Applied Energy 232 (2018) 424–442

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Uncertainty quantification and sensitivity analysis of the domestic hot water usage in hotels

Zhihong Pang, Zheng O'Neill*

Department of Mechanical Engineering, The University of Alabama, Tuscaloosa, AL 35478, USA

HIGHLIGHTS

- The status quo of the domestic hot water (DHW) system related water and energy usage was elaborated.
- A large-scale EnergyPlus-based Monte Carlo simulation of the DHW system was performed.
- Coefficients of variation were computed to quantify the uncertainty of the DHW system.
- PEAR and Sobol indexes were calculated to explore the sensitivities of the DHW system.
- The top two significant parameters are the maximum capacity and efficiency of the main water heater.

ARTICLE INFO

Keywords:
Domestic hot water
Sensitivity analysis
Uncertainty analysis
Karhunen-Loeve expansion

ABSTRACT

The water heating system is a major contributor to building energy consumption and carbon emissions in the United States, especially for the Hotel/Motel sector. Various factors in the design and operation stages are found to have great influences on the hot water usage and associated energy usage. There has been an increased number of studies on optimizing the design and sizing of the water heating system in commercial buildings in recent years. However, most of these studies focused on the collection and analysis of the actual data of hot water usage with rare acknowledgments of uncertainties from a variety of influential parameters such as occupant behaviors and operational schedules. The current understanding of the sensitivity of the hot water usage related to these influential factors is still limited.

This paper aims to conduct an uncertainty and sensitivity analysis (UA & SA) to investigate the behavior of the domestic hot water (DHW) usage in hotels and its key influencing factors. An EnergyPlus Monte Carlo simulation is performed by using the large hotel building prototype model developed by the U.S. DOE as the baseline model. 161 input parameters ranging from equipment parameters (e.g., size, efficiency, operation schedules, etc.) to occupant behaviors are perturbed using Monte Carlo and Karhunen-Loève expansion sampling methods. Eight outputs associated with the hot water usage (i.e., the peak/annual whole building water consumptions, DHW system water consumption, DHW system gas consumptions, and DHW system electricity consumptions) are specified as the outputs of interest. Five locations, which are Burlington, VT; Chicago, IL; San Francisco, CA; Houston, TX; and Miami, FL are selected to investigate the influence of the climate condition. 3000 sample EnergyPlus files are created for each location. Two indicators (i.e., the PEAR index, and the variance-based Sobol index) are computed for the sensitivity analysis. It suggests that the SA results from the PEAR index and the Sobol index are very similar in this case study.

1. Introduction and background

1.1. The status quo of domestic hot water usage

Residential and commercial buildings represent a substantial proportion of energy expenditures and greenhouse gas (GHG) emissions. It's estimated that they together were responsible for approximately 39% of the annual GHG emissions in the United States [1]. Besides, more than 26.4 quintillion Joules of primary energy was consumed by the building sector in 2017, which makes it surpass the industry and transportation to become the largest energy consumer by sector [2]. Typical major areas of building energy consumption include building

* Corresponding author.
E-mail address: zoneill@eng.ua.edu (Z. O'Neill).

https://doi.org/10.1016/j.apenergy.2018.09.221
Received 21 June 2018; Received in revised form 19 September 2018; Accepted 27 September 2018

Nomenclature

Variables, parameters and indices

s_i	stochastic independence
x	Input
y	Output
f_i	first order interaction
$f_{i,j}$	second order interaction
E	mean value of the model output
P	PEAR index
S	standard deviation

Greek letters

μ_χ	mean value
χ	uncertainty
λ_i	weighting factor
ψ_i	basis function

Abbreviations

ACOSSO	Adaptive COmponent Selection and Smoothing Operator
ANOVA	ANalysis Of VAriance
BN	Bayesian Network
BPS	building performance simulation
CV	coefficient of variation
DHW	domestic hot water
DOAS	dedicated outdoor air system
ECM	energy conservation measures
FCU	fan-coil unit
FAST	Fourier amplitude sensitivity testing
GHG	greenhouse gas
GSA	global sensitivity analysis
HDMR	High Dimensional Model Realization
HVAC	heating, ventilation, and air-conditioning
IC	influence coefficient
IQR	interquartile range
KL	Karhunen-Loève
MSE	mean squared error
NN	neural network
OEE	Office of Energy Efficiency
OFAT	one factor at a time
PCC	partial correlation coefficient
PDF	probability distribution function
RF	Random Forest
SA	sensitivity analysis
SHGC	solar heat gain coefficient
SRC	Standardized Regression Coefficient
SVR	Support Vector Regression
UA	uncertainty analysis
UQ	uncertainty quantification
UWG	Urban Weather Generator
VAV	variant air volume

heating, ventilation and air-conditioning (HVAC) system (36%), lighting sector (11%), and major appliances (18%) such as dryers and freezers [3]. Existing researches mainly focused on the optimization of building HVAC system design and operation since it comprises the largest part of the energy usage in buildings. However, some recent studies suggested that water heating, which was always underestimated in the previous researches, also raises enormous demand for energy and water. Hiller and Johnson did some research on the water and energy consumptions in the hotel sector, and found that the domestic hot water (DHW) system is one of the major end users of the energy and water [4–6].

In the United States, accounts for approximately 15–25 percent of the total energy consumed at home [7]. This makes it the third largest energy consumer following the space heating/cooling and lighting in residential buildings. The usage of DHW in the individual house ranges from 119 to 284 liters per capita per day, with an average of 205 liters per capita per day [7,8]. A survey on the DHW usage in hotels revealed that the total hot water use was as high as 9.84 million liters for the business hotel, and 2.91 million liters for the travel hotel over a 13-month monitoring program [6].

In Canada, a survey released by the Office of Energy Efficiency (OEE) suggested that water heating accounted for 8 and 19 percent of the total energy consumptions of the commercial and residential sectors respectively in 2013. The total energy consumed by the residential DHW system increased from 230.8 PJ to 294 PJ in the period from 1990 to 2013. But due to the improvements in the water heater efficiencies, the energy used per household for heating water decreased from 23.3 GJ per household per year to 21.3 per household per year [9].

In Hong Kong, Deng and Burnett [10] conducted a comprehensive survey on the hotel water usage in 17 hotels and found that there was more water usage in a more luxury hotel. In fact, the water demand in a five-star hotel was 50% higher compared with a three-star one. The total annual water consumption of a surveyed five-star hotel with a total area of 37,000 m^2 was approximately 160 million liters, and the annual water and energy bill for DHW was over 1 million HK dollars in 2002.

In the European Union, 14 percent of the energy usage in the residential sector was consumed by the DHW system in 2003. This ratio can be even higher in some of its member countries, e.g., the UK spent 22% of its residential building energy consumption on the DHW system, and in Spain, this ratio was 26% [11].

1.2. Uncertainties in domestic hot water usage

An appropriate design of the DHW system is necessary for achieving energy and water efficiency in buildings. There is a diverse spectrum of varying parameters influencing the water and energy usage associated with the DHW system, such as the water inlet temperature, water tank volume, flow rate and timing [12]. Besides, some factors in the design and operation phases also have significant impacts on the water and energy consumptions of the DHW system, including the layout of the piping system, the selection of the water heater, and the operation management [5]. These parameters are always associated with significant uncertainties [6,12]. For example, the usage pattern of the DHW system is strongly associated with the occupant behaviors, and therefore the usage is stochastics and highly time-diverse [13,14]. The complex collection of the influencing factors together with the associated uncertainties contribute to the fact that it is not easy to properly design and operate a water and energy efficient DHW system.

By conducting a simulating study with a neural network (NN), Aydinalp found that the fuel type of the water heater has a big impact on the energy consumption of the residential DHW system [15]. The average water heating energy consumption was 21 GJ/year/household for the electricity-powered systems, while for the systems using natural gas and propane, the energy consumption increased to 32 and 31 GJ/year/household respectively. This difference was mainly due to the fact that the DHW system using the electricity has a much higher energy end-use efficiency than the natural gas/propane systems.

Occupant behavior also plays an important role in the uncertainties of the DHW usage and energy consumption in buildings. Actually, occupant behavior was considered as the most important driver of the hot water events in [13]. In some early studies [16], the correlation of the