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Modeling temporal variations in global residential energy consumption and pollutant emissions

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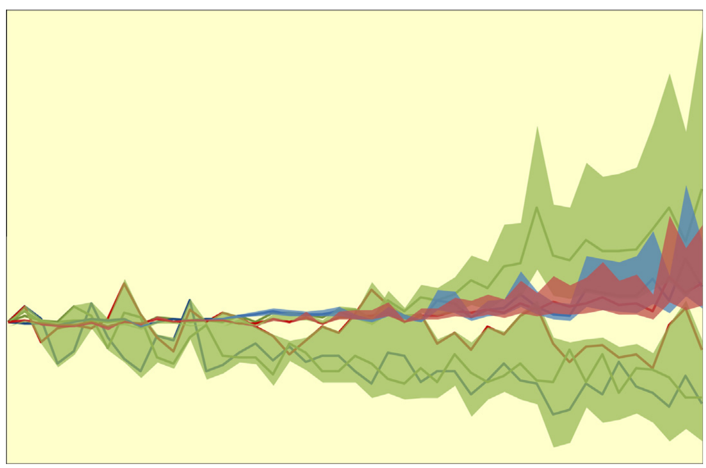
HIGHLIGHTS

- Space-for-time substitution was tested for seasonality of residential energy.
- Regression models were developed to simulate global residential energy consumption.
- Factors affecting the temporal trend in residential energy use were identified.
- Climate warming will induce changes in residential energy use and emissions.

GRAPHICAL ABSTRACT



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ABSTRACT

Energy data are often reported on an annual basis. To address the climate and health impacts of greenhouse gases and air pollutants, seasonally resolved emissions inventories are needed. The seasonality of energy consumption is most affected by consumption in the residential sector. In this study, a set of regression models were developed based on temperature-related variables and a series of socioeconomic parameters to quantify global electricity and fuel consumption for the residential sector. The models were evaluated against observations and applied to simulate monthly changes in residential energy consumption and the resultant emissions of air pollutants. Changes in energy consumption are strongly affected by economic prosperity and population growth. Climate change, electricity prices, and urbanization also affect energy use. Climate warming will cause a net increase in electricity consumption and a decrease in fuel consumption by the residential sector. Consequently, emissions of CO_2, SO_2, and Hg are predicted to decrease, while emissions of incomplete combustion products are expected to increase. These changes vary regionally.

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1. Introduction

1.1. Energy use in residential sector

Energy production and use are the dominant sources of many air pollutants and greenhouse gases. Temporally resolved emissions inventories are needed to quantitatively assess the public health and climate impacts of these pollutants. The residential sector contributes significantly, not only to ambient and household air pollution [1], but also to temporal trends in energy use and pollutant emissions [2]. In general, the seasonal variability of residential energy use is induced by temperature fluctuations [3]. On the other hand, long-term consumption trends are driven by both climate change and socioeconomic development [4].

Residential energy consumption was responsible for 7.0% and 13.6% of primary and total energy consumption, respectively, globally in 2011 [5]. End-use shares are relatively high in developed countries such as the United Kingdom (29%) [6] and the United States (22%) [7]. In China, end-use energy consumed by residents reached 400 million tonnes of coal equivalent in 2012, which represented 11% of the country's total energy use [8]. Because of relatively low combustion efficiency and no abatement measures various solid fuels in residential stoves, comparing with those in industrial facilities, emission factors (EFs, the mass of pollutants emitted from combustion per unit mass of fuel) of various pollutants, especially the incomplete combustion products, from residential sector are much higher than those in other sectors. For residential stoves using solid fuels, combustion efficiencies are often very low and there is no abatement device at all. As a result, emission factors (EFs, the mass of pollutants emitted from combustion per unit mass of fuel) of various air pollutants, especially the incomplete combustion products, for the residential sector are much higher than those for other sectors. Therefore, residential energy use contributes relatively large shares of emissions of many air pollutants, although this sector contributes only a relatively small fraction of total primary energy consumption. For example, 32.6%, 88.6%, and 21.5% of the global emissions of black carbon (BC), benzo(a)pyrene (BaP), and primary particulate matter less than 2.5 μm ($PM_{2.5}$), respectively, come from residential fuel burning [9–11]. Therefore, quantification of residential energy use and pollutant emissions are critical for a better understanding of air pollution.

1.2. Temporal variation of residential energy consumption

Temporally resolved energy consumption data are essential to the development of emissions inventories [12]. The significant contributions of residential energy use to emissions and the impact of that use on the temporal variation of emissions necessitate an increased understanding of the seasonal and interannual trends of energy consumption. Unfortunately, energy consumption statistics are often provided on an annual basis. To our knowledge, such information on a global scale does not exist. With the exception of a few developed countries [13–16], it is difficult to find information on the seasonal variation of residential fuel and electricity consumption, especially in the developing world, where the majority of air pollutants are emitted [1,17].

Attempts have been made to address this issue by modeling the temporal variation of energy consumption. In many cases, simple interpolation has been used to derive seasonal energy consumption and CO_2 emissions. For example, data on monthly natural gas deliveries in the United States were used in one study as a proxy for residential fuel consumption and CO_2 emissions [18]. This method is difficult to apply in developing countries due to the diversity in heating fuels and data gaps. Similarly, a full accounting approach was used to estimate monthly CO_2 emissions in individual states of the United States [19], and a proportional method was developed to generate monthly CO_2 emissions from fossil fuel sources on a global scale [13]. A 2-harmonic Fourier series was also applied to simulate the seasonal variation of global CO_2 emissions from anthropogenic sources by using latitude-dependent parameters developed from monthly energy use statistics in the United States [20].

Regression models are often useful for quantifying temporal trends. Most modeling exercises conducted thus far have focused on a single country or a part of a country [21]. For example, econometric autoregressive models were developed to derive robust elasticity coefficients for various economic indicators and to provide both short- and long-term predictions for Spain [22], the United States [23], and Thailand [24]. Many parameters such as income, expenditures, climate, and lag terms based on historical data are often adopted as independent variables. In addition to climate and socioeconomic factors, household characteristics such as floor space, appliance ownership, and operating frequency are often taken into consideration using data from household surveys [25,26]. Although these regression models can provide refined predictions, they are difficult to apply in developing countries, where similar survey data are rare. In addition to simulating monthly and diurnal variations in energy consumption, these models have been used to predict future trends under the influence of various climate change at various scenarios [27], serving as a supplement to physical simulations [28,29].

Several studies of energy consumption have been conducted at the multi-national or global scale. For example, a general moments method used energy statistics panel data obtained from the IEA for the 1978–2000 period to estimate the long-term elasticity of temperature related to energy consumption in the industrial, residential, and commercial sectors of OECD and several non-OECD countries [30]. The study analyzed data on coal, petroleum, natural gas, and electricity and found that temperature change would have impacts on residential energy consumption and would slightly influence the service and industrial sectors in these countries. Temperature elasticities associated with demand for different energy goods were also studied for 31 countries, and the inherent interactions between temperature and personal income were explored [31]. The study revealed that the intensity of the relationship varies with temperature in a non-linear and discontinuous pattern and that electricity consumption in hot and cold countries are more sensitive to summer and winter temperatures; no major differences in coal and gas use changes were observed between country categories. Additionally, households with higher incomes tended to be more responsive to temperature change.

Of the few studies that have analyzed global data, Petrick et al. [21] expanded on De Cian's study [31], which used four regression equations to analyze temperature-derived variables. More recent work by Isaac and van Vuuren [32] has focused on the impact of climate change on the relationship between worldwide household heating and cooling energy consumption and CO_2 emissions. Energy demand theory and a number of country-specific temperature-derived variables, including heating degree days (The number of degrees that a day's average temperature is below a base temperature and people start to use heating facilities, *HDD*), cooling degree days (The number of degrees that a day's average temperature is above a base temperature and people start to use cooling devices, *CDD*), and unit energy consumption (*UEC*), have also been used to project future energy consumption and CO_2 emissions for scenarios generated by the TIMER/IMAGE model [33].

Zhu et al. have proposed a space-for-time substitution method to fill the data gaps in temporally resolved energy consumption in residential sector [4]. To do so, a hypothesis assuming that the