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Variation of household electricity consumption and potential impact of outdoor $PM_{2.5}$ concentration: A comparison between Singapore and Shanghai

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HIGHLIGHTS

- Monthly household electricity consumption for Singapore and Shanghai are studied.
- Electricity consumption is related to $PM_{2.5}$ concentration in the long-run.
- The effects of temperature and the number of rainy days are considered.
- Electricity consumption costs of $PM_{2.5}$ pollution are comparable to health costs.
- The increased CO_2 emission related to $PM_{2.5}$ pollution is estimated.

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ABSTRACT

The auto-regressive distributed lag (ARDL) bound testing approach was used to study the relationships between the monthly household electricity consumption and outdoor $PM_{2.5}$ concentration with the consideration of ambient temperature and the number of rainy days for Singapore and Shanghai. It is shown that there are significant long-run relationships between the household electricity consumption and the regressors for both Singapore and Shanghai. For Singapore, a 20% increase in the $PM_{2.5}$ concentration of a single month is in the long-run significantly related to a 0.8% increase in the household electricity consumption. This corresponds to an electricity overconsumption of 5.0 GWh, a total of 0.7–1.0 million USD in electricity cost, and 2.1 kilotons of CO_2 emission associated with electricity generation. For Shanghai, a 20% decrease in the $PM_{2.5}$ concentration of a single month is in the long-run significantly related to a 2.2% decrease in the household electricity consumption. This corresponds to a 35.0 GWh decrease in the overall household electricity consumption, 1.6–5.1 million USD decrease in electricity cost, and 17.5 kilotons of CO_2 emission. The results suggest that the cost of electricity consumption should be included in the economic cost analysis of $PM_{2.5}$ pollution in the future. A 1 °C increase in the monthly temperature is in the long-run significantly related to a 13.6% increase in the monthly electricity consumption for Singapore, while a 30 degree days increase in heating & cooling days (*HCDD*) is in the long-run significantly related to a 24.9% increase in the monthly electricity consumption for Shanghai. A 5-day increase in the number of rainy days per month is in the long-run significantly related to a 3.0% and 5.8% increase in the monthly electricity consumption for Singapore and Shanghai, respectively.

1. Introduction

It is important to understand the relationships between electricity consumption and its influential factors because it is critical for planning electricity generation capacity and managing electricity supply. Policy makers and investors often rely on these relationships to evaluate the impact of energy conservation and governmental directives on electricity use [1,2]. Understanding the fluctuations of household electricity consumption also serves an important input for the designing and optimization of new building-related energy plans, such as net zero energy building

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(NZEB) technologies [3,4] and home performance with energy star programs [5,6]. A great number of studies [2,7–12] have been conducted to study the effects of weather (e.g., temperature and rainy days), and economic factors (e.g., income, electricity tariff, GDP, etc.) on electricity consumption. Some prior studies [2,8] have explored the relationships between household electricity consumption and various factors for Singapore. For example, the study by Loi and Loo [2] found that the household electricity consumption in Singapore was positively related to temperature and the number of rainy days, and attributed the relationships to the increased use of air-conditioners during hotter periods, and increased use of air-conditioners and time of staying at home during rainy days, respectively. Their study also found that the household electricity consumption was insensitive to tariff and income due to the fact that the electricity bill only accounts for a small portion of the overall household expenditure. On the other hand, relevant information is still limited for Shanghai with one study exploring the influences of temperature only [9].

Little information has been gathered regarding the influences of outdoor $PM_{2.5}$ (particulate matters smaller than 2.5 μm in aerodynamic diameter) concentration towards electricity consumption. Indeed, most of the existing effort has been put to understand how energy-related systems (e.g., power plant, vehicle, and industry) affect outdoor $PM_{2.5}$ concentrations [13,14] and how $PM_{2.5}$ exposure affects human health [15,16]. $PM_{2.5}$ poses a great threat to the health of human beings via inhalation exposure, as they have a great potential to penetrate deeply into the human respiratory systems and consist of various chemical constituents such as metal, organic compounds, biological components, sulfate, nitrate, other acidic compounds, and surface-adsorbed reactive gases [17]. It has been widely recognized that $PM_{2.5}$ exposure is associated with the increased occurrence of various diseases such as cardiovascular diseases [18,19], respiratory diseases [20,21], asthma [22,23], and lung cancer [24]. Daily mortality data showed that, on a global scale, 4–8% of premature deaths may occur due to exposure to suspended PM and especially $PM_{2.5}$ in the environment [25].

During haze episodes that are signified by the spikes of outdoor $PM_{2.5}$ concentration, people are generally advised to stay indoors, close windows and doors, and use air-conditioners and air purifiers (to clean indoor air) [26,27]. These typical mitigation measures serve to change the style of electricity use and could potentially lead to variation of household electricity consumption. Especially, the prolonged use of air-conditioners could significantly increase household electricity consumption in view of the fact that air-conditioners are widely used in modern megacities in temperate and tropical regions and air-conditioning accounts for a significant proportion of overall household electricity consumption for mechanically ventilated premises [28].

Haze episodes have been one of the severest environmental pollution problems for both Singapore and Shanghai. Singapore suffers from the near-annual spells of haze which is caused by the PM released during uncontrolled forest and peat-land burning activities in Indonesia. The duration, intensity, and impacts of the exogenous haze episodes are largely dependent on prevailing weather conditions (e.g., transboundary wind conditions) and the extent of fires in Indonesia [29]. In Indonesia, current plantation preparation methods still largely rely on land clearing fires, making PM pollution a persistent problem for Singapore, especially during El Niño years. As a developed, tropical country, air-conditioners are commonly used indoors to achieve thermal comfort, but they are one of the most electricity-consuming residential appliances in Singapore [30]. Shanghai experiences frequent, severe haze conditions attributed to various endogenous sources, such as coal power plant combustion, motor vehicle emission, and industrial emission [31,32]. It is worth noting that more than 60% of electricity comes from coal-fired power plants, which serve as a major PM contributor in China, and it was predicted that the proportion of coal as fuel source for power plant would decrease by 10% only in 2020 [33]. At the same time, vehicle ownership of Shanghai had exceeded 2.2 million by the end of 2014 and is expected to increase at a yearly rate of 10% [34]. Hence, $PM_{2.5}$ pollution is expected to pose a long-term burden to the air quality of Shanghai. In pace with the rapid advancement in economy and living standards, the ownership of air-conditioners in Shanghai reached 207 per hundred households in 2013, while electricity shortage was over 1 million kWh or even higher during some high demand periods [35].

In this work, we conduct econometric analysis to evaluate the association between household electricity consumption and ambient $PM_{2.5}$ concentration for Singapore and Shanghai. The effects of ambient temperature and the number of rainy days are also considered to complete the analysis. The haze conditions of Singapore and Shanghai are different, which allows us to explore the relationships with respect to the $PM_{2.5}$ concentrations of different modes and magnitudes. The implication of $PM_{2.5}$ pollution for economic costs and CO_2 emission are further explored in terms of electricity consumption.

2. Methodology

The raw data is firstly compiled, followed by the specification of empirical models. Based on the raw data, descriptive analysis could be conducted and includes the illustration of temporal variations of monthly variables and the calculation of descriptive statistics. In the econometric analysis, the stationarity of variables are examined, which justifies the use of the auto-regressive distributed lag (ARDL) bounds testing approach proposed by Pesaran et al. [36]. The ARDL bounds testing approach involves the determination of long-run relationship and the estimation of long-run and short-run coefficients, respectively. Lastly, the stability of estimated coefficients is evaluated based on parameter constancy tests. A schematic of the methodology in this work is shown in Fig. 1.

2.1. Raw data

Singapore has a total population of 5.54 million and a land area of 719.1 km^2 in 2015 [37]. The climate of Singapore is characterized by a northeast monsoon season from December to early March, a southwest monsoon season from June to September, and two interspersed inter-monsoon period otherwise [38]. Generally, the southwest monsoon season is featured by dry and relatively hot weather which would favor the formation of haze episodes. The hourly 24-h $PM_{2.5}$ mass concentration data of five parts of Singapore (i.e., north, south, east, west, and central corresponding to 12 ambient monitoring stations and 2 road-side stations) from December 2012 to December 2015 was obtained from the website of National Environmental Agency (NEA), Singapore [39]. Since April 1st, 2014, the $PM_{2.5}$ concentration was not reported on its own but subsumed into PSI readings. In this case, the $PM_{2.5}$ concentration data after April 1st, 2014 was back-calculated based on the reported PSI data [40], considering that $PM_{2.5}$ serves as the dominant air pollutant for Singapore, especially during haze episodes [41]. The 24-h $PM_{2.5}$ mass concentration data for the five parts of Singapore at 8 am, 12 pm, and 4 pm each day was averaged to calculate the average daily $PM_{2.5}$ concentration, and based on which the monthly $PM_{2.5}$ mass concentration was calculated. The monthly household electricity consumption data was obtained from the website of Energy Market Authority (EMA), Singapore [42]. The original electricity consumption data denotes the monthly electricity consumed per household and thus the potential effect of population (household) expansion could be