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Modeling of the energy demand of the residential sector in the United States using regression models and artificial neural networks

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HIGHLIGHTS

- We model the energy demand in the residential sector of the United States.
- We used artificial neural networks and regression models.
- The results of the models corresponding to the test period are compared.
- The energy demand in the residential sector of the United States forecasted until 2030.

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ABSTRACT

This paper describes the development of energy-demand models which are able to predict the future energy demand in the residential sector of the United States. One set of models use an artificial neural network (ANN) technique, and the other set of models use a multiple linear regression (MLR) technique. The models are used to forecast future household energy demand considering different scenarios for the growth rates of the effective factors in the models. The household sector includes all energy-consuming activities in residential units (both apartments and houses) including space and water heating, cooling, lighting and the use of appliances. In order to understand the evolution of household energy use, a set of indicators has been developed. For instance, several factors affect energy consumption for space heating as a share of households' energy demand. These factors include, dwelling size, number of occupants, the efficiency of heating equipment and the useful energy intensity. The paper also analyzes the trend of energy consumption in the residential sector of the United States. Moreover, the effects of important indicators on the energy consumption are discussed. The analysis performed in this paper is done for each census region, where possible, to elucidate the effects of different indicators in each region.

1. Introduction

The United States is a nation which consumes a vast amount of energy. In 2009, it ranked 1st globally, with respect to the consumption of primary energy sources such as petroleum, natural gas, coal, hydroelectric, nuclear, geothermal, solar and wind [1]. The United States relies on petroleum imports to meet its oil demand, and therefore is the leader globally in terms of crude oil imports. Also, the country is the largest consumer of natural gas in the world: about 11% of its natural gas in 2010 was supplied by imports, primarily from its North American neighbors [2,3].

The country was self-sufficient in energy until the late 1950s when energy consumption began to outpace domestic production. In 2007, the United States imported 707 Mtoe of energy and exported only 188 Mtoe. By 2007, net energy imports accounted for 22.4% of all energy consumed. At the same time, most (84%) of the imported energy was in the form of oil. The United States now imports more oil and natural gas than any other country [2].

While the United States consumes vast quantities of energy as mentioned above, it has also pledged to cut its greenhouse gas emissions by 2050. This was done through passage of the American Clean Energy and Security Act in June 2009 [4]. This measure aims to promote clean energy investments and to lower US greenhouse-gas emissions by more than 80% by 2050.

In 2009, fossil fuels accounted for 83% of total energy consumption in the United States, while renewable energy supplied 8.0% and nuclear electric power provided 8.8%. The pattern of energy use varies by sector. For example, oil provides 96% of the energy used for transportation but only 1% of energy used to generate electric power. After the electric power sector (40.3%), the transportation sector was the second largest consumer of primary energy (28.5%), followed by industrial (20%), residential (7%), and commercial

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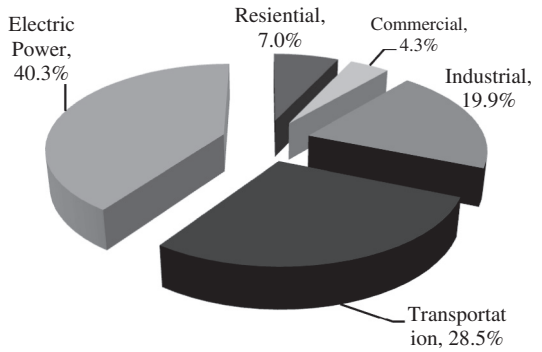

Fig. 1. Energy consumption by sector in United States.

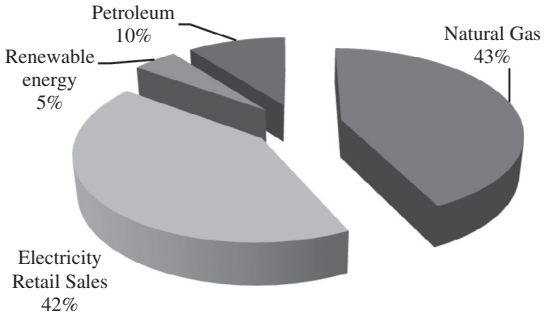

Fig. 2. Major primary energy sources in residential sector.

(4.3%), as shown in Fig. 1. The major primary energy source in the residential sector is natural gas (43%) while electricity (42%) and petroleum (10%) compose most of the reminder as shown in Fig. 2 [3].

In order to assist in planning for future energy needs, the purpose of this study is to develop a model for residential energy demand that incorporates past trends. Two sets of models are developed. The primary model described in this paper employs an artificial neural network (ANN) technique to predict United States residential energy demand. Seven independents variables (resident population, gross domestic product, household size, median household income, cost of residential electricity, cost of residential natural gas, and cost of residential heating oil) have been tested for the modeling. The results of the ANN models are compared to those predicted by the more traditional multiple linear regression (MLR) modeling technique so that any advantages to the ANN modeling technique can be discerned. By studying the possible scenarios for the growth of the parameters, the future residential energy demand in United States can then be forecasted based on the models.

2. Background

Modeling and predicting energy consumption play a vital role in developed and developing countries for policy makers and related organizations. Underestimation of consumption would lead to potential outages that are devastating to life and economy, whereas overestimation would lead to unnecessary idle capacity that means wasted financial resources. Therefore it would be better to model energy consumption with good accuracy in order to avoid costly mistakes. Also it is better to use models that can handle nonlinearities among variables as the expected nature of energy consumption data is nonlinear.

Swan and Ugursal [5] provide a review of the various modeling techniques used for modeling residential sector energy consumption. In their research, two distinct approaches are identified: top-down and bottom-up. Each technique relies on different levels of input information, different calculation or simulation techniques, and provides results with different applicability. A critical review of each technique, focusing on the strengths, shortcomings and purposes, is provided along with a review of models.

Both regression models and neural network models used in the current study are categorized in statistical models which are a division of the bottom-up approach. Models, using a bottom-up approach can account for energy consumption of individual end-uses, individual houses, or groups of houses and then extrapolate to represent the region or nation based on the representative weight of the modeled sample. Researchers have applied a variety of statistical techniques to utilize this and other information to regress the energy consumption as a function of house characteristics.

It is well-known that artificial neural networks (ANNs) can model any nonlinear relationship to an arbitrary degree of accuracy by adjusting the network parameters. In addition to many different algorithms reported in the literature, the accuracy and prediction performance of ANN models need to be studied for energy consumption prediction problems in order to give decision makers an opportunity to make sound decisions in their activities. Finally, as with any other modeling problem, inputs to a model should cover all possible variables that influence the output variable of interest.

The relationship among energy consumption and the economy has been studied and reported in the literature by Min et al. [6], Jin-ming and Xin-heng [7], Geem and Roper [8], Cayla et al. [9], and Swan and Ugursal [5], among others. Total and sectoral energy modeling and prediction studies have been carried out by many researchers. Geem [10] developed ANN models for South Korea's transport energy forecasting by considering various independent variables such as GDP, population, oil price, number of vehicle registrations, and passenger transport amount. In his study, the ANN models obtained robust results in terms of *RMSE* as well as R^2, when compared with multiple linear regression models. Also, Murat and Ceylan [11] described the logic of ANN and *k*-fold cross-validation method. They proposed possible application of ANNs to forecast energy demand for the next 20 years in Turkey.

Regarding the residential sector, Gilland [12] projected the world energy demand for the period between 2000 and 2020 on the basis of plausible assumptions regarding population growth, economic growth and a relation between elasticity of energy demand and growth of gross domestic product per capita by world region. Min et al. [6] presented a novel approach to modeling residential energy by both end use and fuel type for the entire United States at a high resolution. Their model provides an in-depth look at how energy is used by residences in different parts of the country and the variances between home energy use characteristics both within and across different regions.

Cayla et al. [9] characterize quantitatively the impact of income on household energy consumption in the residential and transport sector of France. Their analysis show that the least well-off households are particularly constrained since the share of their budget represented by these energy services is very large. As an alternative fuel used in residential sector, wood energy consumption has been studied by Song et al. [13]. They found that the composite non-wood energy price positively associated with US residential wood energy consumption in the long-run with elasticity 1.82. Wage rate was negatively associated with wood energy consumption in both long-run and short-run. They also suggest that the estimated trend in residential wood energy consumption is significantly negative, about −3% per year.