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Uncertainty and modeling energy consumption: Sensitivity analysis for a city-scale domestic energy model

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ABSTRACT

This paper presents the development and evaluation of the Belgrade Domestic Energy Model (BEDEM) for predicting the energy consumption and carbon dioxide (CO_2) emissions of the existing housing stock. The distribution of energy use in relation to the end use is estimated as: space heating, 71%; light and appliances, 15%; water heating, 9%; and cooking 5%, while the distribution of CO_2 emissions is space heating, 59%; light and appliances, 22%; water heating, 13%; and cooking 6%. Local sensitivity analysis is carried out for dwellings of different type and year built, and the largest normalized sensitivity coefficients were calculated for parameters which almost exclusively influence space heating energy consumption in housing. For all input parameters under investigation, the effects of the input uncertainty were linear for a moderate range of input change ($\Delta x = \pm 10\%$) and superposable for a small range of input change ($\Delta x = \pm 1\%$). However, the non-linear and non-additive properties of some input parameters over the wider range hinder the development of a simple but reliable model for estimating energy and CO_2 reductions. The findings show that the uncertainty in the stock models predictions can be large and more work is needed in the area of the predictive uncertainty of stock models.

1. Introduction

In 2010 the Serbian government adopted a national energy savings target of at least 9% based on 2008 total energy consumption by the year 2019 [1]. This means that the country should ensure energy savings of about 8.8 TWh over the next seven years. Achieving this target will require urgent carbon reductions in most if not all sectors of the economy. For some sectors, such as transport, energy and carbon savings are seen as being difficult to achieve [2], whereas the building sector has been identified as having potential to deliver a larger contribution to energy savings [3,4]. Belgrade is both the political and economic capital of Serbia where live nearly quarter of all households in Serbia [5]. The Belgrade housing stock also accounts for nearly 40% of the city's total annual energy consumption and as such is considered to have a significant potential for application of various energy-efficient measures and renewable energy technologies [6,7]. However, a detailed knowledge and understanding of the nature of the energy use and CO_2 emissions attributable to the housing stock is needed to strengthen the evidence base and to support the development of an effective energy efficiency and carbon reduction strategy.

Energy consumption of the Belgrade housing stock is driven by a range of inter-related factors, including variations in the physical characteristics of buildings, the building services, and the behavior of occupants. There are over six hundred thousand dwellings that differ considerably in their size, shape, and construction. The vast majority of dwellings (~90%) were constructed after World War II using a wide range of materials and techniques, from uninsulated solid brick walls to sandwich wall systems of precast concrete and clay blocks [1]. There is also a great variety in types and efficiencies of space heating system installed in dwellings and the types of fuels used. Occupant behavior, which to a large extent reflects household socio-demographic characteristics, greatly influence space and water heating consumption (other than for district space heating system), and the usage patterns of lights and electrical appliances.

A detailed domestic stock energy model can be used to help formulate optimum carbon reduction strategies by estimating the effects of various technologies, policies and future climate conditions on total energy consumption and CO_2 emissions. However, for policymakers to have confidence in the predictions derived from model outputs the models need to be validated against existing data and the uncertainties within the model fully acknowledged.

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As Box and Draper [8] have commented, “all models are wrong; the practical question is how wrong do they have to be to not be useful”.

One widely accepted approach to modeling of the overall housing stock involves the selection of a number of dwellings to form archetypes that when combined in appropriate proportions can represent the entire dwelling stock. Dwelling archetypes are typically defined by built form (e.g. bungalow, detached, semi-detached, etc.), year built (usually in relation to the corresponding building regulations), and type of space heating systems [2]. In most models, each building archetype is designed to be an average example of its building category. A core building energy model is then used to predict the energy consumption attributable to each building archetype, and the overall housing stock energy use is calculated by aggregating the predictions for each house archetype.

The house archetype approach has been used by several UK physically based bottom-up housing stock modes [2,9–13]. All these models use steady-state heat balance equations to calculate energy consumption and to varying degrees can be considered as modified versions of the BRE Domestic Energy Model (BREDEM) [14]. In most cases, the model validation was performed by comparing a prediction for the total annual energy use attributable to the housing stock against UK national statistics, the English House Condition Survey (1996), or outputs from other UK domestic models. However, only two of the above mentioned models, the CDEM model developed by Firth et al. [2] and the DECM model developed by Cheng and Steemers [13], have examined the effect of uncertainty within the model inputs on model predictions. For energy models to improve in their robustness and support for policy development and refinement, there needs to be a far more detailed understanding of the relationship between the uncertainty in the underlying model parameters and the model predictions.

This paper aims: (a) to present the overall structure and form of the Belgrade domestic energy and carbon model (BEDEM) and its predictions of energy consumption and carbon emissions; (b) to investigate the effect of uncertainty in the model input parameters to the model predictions by incorporating dynamic hourly based calculation engine for calculating space heating energy demand attributable to each house archetype; (c) to compare obtained findings with the results of two steady-state models: the CDEM model [2] and the DECM model [13]; and (d) to quantify the relevant impact of different energy-efficient measures on average dwelling CO_2 emissions.

2. BEDEM model structure and form

The overall structure and form of the BEDEM model is illustrated in Fig. 1. As Fig. 1 indicates, the model has been constructed around three separate but inter-related components: Module 1: Data sources and Building characteristics, Module 2: Base Model scenario and Validation, and Module 3: Explorative scenarios.

Module 1: Data sources and Building characteristics is composed of both externally generated information including building location (urban, suburban), building thermal performances, building service systems and various other energy related characteristics of the Belgrade housing stock, and on-site data obtained through monitoring campaign and questionnaire survey. Detailed analyses of the measured indoor temperatures and relative humidity along with the information on sampling method, sample size and questionnaire survey are given elsewhere [15].

The Belgrade housing stock has been classified according to two built forms (multi-storey buildings and single-family houses), four year built categories (1946–1970, 1971–1980, 1981–1997, and 1998–2010), three major types of space heating system (district heating, individual central heating, and non central heating), and four main energy carriers (thermal energy generated by district heating, electricity, solid fuels, and natural gas). The building archetypes have been designed primarily to include variations in space heating, as space heating is the largest consumer of energy in residential sector, with 60–70% share in the domestic energy consumption [16]. Built form and year built are key factors in space heating as they determine the number of exposed walls, the average floor area, and the building thermal characteristics (e.g. older buildings are built to lower thermal standards than new buildings). Space heating system type and fuel type are also key determinants as the type of space heating system can have a considerable influence on the heating demand temperature (e.g. dwellings with district heating have significantly higher indoor temperatures than other dwellings [15]), whilst the type of fuel affects CO_2 emissions (e.g. coal emits up to 60% more CO_2 emissions than gas when used in power generation).

Apartments located in the multi-storey buildings (MSB) make nearly two thirds of the total housing in Belgrade [16]. While MSB are classified in four year built categories in relation to the historical changes of thermal standards prescribed in the Building Regulations, single-family houses (SFH) are presented with a single house which thermal properties are calculated from a weighted average. This is based on analysis of measured parameters [15] and previous conclusions of Popovic et al. [17] who reported that the majority of individual houses are built by independent builders without any or little enforcement of the corresponding Building Regulations. Furthermore, since there is no data available on houses' built form (e.g. bungalow, detached, semi-detached, etc.), it has been assumed that SFH are composed solely of detached dwellings according to the Master Plan of Belgrade to 2021 [18] where is stated that detached dwellings are predominant house type. Therefore, Belgrade housing stock is presented with four MSB designed to be an average example of their year built categories and one weighted average detached dwelling designed to be an example of all SFH. Defined building categories are presented in Table 1.

Module 2: Base Model scenario and Validation provides information on total energy use and CO_2 emissions attributable to the each building archetype, the corresponding building categories, and the overall housing stock. This information will be used as a starting point for development of four detailed explorative carbon reduction scenarios. Current thermal and construction characteristics of the housing stock have been incorporated within the 'Base Model' scenario. The two-stage validation of model predictions has been done. First, predicted space heating energy demand attributable to each building archetype with district heating have been compared to the energy consumption measured by the service provider (Belgrade Thermal Plants). Second, predictions of total space heating energy consumption and the total energy use of housing stock have been compared to the official top-down data provided by the public institutions (Belgrade Institute of Informatics and Statistics, Belgrade Thermal Plants, and Belgrade Administration for Energy).

The whole building dynamic energy simulation software called 'TRNSYS' [19] has been used to calculate the space heating energy demand attributable to each building archetype. Variations in space heating energy demand in relation to the space heating type are included by setting the corresponding heating demand temperatures [15]. The internal heat gains associated to the occupants, lights and electric appliances, and cooking have been estimated based on information on the mean household size [5], and the type, age, and capacity of electric appliances, type and installation power of bulbs, and frequency and duration of cooking obtained from questionnaire survey in conjunction with the recommendations given within the available publications [20–22]. Obtained internal gains have been defined as kilojoules per hour (kJ/h) and specified by using the average occupancy pattern behavior derived from the