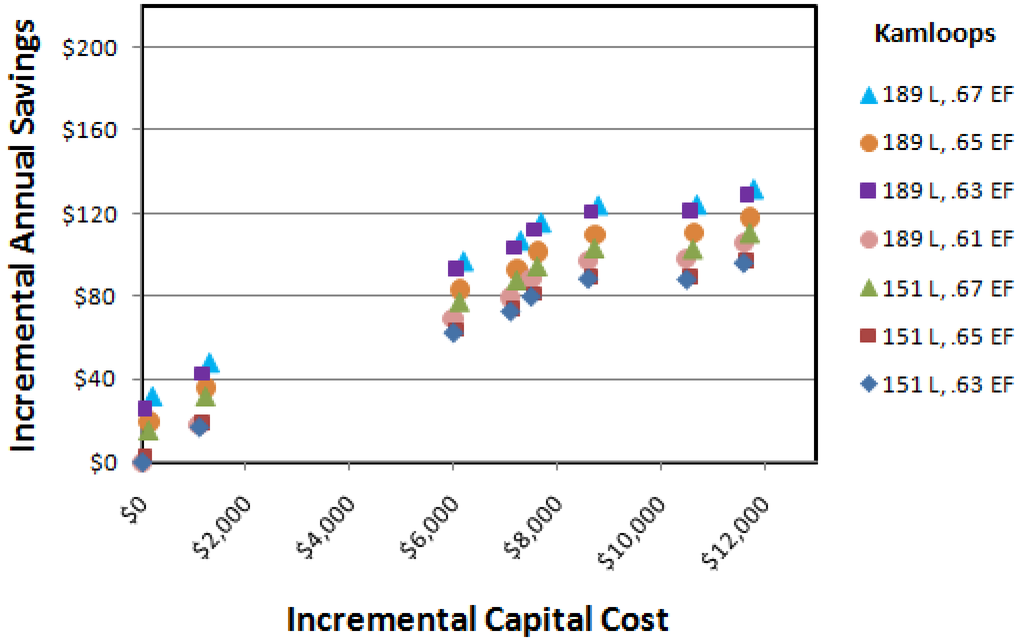


Figure 24: Average incremental annual savings vs. incremental capital cost for gas-based water heating systems in Kamloops.

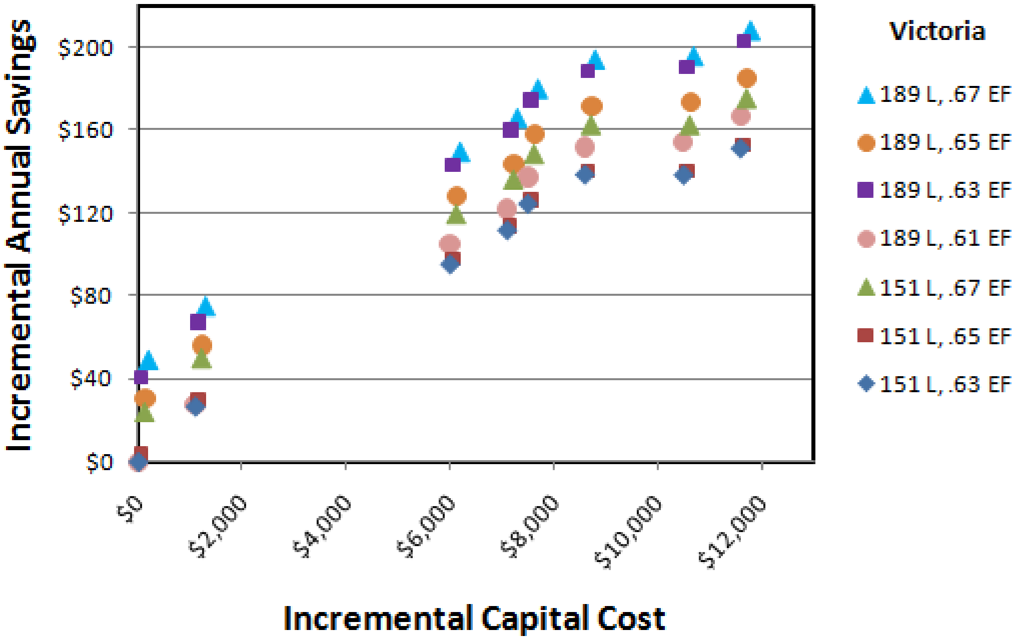


Figure 25: Average incremental annual savings vs. incremental capital cost for gas-based water heating systems in Victoria.

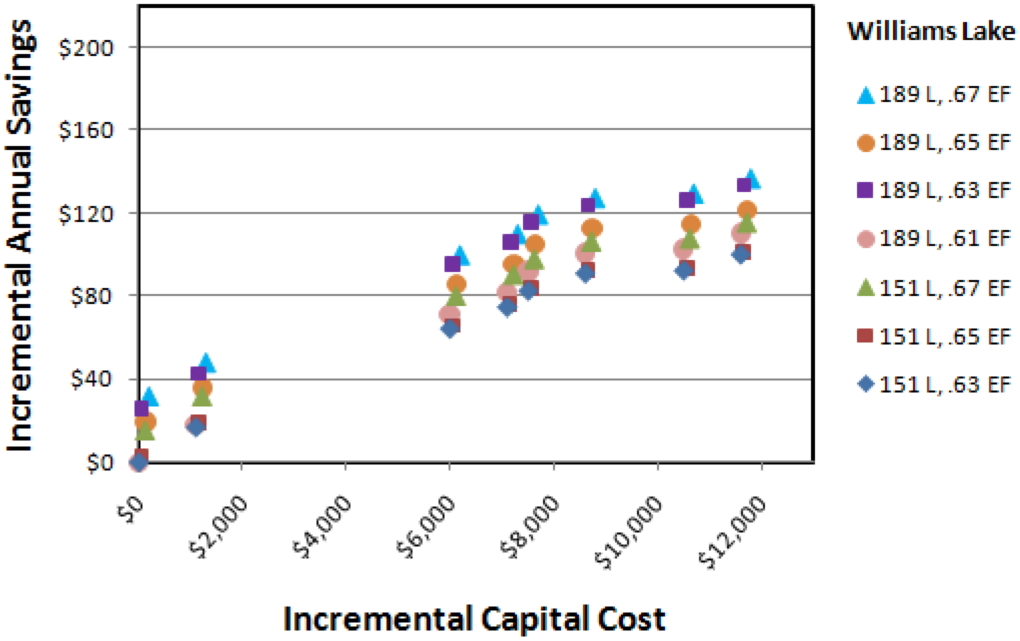


Figure 26: Average incremental annual savings vs. incremental capital cost for gas-based water heating systems in Williams Lake.

As with the electric-based systems, the relationship between cost and savings progresses linearly for each water heater profiled, but jumps off track when a third solar panel is added. For a given technology type, the range of savings is lower for gas-based systems in Kamloops and Williams Lake than for electric-based systems (see Figure 23), but that range of savings is greater in Victoria for gas than for electric. This difference can be attributed to the difference in fuel cost between Victoria and the other two cities, as seen in Table 13. Like the electric-based systems as well, the scale of savings is several orders of magnitude smaller than that of cost.

This impact of this divergence between cost and savings can be borne out by determining the payback period of the installed system, an indicator used in other studies including that of SaskEnergy [38, 69]. Paypack period is largely dependent upon the price of fuel, so several different fuel cost scenarios have been calculated. The *simple payback* calculation assumes no price increase for the lifetime of the technologies. A second calculation assumes a 2.5% annual price increase and, finally, a third calculation assumes an immediate jump to three times the current price, without any subsequent increase.[14]

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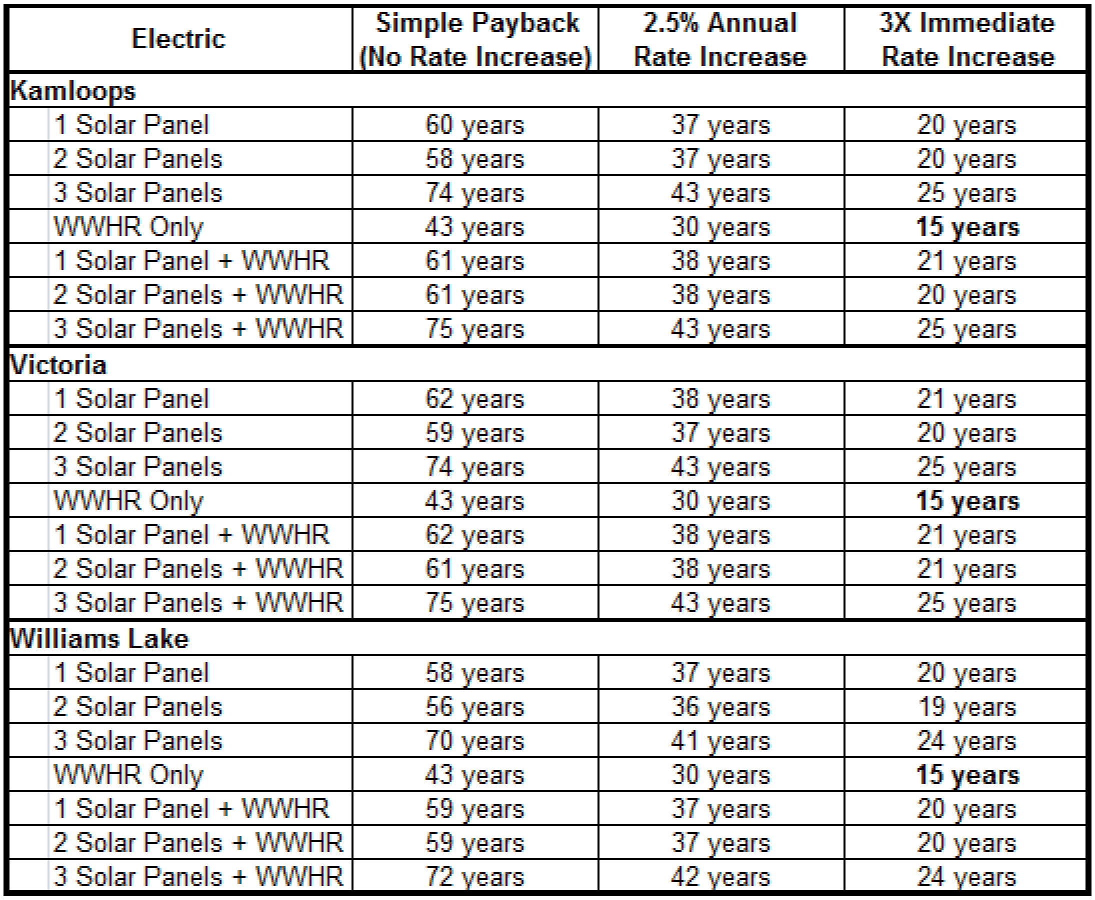
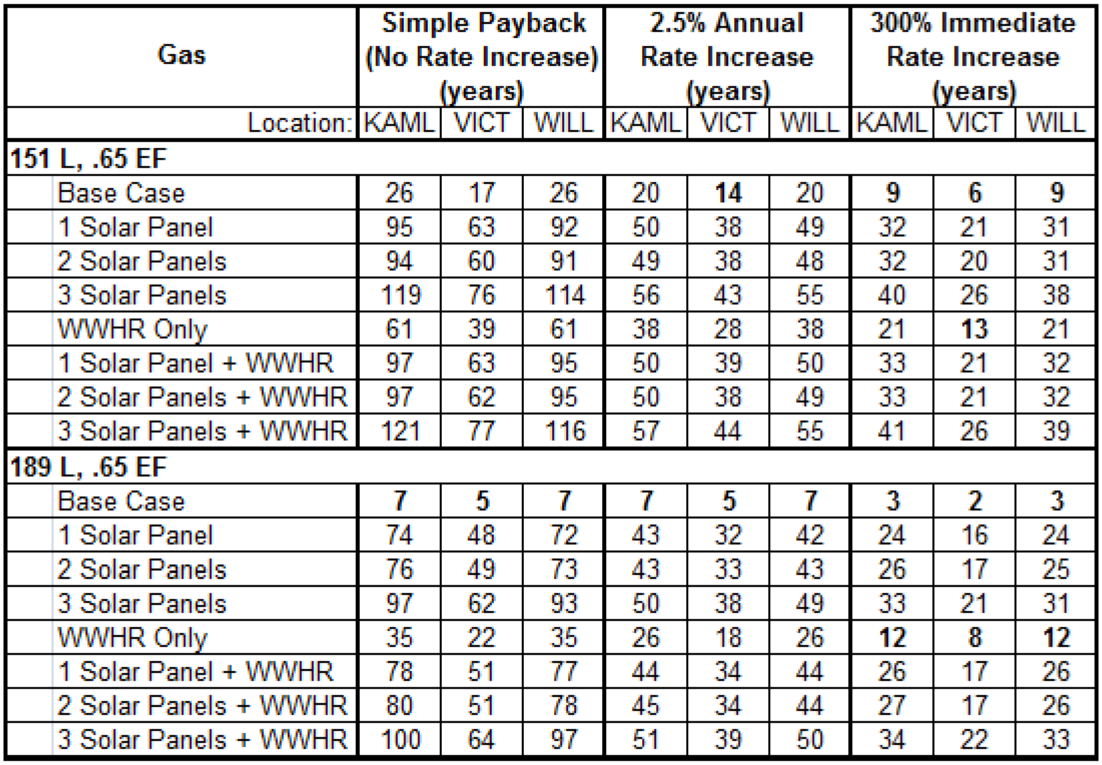
[14] A 300% increase in price is a dramatic and perhaps unrealistic option, but is on the same scale as that used in SaskEnergy's water heating trial analysis [38]. It represents a worst-case scenario in terms of fuel cost increase.

Table 16: Possible payback periods for electric-based water heating systems, using three different electricity price scenarios.



Electric	Simple Payback (No Rate Increase)	2.5% Annual Rate Increase	3X Immediate Rate Increase
Kamloops			
1 Solar Panel	60 years	37 years	20 years
2 Solar Panels	58 years	37 years	20 years
3 Solar Panels	74 years	43 years	25 years
WWHR Only	43 years	30 years	**15 years**
1 Solar Panel + WWHR	61 years	38 years	21 years
2 Solar Panels + WWHR	61 years	38 years	20 years
3 Solar Panels + WWHR	75 years	43 years	25 years
Victoria			
1 Solar Panel	62 years	38 years	21 years
2 Solar Panels	59 years	37 years	20 years
3 Solar Panels	74 years	43 years	25 years
WWHR Only	43 years	30 years	**15 years**
1 Solar Panel + WWHR	62 years	38 years	21 years
2 Solar Panels + WWHR	61 years	38 years	21 years
3 Solar Panels + WWHR	75 years	43 years	25 years
Williams Lake			
1 Solar Panel	58 years	37 years	20 years
2 Solar Panels	56 years	36 years	19 years
3 Solar Panels	70 years	41 years	24 years
WWHR Only	43 years	30 years	**15 years**
1 Solar Panel + WWHR	59 years	37 years	20 years
2 Solar Panels + WWHR	59 years	37 years	20 years
3 Solar Panels + WWHR	72 years	42 years	24 years

Table 17: Possible payback periods for gas-based water heating systems, using three different electricity price scenarios. Only mid-range (.65 EF) water heaters are shown here. A complete list may be found in Appendix C.

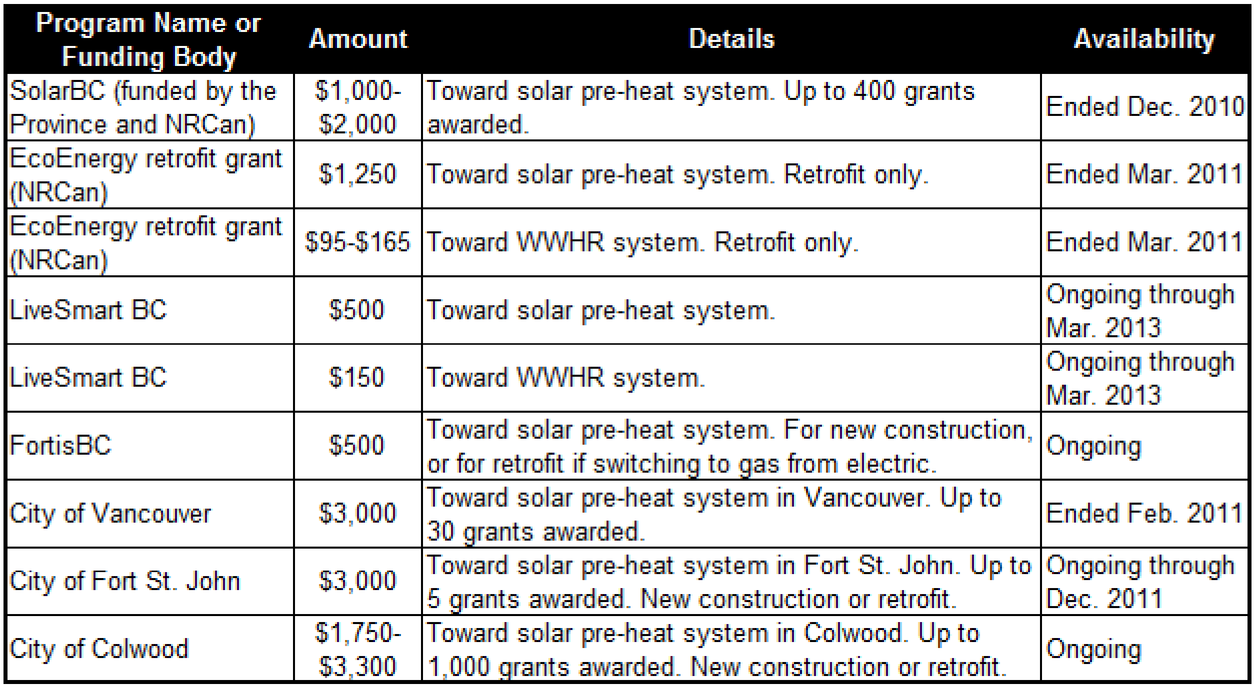


Gas	Simple Payback (No Rate Increase) (years)			2.5% Annual Rate Increase (years)			300% Immediate Rate Increase (years)		
Location:	KAML	VICT	WILL	KAML	VICT	WILL	KAML	VICT	WILL
151 L, .65 EF									
Base Case	26	17	26	20	**14**	20	**9**	**6**	**9**
1 Solar Panel	95	63	92	50	38	49	32	21	31
2 Solar Panels	94	60	91	49	38	48	32	20	31
3 Solar Panels	119	76	114	56	43	55	40	26	38
WWHR Only	61	39	61	38	28	38	21	**13**	21
1 Solar Panel + WWHR	97	63	95	50	39	50	33	21	32
2 Solar Panels + WWHR	97	62	95	50	38	49	33	21	32
3 Solar Panels + WWHR	121	77	116	57	44	55	41	26	39
189 L, .65 EF									
Base Case	**7**	**5**	**7**	**7**	**5**	**7**	**3**	**2**	**3**
1 Solar Panel	74	48	72	43	32	42	24	16	24
2 Solar Panels	76	49	73	43	33	43	26	17	25
3 Solar Panels	97	62	93	50	38	49	33	21	31
WWHR Only	35	22	35	26	18	26	**12**	**8**	**12**
1 Solar Panel + WWHR	78	51	77	44	34	44	26	17	26
2 Solar Panels + WWHR	80	51	78	45	34	44	27	17	26
3 Solar Panels + WWHR	100	64	97	51	39	50	34	22	33

These calculations show that, at their current costs, most of the systems simulated are not financially viable. Assuming an estimated system lifespan of fifteen years, few of the configurations have hope of reaching their payback periods within the lifespan of the system. The systems which do reach their payback period within fifteen years (shown in bold in Table 16 and Table 17) tend to be those which have the lowest incremental capital costs as well as the lowest annual savings: systems which include only an upgraded water heater rather than the additional energy-saving technologies. Only in the worst-case scenario involving a 300% increase in fuel cost do many of the systems involving waste-water heat recovery or solar pre-heat technologies even approach financial viability, and several never approach it at all. The capital costs as they stand are simply too great to be overcome by energy savings alone.

One possible means of reducing the capital costs of these systems is through incentive plans or subsidies. There are several such programs, either currently available within the Province or recently discontinued, which could each reduce the capital cost by some measure, thereby reducing the payback period as well. These programs are listed in Table 18.

Table 18: Subsidies currently or recently available within British Columbia for residential installation of solar pre-heat or WWHR systems [70-78].



Program Name or Funding Body	Amount	Details	Availability
SolarBC (funded by the Province and NRCan)	$1,000-$2,000	Toward solar pre-heat system. Up to 400 grants awarded.	Ended Dec. 2010
EcoEnergy retrofit grant (NRCan)	$1,250	Toward solar pre-heat system. Retrofit only.	Ended Mar. 2011
EcoEnergy retrofit grant (NRCan)	$95-$165	Toward WWHR system. Retrofit only.	Ended Mar. 2011
LiveSmart BC	$500	Toward solar pre-heat system.	Ongoing through Mar. 2013
LiveSmart BC	$150	Toward WWHR system.	Ongoing through Mar. 2013
FortisBC	$500	Toward solar pre-heat system. For new construction, or for retrofit if switching to gas from electric.	Ongoing
City of Vancouver	$3,000	Toward solar pre-heat system in Vancouver. Up to 30 grants awarded.	Ended Feb. 2011
City of Fort St. John	$3,000	Toward solar pre-heat system in Fort St. John. Up to 5 grants awarded. New construction or retrofit.	Ongoing through Dec. 2011
City of Colwood	$1,750-$3,300	Toward solar pre-heat system in Colwood. Up to 1,000 grants awarded. New construction or retrofit.	Ongoing

Subsidies such as these, particularly if combined with one another, could reduce the cost of some systems by anywhere between 5% and 88%, thus improving the payback period by a similar margin. Although a detailed examination of these programs and their potential financial impact is not included here, they are important factors to consider in future analysis.

7.1.2 Cost and CO_2

Another relevant factor when examining financial considerations is the relationship between cost and CO_2 reduction.[15] This relationship is illustrated in Figure 27. The incremental net expenditure is equal to the incremental capital cost of the system minus the incremental savings accrued over fifteen years (an annual fuel price escalation of 2.5% is assumed).

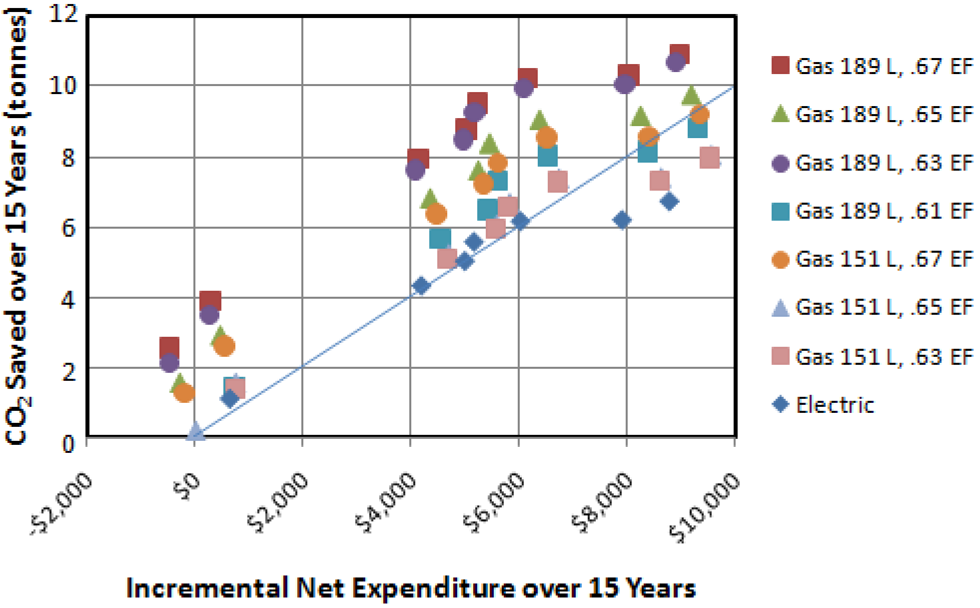


Figure 27: CO_2 saved over base case as a function of net cost. The blue line shows the 1:1 ratio of net \$ spent to kg CO_2 saved.

Base case systems, at the far left of Figure 27, get considerably more "bang for their buck" with apparently negative net expenditures (that is, the systems earn money back for the owners as well as reducing CO_2 emissions). Because the figure of fifteen years and

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[15] It should be remembered that the incremental CO_2 savings shown here are incremental with respect to the base case for each water heater type. That is, incremental CO_2 savings for electric-based systems are shown with respect to the base case electric water heater, incremental CO_2 savings for gas-based systems with 151 L tanks are shown with respect to the base case for that tank size, and likewise savings for gas-based systems with 189 L tanks. As shown in Figure 20, CO_2 production for electric-based systems tends to be 35-40% lower than that for gas-based systems.

the incremental net expenditures themselves are both rough estimates, the actual numbers shown are less important as a point of focus than is the relationship of the various data points to one another. Of particular note is the fact that ratio of cost to CO_2 savings increases as the cost of equipment goes up. The diagonal line on the graph represents a steady 1:1 ratio of dollars spent to CO_2 saved in kg. The proportion of CO_2 reduction per dollar spent gets considerably worse as the cost of the system grows, with 3-panel solar pre-heat systems falling largely below the line.

Figure 28 presents this data in terms of net dollars spent per tonne of CO_2 saved. The base case scenarios, which have only to contend with the small incremental cost of higher-EF water heaters, show, as in Figure 27, a mostly negative net expenditure per tonne of CO_2. WWHR only scenarios range about \$70 to \$570 per tonne, and scenarios involving solar pre-heat components range between \$520 and \$1275 per tonne.

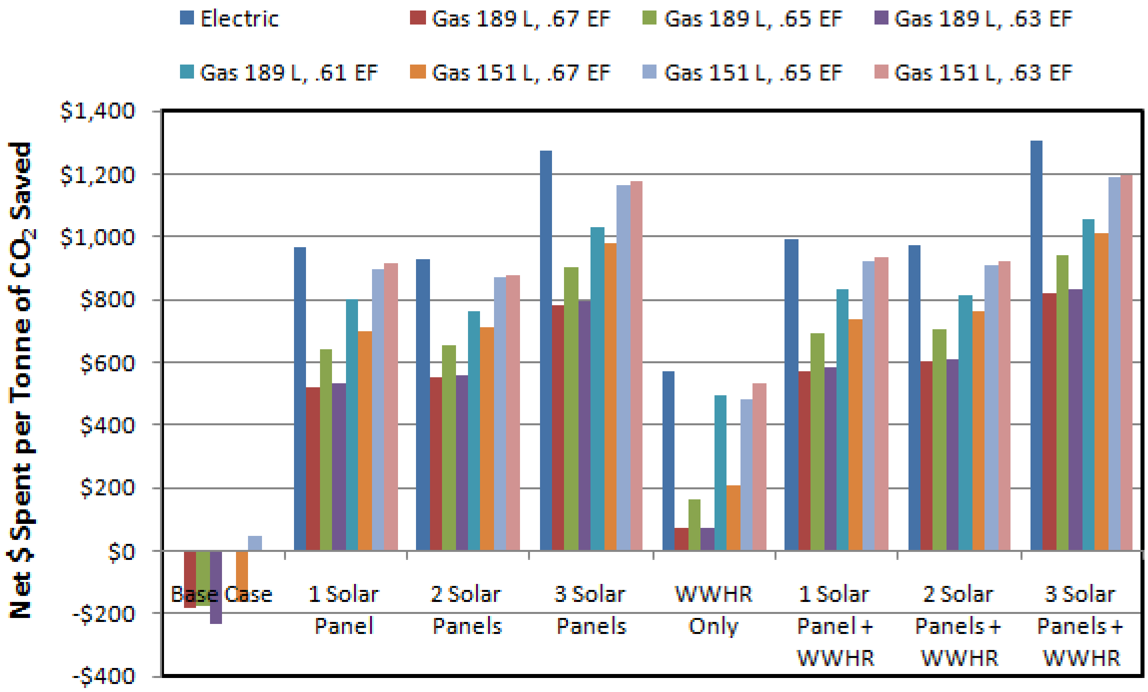


Figure 28: Net dollars spent per tonne of CO_2 saved over a fifteen year period.

But how much is a reasonable amount for a builder or homeowner to pay for the reduction of CO_2 emissions? To answer this question, one might look to the most analogous commodity available to individual consumers, the carbon offset. A survey of twenty carbon offset providers done by the organization EcoBusinessLinks.com found that prices of carbon offsets sold to individuals in North American markets range between USD$2.75/tonne and USD$29.00/tonne [79]. In British Columbia, the Vancouver-based organization, Offsetters - billed as, “Canada’s leading provider of carbon-management solutions,” – sells a majority of their carbon offsets for individuals at $20/tonne, while 10% of customers opt for the “Gold Standard” option at $30/tonne [80].

With these prices for comparison, it is clear that the cost of CO_2 reduction via waste-water heat recovery or solar pre-heat is, from a market standpoint, unreasonably high. WWHR sits at roughly 3 to 25 times the market rate for carbon offsets, and solar pre-heat at 25 to 50 times the market rate. At these capital costs, even a subsidy or incentive-based cost reduction would not be sufficient to make up the difference. These systems, therefore, cannot be concluded to be economically viable solely for their impact on CO_2 reduction.

7.2 Discussion

Points discussed in this section will refer back to data originally presented in previous sections.

7.2.1 Electricity vs. gas

The choice between gas-based and electric-based water heating systems plays a significant role in that system’s overall efficiency and carbon impact. As shown in Figure

10, average SEF is 23% to 29% lower in electric-based systems than in gas for like technology combinations, and Figure 20 shows CO_2 emissions from gas-based systems 34%-41% higher than those of their electric-based counterparts. Based solely on these factors, selection of fuel type may seem relatively straightforward. Yet the decisions of consumers are decidedly more complex, and the impact of financial considerations must not be underestimated.

When it comes to consumer choice, market forces may, in fact, push the pendulum in the opposite direction. The BC Utilities Commission has approved tiered electricity rates as part of BC Hydro's long-term plan to reduce electricity consumption via demand-side management [81]. This means electricity prices can be expected to go up in the coming years, whereas natural gas prices have declined by more than 50% over the past five years, and their outlook remains low and stable [82]. This trend could incentivize consumers to choose gas-based water heaters over electric despite the fact that gas is higher in GHG intensity than BC's aggregate electricity supply, so the overall benefit to the province in terms of emissions could be negative.

7.2.2 Seasonal limitations

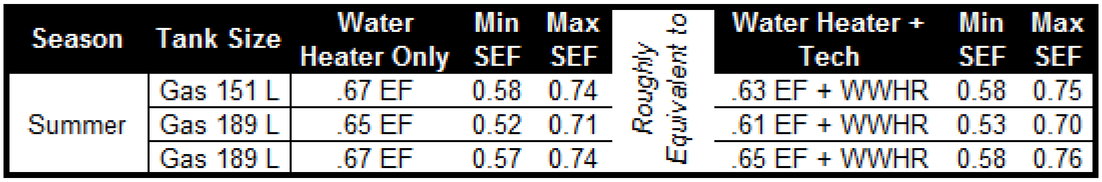
The seasonal and/or intermittent nature of renewable energy resources is a fact which often complicates efforts toward renewable electricity generation. Solar-assisted water heating must contend with this as well. Figure 11 through Figure 14 demonstrate the limited benefit of a solar pre-heat component in winter as opposed to summer. The practical implication of this is that a homeowner in BC cannot rely upon a solar water heating component as a primary water heating source. A full conventional system must be maintained as well which, as seen in section 7.1, results in capital cost penalties which may be insurmountable to the homeowner.

7.2.3 Limited impact of water heater EF

As discussed in section 6.4, the potential impact of water heater EF on the overall SEF of the system is less than 6% for electric-based systems and only as much as 33% for some gas-based systems. Perhaps more telling than the strict numerical impact, however, is to frame that impact in comparison to the potential impact of the other simulated technologies.

One question posed by MEMPR at the onset of this research is whether the addition of an energy-saving technology to a low-rated water heater might increase the performance of the system to a level equivalent to the performance of a higher-rated water heater alone. In most cases, this does not happen. The addition of a solar preheat component to a low-rated water heater invariably raises the SEF of the system much higher than would simply increasing the water heater EF. This is usually the case when adding a WWHR component as well. There are only a few cases in which adding a WWHR component and raising the water heater EF increase the SEF to roughly equivalent levels. These few examples, which can be viewed graphically in Figure 17, are shown in Table 19.

Table 19: The few cases in which a higher water heater EF yields an SEF range equivalent to adding a WWHR component.



Season	Tank Size	Water Heater Only	Min SEF	Max SEF	Roughly Equivalent to	Water Heater + Tech	Min SEF	Max SEF
Summer	Gas 151 L	.67 EF	0.58	0.74		.63 EF + WWHR	0.58	0.75
	Gas 189 L	.65 EF	0.52	0.71		.61 EF + WWHR	0.53	0.70
	Gas 189 L	.67 EF	0.57	0.74		.65 EF + WWHR	0.58	0.76

All such examples occur with gas water heaters in the summer. Such equivalency is never achieved with electric water heaters, and is never achieved in the winter.

This illustrates that the current practice of regulating water heating efficiency based solely on the EF of the water heater leaves much to be desired. The overall impact of such a standard is extremely limited when compared with the potential impact of incorporating other energy-saving technologies into the standard. The cost to the consumer to choose a higher rated water heater is low, but so is the relative impact of that choice in terms of energy savings and CO_2 reduction.

7.2.4 Proposed tiers

As discussed in the previous section, the focus on water heater EF as the only standard for water heating regulation has a fairly low impact as compared with the impact that might be achieved by focusing the standard on the overall system. The metrics considered in this analysis provide building blocks from which new, system-based criteria for regulation might be formulated.

Figure 21 and Figure 22 bring together SEF and CO_2 production rate data, which together may be taken as means to evaluate the desirability of a given system type. Taking the data generated in this study as representative, the patterns which emerge in these figures can inform the creation of performance tiers. Figure 29, below, uses the condensed data of Figure 21 as a basis for tier distillation.

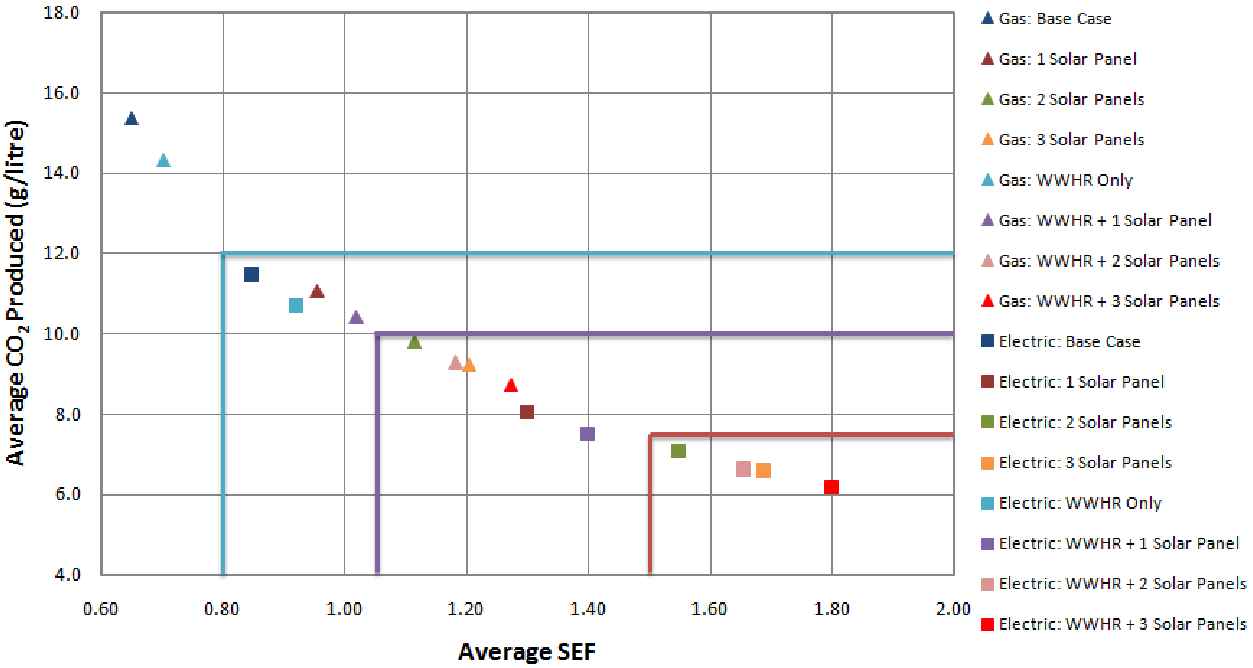


Figure 29: One proposed set of performance tiers, using as a basis condensed CO_2 and SEF data for each fuel and technology combination.

A set of four tiers is proposed here. The tiers are devised based on natural gaps that arise between visual groupings of data.[16] The lowest-performing set, with SEF below 0.80 and CO_2 production above 12 g/litre, includes only lone gas water heaters and those same units plus the inclusion of WWHR. The second tier, with SEF between 0.81 and 1.05 and CO_2 production between 10 and 12 g/litre, includes lone electric water heaters and electric plus WWHR systems, as well as gas-based systems with a 1-panel solar preheat component, both with and without WWHR. The third tier, with SEF between 1.06 and 1.50 and CO_2 production between 7.5 and 10 g/litre, includes gas-based systems with 2 and 3-panel solar preheat components as well as electric-based systems with 1-panel solar preheat components, all with or without the addition of WWHR. And finally the highest tier, with SEF above 1.50 and CO_2 production below 7.5 g/litre, which

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[16] The exact numerical placement of the tier lines is less important than the make-up of systems in each group. An individual system, after all, may perform outside any prescribed tier boundaries, but the purpose here is to draw distinctions between systems which can, in general, be expected to outperform others and those which underperform.

contains the electric-based systems with 2 and 3-panel solar preheat components, both with and without WWHR.

The tiers proposed using this approach are straightforward and easy to understand, with a new level reached whenever solar preheat is added, and again if multiple solar panels are included. Yet because this plan does not differentiate between water heaters, any benefit that may be gained from choosing a water heater with a higher EF is ignored, thus eliminating potential incentive to choose that option. Figure 30 uses the expanded water heater data of Figure 22 to draw distinctions between groupings.

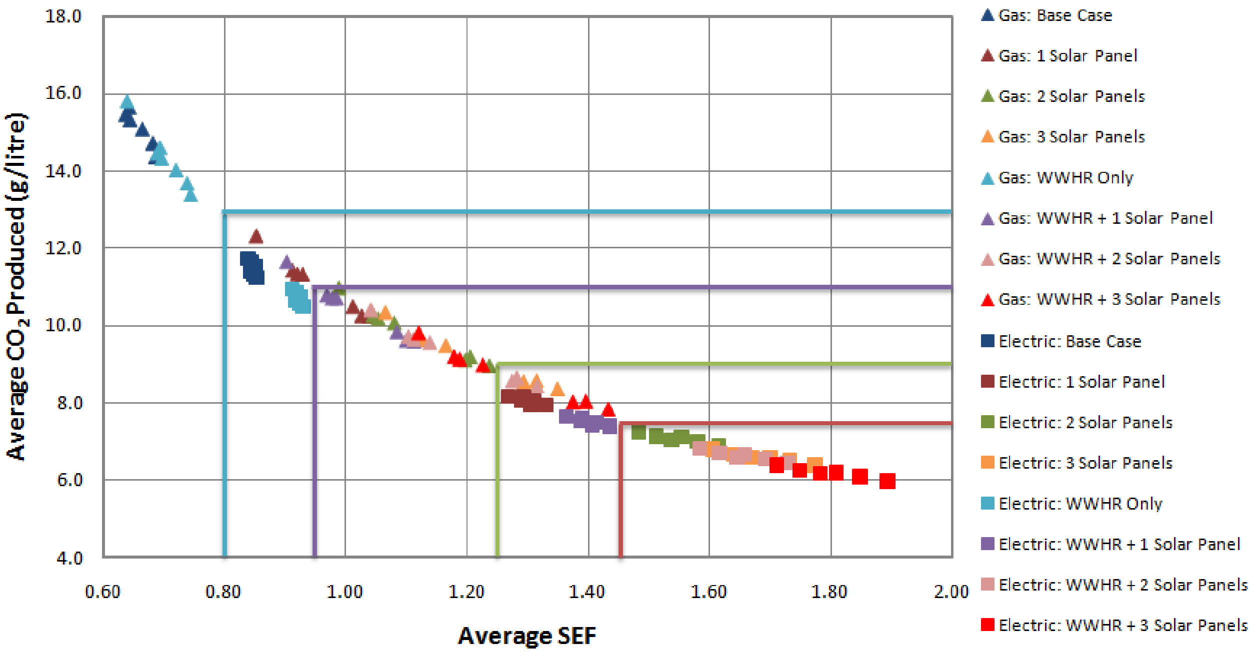
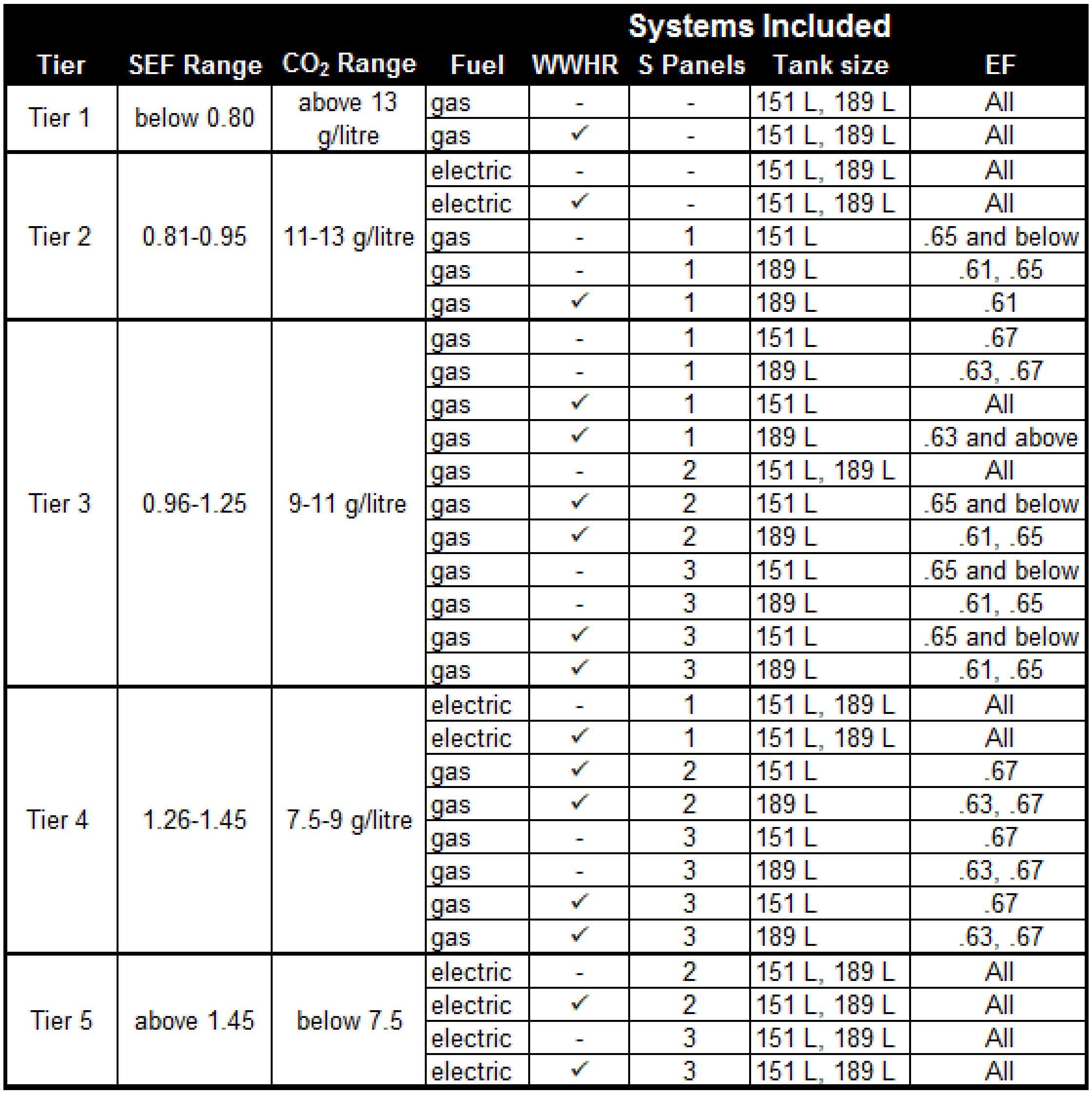


Figure 30: A second proposed set of tiers, this time distinguishing between data for various water heater types.

Because of the density of data points, natural gaps in the data are harder to distinguish, yet several do emerge. Here, five tiers are proposed, falling in slightly different places than in the previous example. Because it is not readily apparent which water heaters fall into which tiers, the tier definitions are clarified in Table 20.

Table 20: Proposed tiers including distinctions between water heaters, based on Figure 30.[17]



			Systems Included				
Tier	SEF Range	CO_2 Range	Fuel	WWHR	S Panels	Tank size	EF
Tier 1	below 0.80	above 13 g/litre	gas	-	-	151 L, 189 L	All
			gas	✓	-	151 L, 189 L	All
Tier 2	0.81-0.95	11-13 g/litre	electric	-	-	151 L, 189 L	All
			electric	✓	-	151 L, 189 L	All
			gas	-	1	151 L	.65 and below
			gas	-	1	189 L	.61, .65
			gas	✓	1	189 L	.61
Tier 3	0.96-1.25	9-11 g/litre	gas	-	1	151 L	.67
			gas	-	1	189 L	.63, .67
			gas	✓	1	151 L	All
			gas	✓	1	189 L	.63 and above
			gas	-	2	151 L, 189 L	All
			gas	✓	2	151 L	.65 and below
			gas	✓	2	189 L	.61, .65
			gas	-	3	151 L	.65 and below
			gas	-	3	189 L	.61, .65
			gas	✓	3	151 L	.65 and below
			gas	✓	3	189 L	.61, .65
Tier 4	1.26-1.45	7.5-9 g/litre	electric	-	1	151 L, 189 L	All
			electric	✓	1	151 L, 189 L	All
			gas	✓	2	151 L	.67
			gas	✓	2	189 L	.63, .67
			gas	-	3	151 L	.67
			gas	-	3	189 L	.63, .67
			gas	✓	3	151 L	.67
			gas	✓	3	189 L	.63, .67
Tier 5	above 1.45	below 7.5	electric	-	2	151 L, 189 L	All
			electric	✓	2	151 L, 189 L	All
			electric	-	3	151 L, 189 L	All
			electric	✓	3	151 L, 189 L	All

The top and bottom tiers in each of these scenarios remain the same. It is only in choosing to distinguish between water heaters in the middle tiers that the differentiation becomes so complex. Whether or not the benefit derived from considering each water heater individually is worth the complexity is an issue which bears consideration.

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[17] It should be noted that the 189 L .63 EF water heater, the inconsistency of which has been discussed in section 6.4, is grouped with the .67 EF water heater in this table, while the .65 EF water heater often falls into a lower tier. It is presumed that this is a result of the faulty data associated with the particular .63 EF water heater simulated and that, should that issue be resolved, the .63 EF water heater would not outperform the .65 EF water heater but would in fact fall into the lower tier with it.

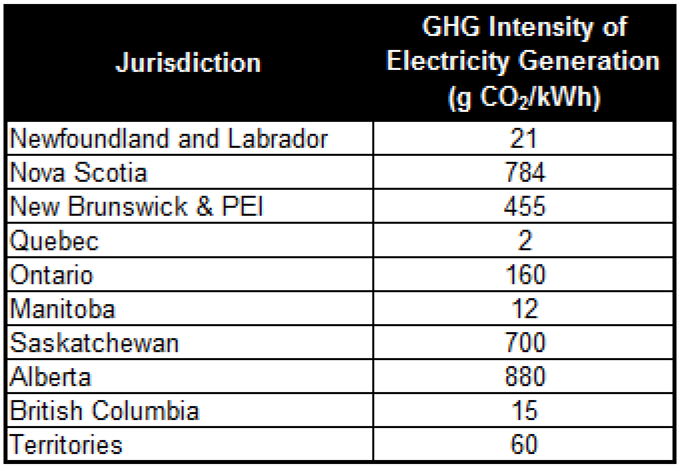
It is important when considering these tier proposals to note that they, of course, reflect only the technologies simulated in this study. The impact of other technologies, such as tankless water heaters, heat pump water heaters and changes in pipe configuration, should be similarly tested. Once those technologies and combinations of technologies can be evaluated alongside these, the proposed tier placement may change to reflect that data.

7.3 Possibilities for other jurisdictions

Because this research arose out of interest on behalf of the BC government to pursue a systems-based approach to water heating, this study is concerned primarily with results within the Province. It may be useful, however, to consider how a systems-based approach might play out in other jurisdictions across Canada as well.

A contributing factor to the consistent relegation of gas-based systems to the lower performance tiers is the fact that the GHG intensity of electricity in British Columbia is relatively low, due to the fact that a majority of the Province's electricity comes from hydro. In other provinces, however, where fossil fuels are more heavily in use for electricity generation, the GHG intensity is considerably higher [83]. Table 21 shows the GHG intensity of electricity generation in various jurisdictions across Canada.

Table 21: GHG intensity of electricity generation in different jurisdictions across Canada, as of 2008 [84].

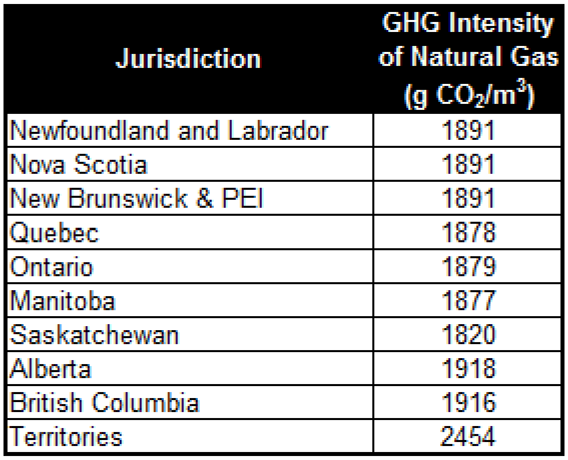


Jurisdiction	GHG Intensity of Electricity Generation (g CO_2/kWh)
Newfoundland and Labrador	21
Nova Scotia	784
New Brunswick & PEI	455
Quebec	2
Ontario	160
Manitoba	12
Saskatchewan	700
Alberta	880
British Columbia	15
Territories	60

In Provinces such as Quebec, Manitoba, and Newfoundland and Labrador, where more than 90% of electricity generation comes from renewable resources as in BC [83], the scale of GHG intensity is similar to that of BC, therefore the CO_2 emissions of electric-based water-heating systems in those jurisdictions are likely to be on a similar scale to those in BC. In places like Alberta, Saskatchewan and Nova Scotia, however, which generate more than 75% of their electricity from fossil fuels [83], the GHG intensity is more than forty-five times that of BC. In these jurisdictions, the CO_2 emissions of electric-based water-heating systems would be accordingly higher, which would likely necessitate a re-scaling and re-evaluation of the performance tiers as proposed here.

Natural gas, on the other hand, maintains a fairly consistent GHG intensity across Canada, as seen in Table 22.

Table 22: GHG intensity of marketable natural gas in jurisdictions across Canada, as of 2009 [85].



Jurisdiction	GHG Intensity of Natural Gas (g CO_2/m^3)
Newfoundland and Labrador	1891
Nova Scotia	1891
New Brunswick & PEI	1891
Quebec	1878
Ontario	1879
Manitoba	1877
Saskatchewan	1820
Alberta	1918
British Columbia	1916
Territories	2454

With the exception of the Territories, the GHG intensity of natural gas in other Provinces varies by only ~2% from that of British Columbia. (And even in the Territories, the GHG intensity is only 28% higher than that of BC; not at all on the same scale as the differences in GHG intensity for electricity.) This indicates that while the CO_2 emissions of electric-based water-heating systems may change considerably in different jurisdictions, the emissions of gas-based systems may not, therefore the crux of the change may be the increase in CO_2 emissions from electric-based systems in relation to the steady emissions of gas-based systems. This change in relationship may even be enough to cause an inversion of the tiers proposed here, with gas-based systems yielding lower CO_2 emissions than their electric-based counterparts.

Differences in climate will also play a role in changes in system performance. Since other parts of the country experience seasonal changes more extreme than those of BC, inlet water temperature may be considerably lower in winter, while ambient air temperature may be higher in the summer, both of which could affect the overall performance of a system. Moreover, the solar resource will be different in different jurisdictions, which may increase or decrease the effectiveness of solar preheat components depending on the location.

These considerations bear closer examination in the future if the adoption of system-based water heating regulation is to be encouraged in a wider range of jurisdictions.

Chapter 8

Conclusions and Recommendations

8.1 Conclusions

The research presented here represents a first step toward creating a systems-based standard for water heating rather than one which focuses simply upon the water heater itself. The model outlined in this study simulates single-family, residential water heating systems using either electric or gas-fired tank water heaters, including options for waste water heat recovery components and solar pre-heat components of several different capacities. The System Energy Factor metric provides a means for evaluating the relative energy efficiency of a given system, and that metric is examined together with CO_2 emissions to provide a basis for establishing system performance tiers.

Yet there is still much work to be done. While this study suggests some potential options for how performance tiers might be structured, it is too early in the process to quantify concretely what the possible ranges of performance may be, and where on the scale exact tiers of performance should ultimately be designated. Not only are there other technology component types to be evaluated within this systems framework, but there are pending regulatory factors to be considered as well. The federal government's intention to shift the market of gas-fired water heaters entirely toward tankless heaters demonstrates an acknowledgement of the relative inefficiency of gas storage tank heaters, which has been quantified in this study. This is, of course, as step in the right direction, and one which would require a re-evaluation of the tiers as proposed here, eliminating the bottom tier as proposed entirely and likely necessitating other reconsiderations of scale.

As more information is generated, the designation and refinement of performance tiers will hopefully become more clear.

Even as the criteria for ranking systems from a purely performance-based perspective are refined, however, it is clear that translating a systems-based standard into a new basis for regulation will be difficult. As section 7.1 shows, the financial challenges involved in incorporating technologies such as solar preheat or WWHR components are substantial. Given current market conditions, and even projecting reasonable increases in the prices of gas and electricity, there is still a wide gap between the capital cost of the equipment and the probable payback to the homeowner. In order to enact legislation encouraging the widespread adoption of these technologies, that gap must be significantly reduced or closed.

8.2 Recommendations

There are several areas in which future work on this subject would be warranted.

The model as it exists is still quite limited. It simulates only a few different technology component types and only one building-type, a single-family detached dwelling. If sufficient data is to be generated to represent the full range of possible combinations for domestic water heating, the model must be expanded. The first recommendation is that work be performed incorporating other technologies which have the potential to save energy in residential water heating. Simulation components modeling tankless water heaters, heat pump water heaters, combined space and water heating devices, and options for pipe configuration should all be incorporated. The program should also be refined to include modeling for other housing types besides single-family dwellings, such as row houses and multi-unit residential buildings (MURB) with individual hot water systems in each suite. Higher-rated gas water heaters should also be included in future simulations, since the federal minimum EF for these size water heaters will likely be increased to .66 or .67 within the next few years. As further modifications are made and further data generated, the proposed tiers must, of course, be re-evaluated based on this more complete set of info.

Some aspects of the data that was used in this round of simulations should also be examined and possibly improved upon. As Figure 11-Figure 14 show, energy demand for a given load profile is about 20% higher in winter than it is in summer, a fact which is due primarily to lower inlet water temperature in winter. The inlet temperatures used in these simulations are estimates, but since it is clear that this has an impact on the performance requirements of the system, more complete data on inlet water temperatures in each location should be explored. Since the current model assumes a constant temperature distribution of the water inside the pipes it would also be useful to develop a more robust representation of pipe temperature distribution. Also, as discussed in section 6.4, there is a performance discrepancy among the 189 L gas water heaters simulated, causing the .63 EF gas water heater to consistently outperform the .65 EF version. It should be determined what about the model’s structure and/or the choice of water heaters caused this discrepancy to occur, and adjustments should be made to avoid this happening in the future.

Finally, as discussed previously, there are many financial limitations which currently limit realistic possibilities for transitioning to a systems-based approach to water heating. These financial limitations must be grappled with, particularly if standards are to be reformatted to incorporate a full-system approach. The impact of subsidies, such as those shown in Table 18, should be explored further, and serious consideration should be given to other strategies and market transformation measures that might make the implementation of technologies which are attractive from the standpoint of CO_2 and energy impact more attractive from a fiscal standpoint as well.

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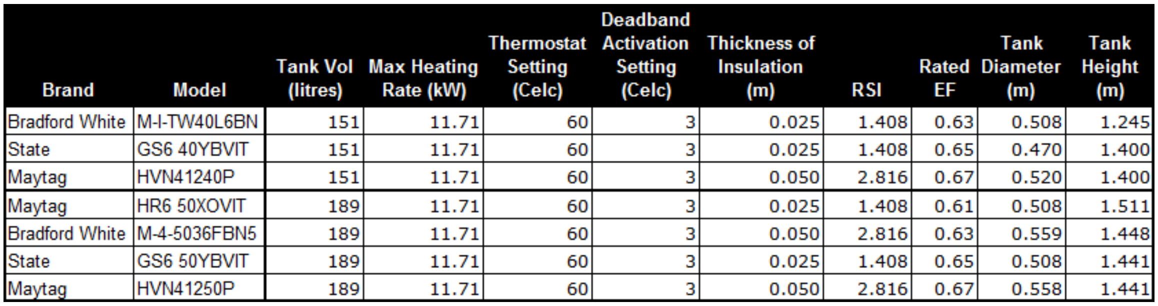
Appendix A

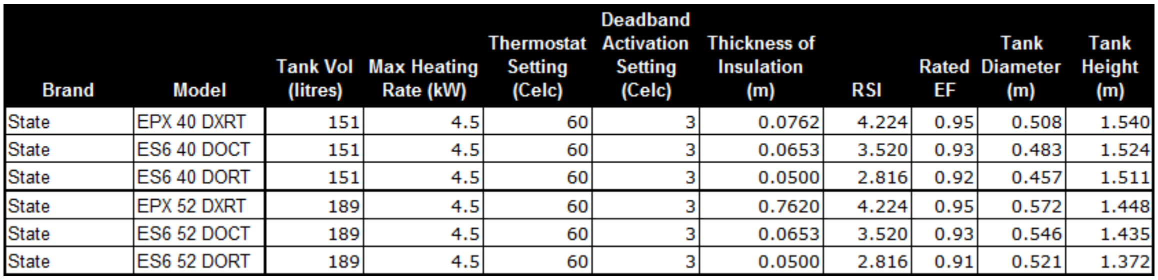
Water heater models used in simulation

Gas-Fired Water Heaters



Brand	Model	Tank Vol (litres)	Max Heating Rate (kW)	Thermostat Setting (Celc)	Deadband Activation Setting (Celc)	Thickness of Insulation (m)	RSI	Rated EF	Tank Diameter (m)	Tank Height (m)
Bradford White	M-I-TW40L6BN	151	11.71	60	3	0.025	1.408	0.63	0.508	1.245
State	GS6 40YBVIT	151	11.71	60	3	0.025	1.408	0.65	0.470	1.400
Maytag	HVN41240P	151	11.71	60	3	0.050	2.816	0.67	0.520	1.400
Maytag	HR6 50XOVIT	189	11.71	60	3	0.025	1.408	0.61	0.508	1.511
Bradford White	M-4-5036FBN5	189	11.71	60	3	0.050	2.816	0.63	0.559	1.448
State	GS6 50YBVIT	189	11.71	60	3	0.025	1.408	0.65	0.508	1.441
Maytag	HVN41250P	189	11.71	60	3	0.050	2.816	0.67	0.558	1.441

Electric Water Heaters

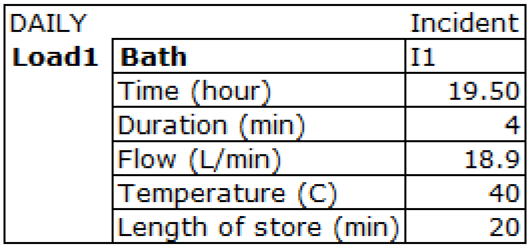


Brand	Model	Tank Vol (litres)	Max Heating Rate (kW)	Thermostat Setting (Celc)	Deadband Activation Setting (Celc)	Thickness of Insulation (m)	RSI	Rated EF	Tank Diameter (m)	Tank Height (m)
State	EPX 40 DXRT	151	4.5	60	3	0.0762	4.224	0.95	0.508	1.540
State	ES6 40 DOCT	151	4.5	60	3	0.0653	3.520	0.93	0.483	1.524
State	ES6 40 DORT	151	4.5	60	3	0.0500	2.816	0.92	0.457	1.511
State	EPX 52 DXRT	189	4.5	60	3	0.7620	4.224	0.95	0.572	1.448
State	ES6 52 DOCT	189	4.5	60	3	0.0653	3.520	0.93	0.546	1.435
State	ES6 52 DORT	189	4.5	60	3	0.0500	2.816	0.91	0.521	1.372

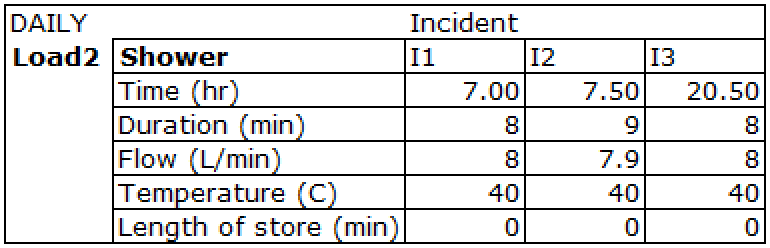
Appendix B

Sample load scenario

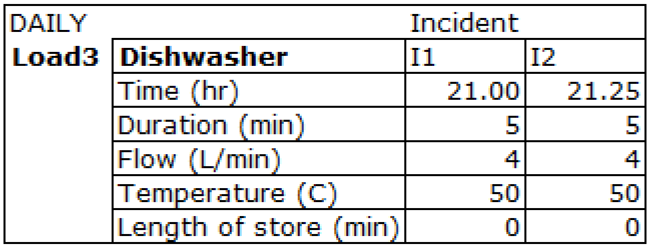
The following is a reproduction of the load data laid out for Load09_5HD, a high-demand, 5-person home on a weekday. Each of six different fixture types is laid out in its own worksheet, with a column for each individual hot water incident by fixture. Daily totals are calculated in a separate worksheet.



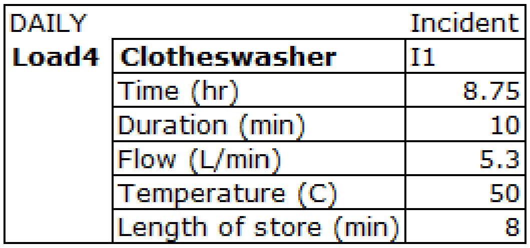
DAILY		Incident
Load1	**Bath**	I1
	Time (hour)	19.50
	Duration (min)	4
	Flow (L/min)	18.9
	Temperature (C)	40
	Length of store (min)	20



DAILY		Incident		
Load2	**Shower**	I1	I2	I3
	Time (hr)	7.00	7.50	20.50
	Duration (min)	8	9	8
	Flow (L/min)	8	7.9	8
	Temperature (C)	40	40	40
	Length of store (min)	0	0	0



DAILY		Incident	
Load3	**Dishwasher**	I1	I2
	Time (hr)	21.00	21.25
	Duration (min)	5	5
	Flow (L/min)	4	4
	Temperature (C)	50	50
	Length of store (min)	0	0



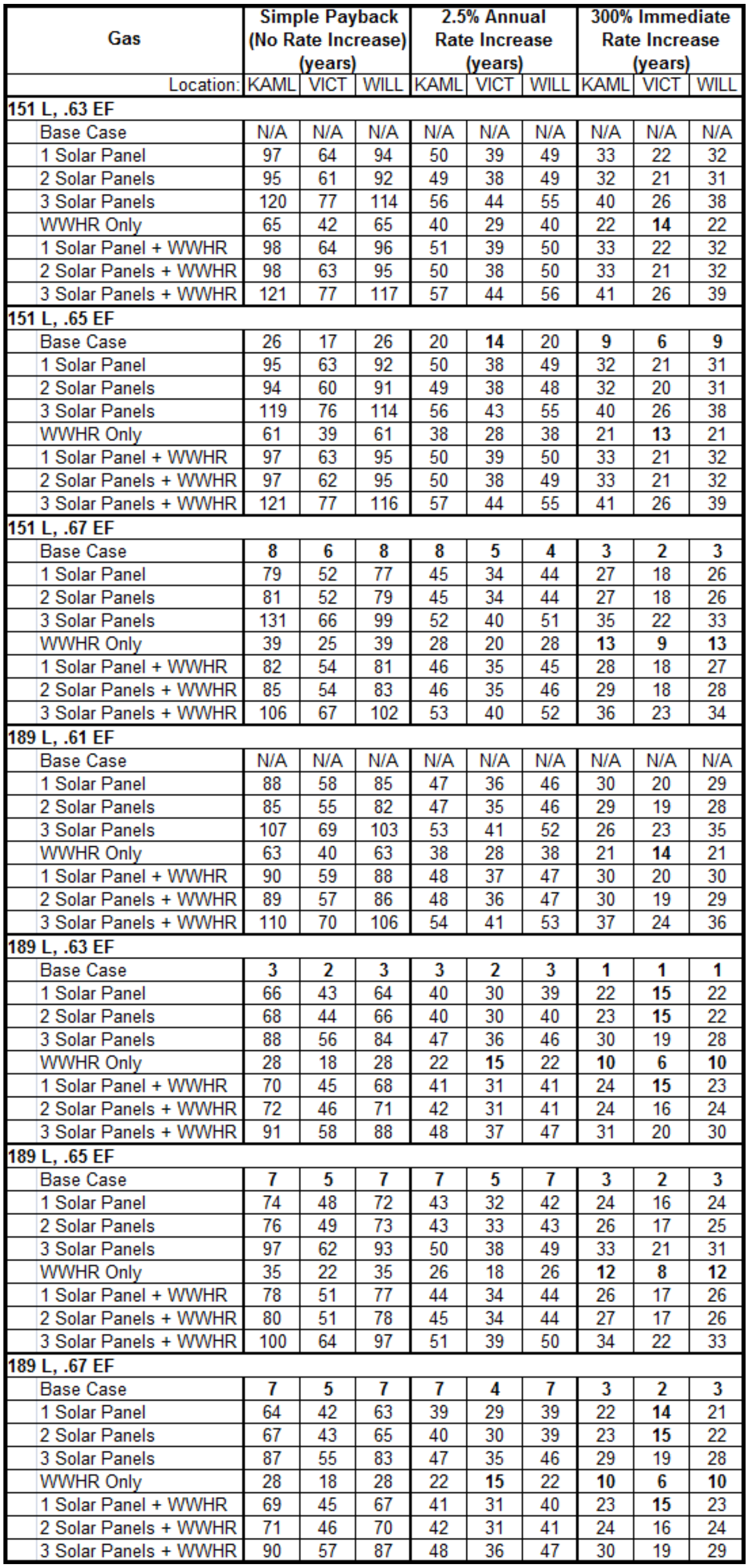
DAILY		Incident
Load4	**Clotheswasher**	I1
	Time (hr)	8.75
	Duration (min)	10
	Flow (L/min)	5.3
	Temperature (C)	50
	Length of store (min)	8

DAILY		Incident												
Load5	**Kitchen Sink**	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13
	Time (hr)	7.00	7.50	7.75	8.00	8.50	8.75	15.50	15.75	17.75	19.00	19.25	22.25	22.50
	Duration (min)	2	1	2	1	1	1	1	1	3	3	1	1	1
	Flow (L/min)	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
	Temperature (C)	40	40	40	40	40	40	40	40	40	40	40	40	40
	Length of store (min)	0	0	0	0	0	0	5	0	0	5	0	0	0

DAILY		Incident																		
Load6	**Bathroom Sink**	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	I15	I16	I17	I18	I19
	Time (hr)	6.75	7.00	7.08	7.50	7.75	8.70	15.00	15.50	15.75	16.75	17.25	18.00	18.50	19.50	20.00	20.75	21.00	22.00	22.75
	Duration (min)	2	2	1	2	1	1	1	1	1	1	1	1	2	2	1	1	1	2	2
	Flow (L/min)	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
	Temperature (C)	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
	Length of store (min)	0	3	0	0	2	0	0	5	0	0	0	0	0	0	0	0	0	0	0

DAILY	Litres/incident																				Litres/day
	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	I15	I16	I17	I18	I19	I20	Total
Bath	75.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	75.6
Shower	64.0	71.1	64.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	199.1
DW	20.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	40.0
CW	53.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	53.0
Sink-K	5.6	2.8	5.6	2.8	2.8	2.8	2.8	2.8	8.4	8.4	2.8	2.8	2.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	53.2
Sink-B	3.8	3.8	1.9	3.8	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	3.8	3.8	1.9	1.9	1.9	3.8	3.8	0.0	49.4
																				Total:	470.3
																				Target	470

Appendix C
Payback periods for gas-based water heating systems



Gas	**Simple Payback (No Rate Increase) (years)**			**2.5% Annual Rate Increase (years)**			**300% Immediate Rate Increase (years)**		
Location:	KAML	VICT	WILL	KAML	VICT	WILL	KAML	VICT	WILL
151 L, .63 EF									
Base Case	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1 Solar Panel	97	64	94	50	39	49	33	22	32
2 Solar Panels	95	61	92	49	38	49	32	21	31
3 Solar Panels	120	77	114	56	44	55	40	26	38
WWHR Only	65	42	65	40	29	40	22	**14**	22
1 Solar Panel + WWHR	98	64	96	51	39	50	33	22	32
2 Solar Panels + WWHR	98	63	95	50	38	50	33	21	32
3 Solar Panels + WWHR	121	77	117	57	44	56	41	26	39
151 L, .65 EF									
Base Case	26	17	26	20	**14**	20	**9**	**6**	**9**
1 Solar Panel	95	63	92	50	38	49	32	21	31
2 Solar Panels	94	60	91	49	38	48	32	20	31
3 Solar Panels	119	76	114	56	43	55	40	26	38
WWHR Only	61	39	61	38	28	38	21	**13**	21
1 Solar Panel + WWHR	97	63	95	50	39	50	33	21	32
2 Solar Panels + WWHR	97	62	95	50	38	49	33	21	32
3 Solar Panels + WWHR	121	77	116	57	44	55	41	26	39
151 L, .67 EF									
Base Case	**8**	**6**	**8**	**8**	**5**	**4**	**3**	**2**	**3**
1 Solar Panel	79	52	77	45	34	44	27	18	26
2 Solar Panels	81	52	79	45	34	44	27	18	26
3 Solar Panels	131	66	99	52	40	51	35	22	33
WWHR Only	39	25	39	28	20	28	**13**	**9**	**13**
1 Solar Panel + WWHR	82	54	81	46	35	45	28	18	27
2 Solar Panels + WWHR	85	54	83	46	35	46	29	18	28
3 Solar Panels + WWHR	106	67	102	53	40	52	36	23	34
189 L, .61 EF									
Base Case	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1 Solar Panel	88	58	85	47	36	46	30	20	29
2 Solar Panels	85	55	82	47	35	46	29	19	28
3 Solar Panels	107	69	103	53	41	52	26	23	35
WWHR Only	63	40	63	38	28	38	21	**14**	21
1 Solar Panel + WWHR	90	59	88	48	37	47	30	20	30
2 Solar Panels + WWHR	89	57	86	48	36	47	30	19	29
3 Solar Panels + WWHR	110	70	106	54	41	53	37	24	36
189 L, .63 EF									
Base Case	**3**	**2**	**3**	**3**	**2**	**3**	**1**	**1**	**1**
1 Solar Panel	66	43	64	40	30	39	22	**15**	22
2 Solar Panels	68	44	66	40	30	40	23	**15**	22
3 Solar Panels	88	56	84	47	36	46	30	19	28
WWHR Only	28	18	28	22	**15**	22	**10**	**6**	**10**
1 Solar Panel + WWHR	70	45	68	41	31	41	24	**15**	23
2 Solar Panels + WWHR	72	46	71	42	31	41	24	16	24
3 Solar Panels + WWHR	91	58	88	48	37	47	31	20	30
189 L, .65 EF									
Base Case	**7**	**5**	**7**	**7**	**5**	**7**	**3**	**2**	**3**
1 Solar Panel	74	48	72	43	32	42	24	16	24
2 Solar Panels	76	49	73	43	33	43	26	17	25
3 Solar Panels	97	62	93	50	38	49	33	21	31
WWHR Only	35	22	35	26	18	26	**12**	**8**	**12**
1 Solar Panel + WWHR	78	51	77	44	34	44	26	17	26
2 Solar Panels + WWHR	80	51	78	45	34	44	27	17	26
3 Solar Panels + WWHR	100	64	97	51	39	50	34	22	33
189 L, .67 EF									
Base Case	**7**	**5**	**7**	**7**	**4**	**7**	**3**	**2**	**3**
1 Solar Panel	64	42	63	39	29	39	22	**14**	21
2 Solar Panels	67	43	65	40	30	39	23	**15**	22
3 Solar Panels	87	55	83	47	35	46	29	19	28
WWHR Only	28	18	28	22	**15**	22	**10**	**6**	**10**
1 Solar Panel + WWHR	69	45	67	41	31	40	23	**15**	23
2 Solar Panels + WWHR	71	46	70	42	31	41	24	16	24
3 Solar Panels + WWHR	90	57	87	48	36	47	30	19	29