Applied Energy 213 (2018) 415–425

Contents lists available at ScienceDirect

Applied Energy

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

Using change-point and Gaussian process models to create baseline energy models in industrial facilities: A comparison

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HIGHLIGHTS

- Change-point nor Gaussian process regression models proved significantly better.
- Change-point and Gaussian process models meet ASHRAE Guideline 14 requirements.
- Natural gas usage is more dependent than electricity on only ambient temperature.

ARTICLE INFO

Keywords:
Industrial energy
Baseline modeling
Change-point
Gaussian

ABSTRACT

Industrial facilities account for approximately a third of energy usage in the world, and effective energy assessments of these facilities require a reliable baseline energy model. Commercial and residential buildings have been baselined with both simple change-point models and models that are more complex, such as Gaussian process and artificial neural networks, and these models are developed and tested with dense high-frequency data. However, industrial facilities have only been baselined using change-point models, and data for the models are typically restricted to monthly utility bills and, therefore, generally sparse data.

This investigation compares the effectiveness of change-point models with that of Gaussian process models for baselining industrial facilities using only monthly utility billing information as data. Two case studies are presented to predict electricity usage and two case studies are presented to predict natural gas usage. Both change-point and Gaussian process models provided similar results, and both models meet the recommended NMBE and CV-RMSE from the ASHRAE Guideline 14. For one case study, both change-point and Gaussian process models were applied using available test data not contained in the training data, and both models predicted the monthly energy usage within 10% for 4 of the 5 months of testing data used.

1. Introduction

Understanding energy usage and increasing end-use energy efficiency of existing residential, commercial, and industrial facilities is one of the important solutions to the problem of rapidly growing worldwide energy demand. Industrial facilities account for 33% of the annual energy usage within the United States [1], and increasing industrial buildings' energy efficiency by at least 20% over the next 10 years is the primary goal of the US Department of Energy's "Better Buildings, Better Plants Program" [2]. The U.S. House Committee on Appropriation stated that "Energy costs are a major contributor to manufacturing costs and technology innovations that steeply reduce energy consumption in industrial and manufacturing processes can give American manufacturers competitive advantages in the global marketplace" [3].

Industrial facilities are classified as those that are not residential or commercial buildings and consist primarily of manufacturing facilities. Analysis of industrial facilities is needed to understand energy usage within the facility and to identify energy saving opportunities. While both residential and commercial buildings have been extensively analyzed [4–23], industrial buildings have enjoyed minimal investigations [24–31].

The study of industrial energy usage has gained attention in the past few decades. Energy auditing has become an effective way to help industrial facilities understand and reduce energy usage at the facility. Some energy auditors specialize in industrial facilities, such as Saidur [29], and Kissock [25,26]. Others have studied barriers that prevent industrial facilities from incorporating energy efficiency measures in their plant [30,31].

Henriques and Catarino [30] describe the barriers that prevent

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https://doi.org/10.1016/j.apenergy.2018.01.043
Received 1 November 2017; Received in revised form 12 January 2018; Accepted 13 January 2018
Available online 28 January 2018

Nomenclature

EU	energy consumption
β_1	independent variable
β_2	cooling weather dependent variable
T_{amb}	ambient temperature
$T_{b,c}$	cooling change-point temperature
$T_{b,h}$	heating change-point temperature
β_3	heating weather dependent variable
R^2	coefficient of determination
y_{act}	actual monthly energy consumption
y_{mod}	model monthly energy consumption
y_{avg_bar}	average facility energy consumption
RMSE	root mean square error
n	number of observed values
p	number of regression parameters
CV-RMSE	coefficient of variation of the root mean square error
x	input variable (temperature)
M(x)	mean value function
F(x)	function of input variable
E[ ]	expected value of function
K(x,x′)	covariance matrix
σ	height parameter
L	length parameter
P(y|x,θ)	probability of y given x and hyperparameters θ
Y	prior output variable (energy)
$Y_{bar,*}$	mean value of energy prediction
$Var(y_*)$	variance of energy prediction
U	overall building envelope conductance
A	surface area of building
θ	hyperparameters
N(a,b)	normal distribution of a and b

Superscript

+	only positive values in parenthesis considered, otherwise zero

small and medium industrial facilities from improving energy efficiency within the facilities. The main barriers they cite are facility personnel's lack of time to identify energy conservation measures (ECMs) within their facility and lack of capital to implement ECMs when they are found.

Trianni et al. [31] conducted a detailed survey on the barriers and drivers of improving energy efficiency in small and medium manufacturing facilities in Italy. Their findings echoed those of Henriques and Catarino as they found the largest barrier to be the lack of finances available for ECMs.

Most industrial facilities do not have sub-metering of individual energy systems and/or components (e.g., air conditioning, lighting, processing equipment, etc.), so the only source of energy consumption data commonly available is the monthly utility bills. The highest energy consumption in a manufacturing facility is related to manufacturing processes, followed by the heating, ventilation, and air-conditioning (HVAC) system [32]. For example, in automobile assembly facilities an HVAC system can consume up to 20% of the electricity [33]. Therefore, the combined energy demand of the production and HVAC systems largely determines the total energy cost. Even facilities that are not conditioned year round will have equipment that is weather dependent (e.g., chillers for process cooling, cooling towers, etc.). In this study, the baseline energy estimation is for building energy systems (e.g., HVAC and lighting) and production process.

Establishing a baseline energy model allows a facility to understand the energy consuming behavior of their building or facility. A baseline energy model provides a reference on energy usage for future prediction and/or energy management. Fig. 1 displays the basic concept for creating a baseline model as defined by ASHRAE Guideline 14 [34]. While baseline energy models are generally used for determining energy savings after implementing ECMs, a baseline energy model provides other useful data as well. Baseline energy models can help characterize end-user consumption, identify energy-saving retrofit projects and estimate the savings potentials of those proposed projects, and calculate actual energy savings of retrofit projects after implementation. In industrial facilities, a baseline energy model also shows if energy is mostly being used for production or other applications (e.g., facility lighting, heating and cooling, etc.). With this knowledge, an industrial facility is better able to determine the best ways to reduce energy in their facility. Thus, it will reduce overall manufacturing cost,

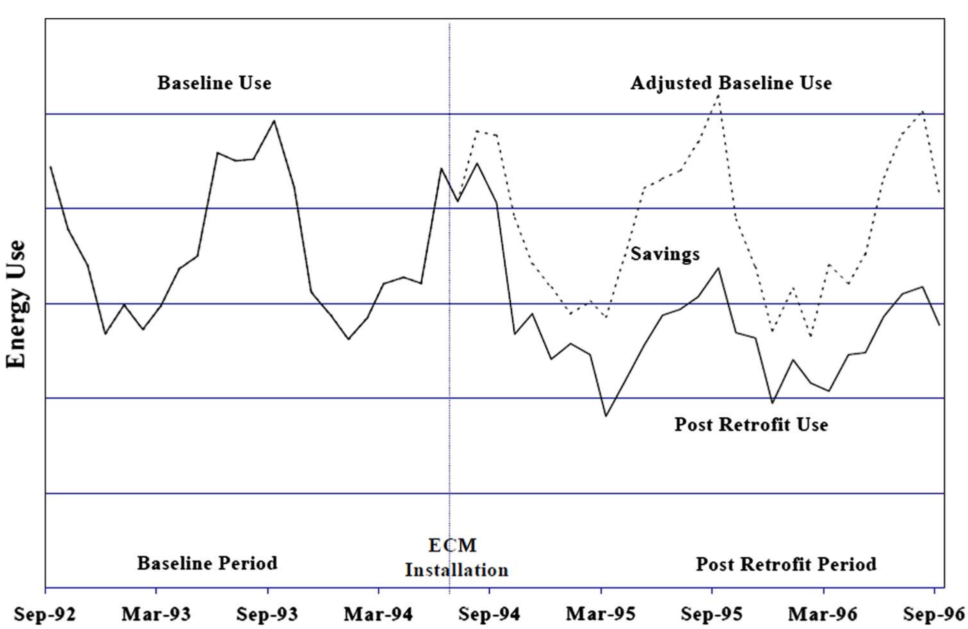

Fig. 1. ASHRAE guideline 14 basic method for determining savings [34].