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A two-step approach to forecasting city-wide building energy demand

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ABSTRACT

This paper presents a two-step approach to forecasting city-wide building energy demand. The initial engineering estimates with input from typical buildings are used as the priori beliefs, and are transformed into the posteriori distributions that describe energy consumption patterns of plots. This two-step approach takes advantage of the engineering estimate in analysis of physical factors that determine building energy consumption and uses demand regression to further correct the priori engineering estimates based on the observed energy consumption of plots. The results of a case study shows that the two-step approach makes the standard deviation of the predicting factors within 0.001 kWh/(m^2·a) compared with 6.186 kWh/(m^2·a) of the engineering estimate or 53.020 kWh/(m^2·a) of the demand regression. It means that the bottom-up two-step approach has a high confidence in forecasting the city-wide building energy demand if the priori engineering estimates are critically accepted and Bayesian analysis is performed according to the observed energy consumption of plots. It is a general methodology and can be applied in most cities to forecast the city-wide building energy demand aiming to enable policymakers to establish the medium or long-term targets related to buildings stock energy consumption and associated CO2 emissions.

1. Introduction

Building sector accounts for 17%–21% of the total energy consumption in China [1]. In our cities, there is a special phenomenon. The total amount of energy supply is surplus in the city, whereas local areas are in deficit. A best practice is to build on the city's demand assessment and allocate the potential energy resources to the most needed. Consequently, it is necessary to develop a forecasting model of city-wide building energy demand. During recent decades, some methods have been explored in forecasting energy consumption of building sector. They are roughly classified into two categories, i.e., the top-down approach and the bottom-up approach [2].

1.1. Top-down approach

The top-down approach tends to seek the connection between the energy sector and the economic output, i.e., energy use in relationship to variables such as income, fuel prices and gross domestic product. The use and development of the top-down approach was proliferated with the energy crisis of the late1970s. In an effort to understand consumer behavior with changing supply and pricing, some broad econometric models are developed. For instance, Hirst et al. [3] initiated the annual housing energy model of the USA which relied on econometric variables and included a component for growth/contraction of the housing stock. Their work was improved over the following years and an econometric model including both housing and technology components was developed [4,5]. The top-down approach was also applied to estimate climate-impacts on regional energy demand and assisted regional energy suppliers to develop short-term energy planning [6–8]. Matthias et al. [9] used the main monthly time-series data of heating and cooling degree-days along with energy price, daylight time and trend variables, in a fixed-effects regression model to quantify the historic sensitivity of end use energy demand by the residential and commercial sectors. Summerfield et al. [10] developed annual delivered energy, price, and temperature (ADEPT, multiple linear regressions) models to help identify the trajectory of the total delivered energy to UK households. Chinese National Development and Reform Commission [11] used Long Range Energy Alternative Planning (LEAP) to forecast the trend of building sector energy demand by 2020 corresponding to different scenarios in terms of some factors, such as population, urbanization, standard of living, technology level and policy measures. The results showed that policy measures had significant effort on energy consumption of the build-

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ing sector, and resulted in reduction of 200 million tons of coal equivalent.

The top-down approach places emphases on the macroeconomic trend and the relationship observed in the past rather than the physical factors that can influence energy demand, and consequently lacks details on some current and future technological options implemented [12].

1.2. Bottom-up approach

1.2.1. Engineering estimation (EE)

In contrast to the top-down approach, the bottom-up approach works at a disaggregated level, and is usually associated with engineering simulation [13]. Huang et al. [14] categorized the entire US commercial buildings sector into 37 building types by their energy use patterns and/or thermal/electric ratios. 481 prototypical buildings were combined with building sector areas to assess the potential of cogeneration in commercial and multi-family buildings. They [15] utilized commercial and residential prototypical buildings with the DOE-2 results to estimate the total heating and cooling loads in U.S. buildings and explored the national conservation potential in building energy efficiency improvement. In Europe [16–18], the concept of "average buildings" was developed in the common methodical framework with a harmonised data structure in the TABLE project, and it was further developed and used as a common means to map the current state of the building stocks in the EPISCOPE project. Structural data about the existing state – e. g. the current share of wall areas already insulated-delivered the starting point of building stock modeling, while information about recent dynamics – e.g. the share of wall areas insulated per year – performed trend analysis. The harmonised bottom-up approach was used for projections of the energy consumption of the countries' residential building sectors. Due to based-area addition of energy consumption, these prototypical buildings were usually combined with the geographic data to produce a resolution of energy consumption in a city. For instance, Ichinose et al. [19] used energy statistics to develop energy use profiles of nine types of buildings in Tokyo. The results of energy use profiles were linked to a geographic land use dataset to produce maps of anthropogenic heat in the city. Similarly, Heiple et al. [20] used the simulating output of prototypical buildings along with available geospatial data and obtained an estimate of the hourly energy consumption within each tax lot across the entire city. The GIS (geographic information system) bottom-up engineering approach was applied by Carlos et al. [21] to estimate per dwelling gas and electricity consumption in a local authority level in Newcastle. The sub-city model determined the energy consumption of the sub-city areas based on the type of each dwell in the city and the corresponding archetype. In the case, individual building energy calculation was based on a physics-based Domestic Energy Model developed by the Building Research Establishment, and the aggregate estimates were determined by summing up individual energy values for every dwelling within the study reporting areas.

The bottom-up engineering approach excessively depends on the physical result of individual buildings. This means that it would lead to an uncontrollable deviation of the aggregate result from the true value at a district level due to lack of regional constraint.

1.2.2. Demand regression (DR)

The demand regression method usually disaggregates the total consumption of a household sector into its constituent parts, each associated with a particular end-use or appliances (known as demand conditional analysis). It was first presented by Michael et al. [22] to estimate the monthly and annual average energy use for the household appliances and also used by them to assess the impact of the commercial DSM programs run by Southern California Edison [23]. Marcos et al. [24] applied the DR to estimate the aggregated consumption of household appliances in Brazil based on a household energy consumption survey carried out by the Brazilian electric utility companies. Howard et al. [25] utilized Huber M-estimation regression to forecast the building energy consumption in New York City. Electricity or fuel consumption of every ZIP code was fit by building floor area of 8 different building functions, and energy use intensities were combined with building floor areas to obtain the whole energy consumption in the city.

The demand regression approach completely depends on a set of statistical relationships among variables, decomposing the total consumption into its constituent parts. The pure mathematics method would produce some unreasonable coefficients, even some negative values due to the multicollinearity of actual samples.

From the above analysis, the EE or DR approach is more direct and fully based than the top-down approach. Each of these two bottom-up approaches has its own benefits and limitations. The engineering estimates can be validated by samples of individual buildings, but the aggregate results might be inconsistent with the measured consumption of sub areas. The demand regression can obtain a better fit to the measured consumption of sub areas, but the regression results might be inconsistent with the samples of individual buildings. Consequently, a key issue is how to address the inconsistency and at the same time to take advantages of the two bottom-up approaches. In this paper, a two-step approach is presented, where the EE and DR approaches are combined and harmonised by Bayesian technique. Yongding city in China as a case is analyzed to display how to develop a forecasting model of the city-wide building energy demand step by step. Some other issues are also discussed in this paper, such as validation in the city-wide energy consumption and/or load, and uncertainty compared with the existing approaches of the engineering estimate and demand regression.

2. Methodology

This two-step approach is based on the concerted combination of the engineering simulation and the regression analysis. An attempt is made to establish a bridge between them through Bayesian technique. The initial engineering estimates with input from building prototypes are used as the priori beliefs, and are transformed into the posteriori distributions that describe energy consumption patterns of plots. The finally obtained predicting factors can be used along with a geospatial dataset to forecast the city-wide building energy demand (Fig. 1).

Two types of data sources are useful in the two-step approach, i.e., the information of energy consumption of individual buildings and the observed aggregate energy consumption at a sub-area level. China Ministry of Housing and Urban-Rural Development have developed a nationwide Building Energy Consumption Survey (BECS) [26] for residential and public buildings. BECS contains data of energy consumption by electricity, fuel or heat along with completion time of buildings, where buildings differ by types, functions, number of stories, cooling/heating mode. The survey is conducted biennially in each city with a scale of up to thousands of buildings. In addition, energy consumption data of plots is available in most cities because it would be not disclosive at a sub-area level. The predicting factors should be updated on a certain year basis due to change of building categories in BECS or city expanding.

2.1. Energy model of building prototypes

Since the building prototype is hypothetical, it is desirable to simplify the building description as much as possible, while still capturing the characteristic of actual buildings. Some factors should