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High resolution measured domestic hot water consumption of Canadian homes

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ABSTRACT

The modeling and simulation of domestic hot water systems, including solar thermal and co-generation technologies, relies on accurate, high time-step resolution water consumption profiles. Due to the expensive nature of field studies, previous profiles have been limited in number of participants, or have been generated synthetically using probabilistic modelling techniques. The Solar City program in Halifax has measured hot water flow rate and temperature data in 119 homes at a time-step of 1 min; and includes a survey of occupancy rates and other relevant meta-data. In this paper, we discuss the data acquisition and processing (with a focus on flow rate data), and conduct analysis to reveal consumption trends and produce a new set of time-step profiles for modeling and simulation. Average hot water consumption per household is 172 L/day with a strong dependency on number of occupants. The hourly profile peaks twice daily, and shifts by several hours on Sunday. The average draw temperature was found to be 51.8 °C, which is lower than the default value of 55 °C applied by many building modeling/simulation packages. The average cold water supply temperature was found to be roughly sinusoidal about 12.4 °C with approximately one-month lag compared to ambient air temperature.

1. Introduction

Energy consumed for domestic hot water heating is significant. In 2011, the heating of domestic hot water (DHW) accounted for 20% of residential end-use energy consumption in Canada [1]. Numerous technologies have, and are, being developed to reduce DHW consumption and make the conversion of energy more efficient. The creation of energy policy to support implementation of such technologies relies on accurate modeling and simulation of the performance of such systems. It is critical that such simulation captures the high time-step resolution effects of water draws to insure high fidelity representation of such systems.

At present, technologies such as residential solar DHW systems, solar combi-systems, combined heat and power systems, 'net-zero' energy building design and 'smart-grid' applications can be modeled using two classes of simulator packages. Simplified software such as RETScreen and HOT2000 accepts an average daily DHW consumption estimate [2,3], while more advanced simulation software such as Energy Plus, TRNSYS and ESP-r require occupant load profiles at more frequent time-steps to generate high resolution energy end-use estimates. Temporal consumption patterns and the magnitude of consumption can impact not only the accuracy of these models but also the performance of DHW systems [4,27]. Therefore it is important to use realistic profiles, preferably from measured data, for simulations.

Measuring domestic hot water consumption at high temporal resolution requires a flow meter and a data acquisition system which are relatively expensive to purchase and install. Historically, measured data at time-steps under 5 min have been unavailable and researchers have instead relied upon repeated daily profiles (e.g. [5]), synthetic profiles (e.g. [6]), or have utilized profiles based on limited or historic datasets (e.g. [27]).

"Solar City" in Halifax, Nova Scotia is a municipal government pilot program which provides financing, sourcing and installation of solar DHW systems to home owners in Halifax Regional Municipality [7]. At homeowners' discretion, the installation includes a data monitoring system which measures flow rate and fluid temperatures at 1-min time-steps. By the end of July 2015, over 100 systems that include data monitoring had been installed throughout the Municipality. In addition, each monitoring system is linked to occupancy information and other relevant meta-data gathered through a survey of participants. The Solar City program has made available measured data of DHW temperature flow measurements

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for complete-year and multi-year periods at high temporal resolution (1 min).

This study achieves the following: (1) it introduces the data acquisition system and participants, with data continuing to collect and be made available; (2) it presents a new method to calibrate and interpret water flow rate measurements made on 1-min time-steps; (3) it examines DHW consumption characteristics such as mean daily DHW consumption, occupancy influence, day/time-of-use influences, and supply and draw temperatures; and (4) it describes new profiles for incorporation with building performance simulator packages.

2. Background and literature review

Several studies of DHW consumption have been in conducted in Canada and the USA. Beginning in 1981, Perlman and Mills [8] collected DHW flow measurements at 15 min time-steps in 59 homes throughout Ontario and examined household DHW consumption based on a variety of occupancy variables. Daily, monthly, and seasonal (winter/summer) average usage patterns were analyzed and representative daily profiles were generated for the entire population, and for what was deemed to be a 'typical' family. In order to aid with DHW system sizing, 'probabilistic' profiles were developed to represent DHW requirements of 95% of the sample population.

Becker and Stogshill [21] compiled a database from nine studies totalling more than 30 million DHW consumption measurements at 15 min time-steps for both apartment buildings and homes throughout Canada and the USA. The Perlman and Mills [8] study is included in this database and although many of the same factors of influence were investigated, it was possible to expand on these factors due to the breadth of data. It was found that location also had an influence on DHW consumption, which is likely due to differences in outdoor temperatures.

Over the past three decades, several confounding influences including technology, behavior, and demographics may also have changed DHW consumption. For example, faucet and showerhead flow rate standards have decreased consumption. Second, 'low-flow' faucets are being installed through many energy and water conservation programs (e.g. [9]). Third, the frequency of ownership of household appliances such as dishwashers and clothes washing machines has increased. Additionally, attitudes may have changed; a large proportion of Perlman and Mills [8] survey participants 'considered automatic dishwashing as only an occasional alternative to manual dishwashing'. Finally, Canadian demographics have also changed; the average number of persons per private household in Canada has decreased from 2.8 in 1986 to 2.5 in 2011 [15].

Thomas et al. [10] conducted a study of 74 households in Ontario aimed to evaluate the daily consumption profiles used in current water heater performance test standards. Measurements were taken for two to three weeks at each house at very high-resolution time-steps of 2 to 4 s. They found that average daily DHW consumption was lower than current standards developed from earlier studies.

A recent study by Edwards et al. [27] included measured DHW consumption data from 73 households in Quebec at a 5 min time-step. They selected twelve annual profiles to represent four aggregate consumption levels at three temporal demand patterns for those who consumed primarily: (i) in the mornings, (ii) in the evenings or (iii) evenly throughout the day. These profiles were then incorporated into the TRNSYS 17 simulation program to analyze the performance of a typical solar DHW heating system and use of auxiliary heat. For morning users, the auxiliary heater would operate primarily during the day, while for evening users, the auxiliary heater would function primarily overnight, a result more appealing to those with time-of-use electricity rates.

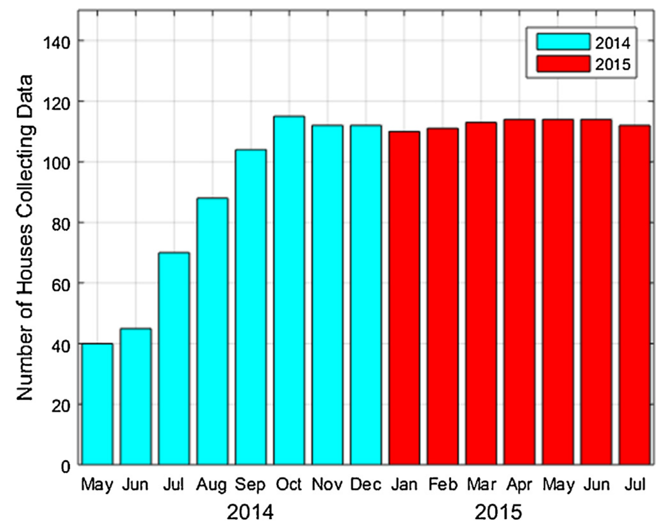

Fig. 1. Number of active data acquisition systems through time.

Researchers have also estimated average daily hot water consumption based on energy consumption. Evarts and Swan [25] estimated average daily DHW consumption based on a sample of homes in the Solar City program. A survey of each home gathered occupancy, water source, method of DHW heating, energy use and energy costs. Average consumption was estimated from fuel oil consumption for occupancies of 1 to 6 people. Since the sample set of homes in this study were initial applicants to the Solar City program, it provides an excellent opportunity to compare the results of this method with the findings of the current study of measured data.

Other research efforts have generated synthetic profiles, where probabilities are assigned to individual end uses such as dishwashing and clothes washing. Jordan and Vajen [11] used this approach to create consumption profiles at various time steps and load magnitude based on data gathered in Germany and Switzerland [12]. Hendron and Burch [13] used a similar method to generate profiles based on data collected by the American Water Works Association. A drawback of synthetic profiles is the inability to capture the true temporal variability in consumption patterns, as they rely on engineering judgment and expectation.

3. Data sources and methods

All of the Solar City data are the result of acquisition systems being installed with solar DHW heating systems on homes in the Halifax Regional Municipality. To July 2015, 250 data collection systems had been installed; however, data from 77 systems using an earlier version of the control software were not considered. Of the remaining systems, many were installed during the spring and summer of 2015. Only data from systems installed prior to November 2014 were considered to ensure sufficient data for each site. This study includes data from May 2014 to July 2015 for a total of 119 houses. The data collection systems progressively came online with new system installations, with Fig. 1 illustrating system availability. Note that for several systems, connection failures occurred throughout the timeline, explaining the variable system availability beginning in November 2015.

Occupancy data was collected by a household survey during initial consultations. Of those, 77 homes had detailed occupancy categorized by class with results presented in Table 1. The defining ages of each class were not given. Only a total occupancy with no detailed categorization was recorded for 26 additional homes, thus