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# Adapting to climate change: substitution effect of water on residential electricity consumption

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## Abstract

**Purpose** – As climate change impacts residential life, people typically use heating or cooling appliances to deal with varying outside temperatures, bringing extra electricity demand and living costs. Water is more cost-effective than electricity and could provide the same body utility, which may be an alternative choice to smooth electricity consumption fluctuation and provide living cost incentives. Therefore, this study aims to identify the substitute effect of water on the relationship between climate change and residential electricity consumption.

**Design/methodology/approach** – This study identifies the substitute effect of water and potential heterogeneity using panel data from 295 cities in China over the period 2004–2019. The quantile regression and the partially linear functional coefficient model in this study could reduce the risks of model misspecification and enable detailed identification of the substitution mechanism, which is in line with reality and precisely determines the heterogeneity at different consumption levels.

**Findings** – The results indicate that residential water consumption can weaken the impact of cooling demand on residential electricity consumption, especially in low-income regions. Moreover, residents exhibited adaptive asymmetric behaviors. As the electricity consumption level increased, the substitute effects gradually get strong. The substitute effects gradually strengthened when residential water consumption per capita exceeds 16.44 tons as the meeting of the basic life guarantee.

**Originality/value** – This study identifies the substitution role of water and heterogeneous behaviors in the residential sector in China. These findings augment the existing literature and could aid policymakers, investors and residents regarding climate issues, risk management and budget management.

**Keywords** Climate change, Residential sector, Electricity consumption, Water use, Substitution

**Paper type** Research paper

## 1. Introduction

Temperature shock impacts residential energy consumption and causes energy-dependent behaviors; however, water may reduce energy consumption fluctuations and facilitate adaptive

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behaviors. Air conditioners are a major adaptation solution for extreme temperatures (He *et al.*, 2021). Residents typically use heating or cooling appliances to deal with varying outside temperatures when pursuing body comfort (He *et al.*, 2023), which directly increases residential electricity demand (Auffhammer, 2022; Du *et al.*, 2020a). Alternatively, showers are regarded as a choice that can yield the same temperature utility (Hami *et al.*, 2019; Salvo, 2018). The lower unit price of water compared with electricity may help people stabilize their budgets. This provides electricity conservation and living cost incentives to residents (Tiefenbeck *et al.*, 2019), which may act as a substitution effect and change the impact of climate change on residential electricity consumption. Moreover, as illustrated in Figure 1, this substitution effect may be heterogeneous. On the one hand, residents face different degrees of water scarcity (Huang *et al.*, 2017). China has disparate water resource endowments in the north and south (Fan *et al.*, 2020). The discrepancy in water resources leads to different living habits in the residential sector (Russell and Knoeri, 2020). People living in water-rich regions can easily use water to improve their body comfort, which may lead to a larger substitution effect on electricity consumption. However, energy poverty has become increasingly prominent due to climate change (Jessel *et al.*, 2019). Although air conditioning meets residents' temperature needs, this adaptation measure depends on households being able to afford the associated adaptation costs (Doremus *et al.*, 2022), for example, tiered electricity pricing improves electricity use cost levels for residents (Zhang and Lin, 2018). When climate shocks push residents to pursue body comfort with air conditioners, different usage frequencies correspond to different electricity consumption levels and charging standards (Zhang and Qin, 2015; Prabakaran *et al.*, 2020). This brings about a disparate cost of electricity consumption and adaptive behaviors (Du and Ma, 2021), which may stimulate residents to consume heterogeneous water and avoid expensive electricity use constrained by their living budget. To this end, the key issues are identifying climate change adaptive behaviors that include the substitution mechanism and heterogeneous effects of water on the relationship between climate change and residential electricity use, supporting policy formulation and constituting the focus of this study.

China is the largest developing country with rapid urbanization, economic growth and enormous residential electricity demand (Du *et al.*, 2020a; Li *et al.*, 2022; Duan *et al.*, 2022).

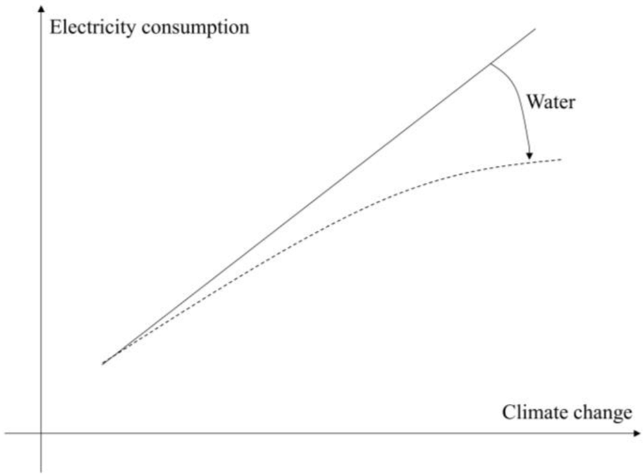


**Figure 1.**
Possible substitution effect of water on the impact of climate change on residential electricity consumption

**Source**: Created by author

Residential energy consumption in China has increased from 107.87 Mtec in 2004 to 310.10 Mtec in 2019. Electricity consumption has increased from 244.1 kWh in 2004 to 1057.7 kWh in 2019, and the share of electricity increased from 28% to 42%. Meanwhile, extreme weather intensifies the matching pressure on both sides of electricity supply and demand (Rizzati *et al.*, 2022; Cai *et al.*, 2022), for example, the power outage in Northeast China (Cao *et al.*, 2022). People need reliable substitutes that could help residents break the lock-in effect of electronic appliances and transfer pressure from the electricity system. However, China's per-capita water resources are only 1/4 of the global average level (Zhang *et al.*, 2021a, 2021b). The poor per-capita water resources may inhibit the substitution effect and obstruct adaptive behaviors to climate change. Overall, electricity and water are the most common commodity in household consumption (Wang *et al.*, 2020). Household consumption behavior plays a crucial role in the business cycle and macroeconomic policy (Lai *et al.*, 2022). Determining the substitution link and heterogeneous effects would have an extensive influence on climate adaptive behaviors of household consumption and macroeconomics. This supplements the chain of socio-economic impacts of climate change and adds important information that needs to be considered in developing climate mitigation policies. The results could have implications for other developing countries when they suffer temperature shocks. Therefore, identifying the adaptive consumption mechanism of water consumption on the climate sensitivity of China's residential electricity demand is of interest.

Therefore, this study identifies the substitution role of water and heterogeneous behaviors in the residential sector in China. This study augments the existing literature from the following aspects. First, it investigates the substitution effect of water on the link between climate change and residential electricity consumption and discusses the adaptive consequences of temperature shocks on household consumption behaviors. By contrast, existing studies estimate the water–energy nexus (Kiziltan, 2021; Wang *et al.*, 2020) or assess the impact of climate shocks on residential electricity demand (Eshraghi *et al.*, 2021; Zhang *et al.*, 2021a, 2021b). They neglect potential substitution mechanisms and do not consider climate factors. Second, we use a novel empirical strategy to identify the consumption patterns of household adaptation. This approach could reduce the risks of model misspecification and enables detailed identification of the substitution mechanism, which is in line with reality and precisely determines heterogeneity at different consumption levels. Third, this study provides forward-thinking expectations for stakeholders regarding climate risks. This could aid policymakers, investors and residents regarding climate issues, risk management and budget management.

The remainder of this paper is organized as follows. Section 2 briefly reviews the temperature–electricity curve and the water–energy nexus. In Section 3, we describe the variables and the model specification. Section 4 reports the empirical findings, further discussion and robustness check. Finally, Section 5 presents the main conclusions.

## 2. Literature review

Existing studies discuss the adverse shocks of climate change, including agriculture, fitness and social stability (Belford *et al.*, 2022; Paniw *et al.*, 2022; Beckage *et al.*, 2022). How temperature impacts society and the economy is challenging (Li *et al.*, 2018) and an increasing number of studies have focused on this. Auffhammer *et al.* (2013) discuss the economic impacts of climatic influence using weather data, climate models and their use in the social sciences. Hsiang (2016) provides a synthetic review to interpret recent advances in theoretical and empirical methods used to identify and measure the effect of climate on societies.

The relationship between electricity demand and temperature has received significant attention (Gupta, 2012; Zheng *et al.*, 2020). Gustavsson and Truong (2016) examine the relationship between climate and electricity use of transport services. Belford *et al.* (2022) collect evidence from the agricultural sector. Aldy and Pizer (2015) explore the relationship between manufacturing industries. Chen *et al.* (2021a) focused on the temperature–electricity curve of the construction industry. These studies mainly use parametric, nonparametric and semiparametric models to assess the link between temperature and electricity (Du *et al.*, 2020b). For parametric models, a quadratic function is commonly adopted to estimate nonlinear relationships. Lee and Chiu (2011) demonstrate a nonlinear association between electricity, temperature and real income using a panel smooth transition regression model. Fan *et al.* (2015) used a multivariable regression model to analyze the effects of climate change on the electricity consumption of four sectors. Zhang *et al.* (2022a, 2022b) apply a piecewise regression and nonlinear methods to determine the dose-response function and predict Beijing's power demand in the next 40 years. However, parametric models must assume specific functional forms (McDonald, 1996). Although they are easy to understand and explain, they are constrained by a given specific form and may suffer from model misspecification (Areosa *et al.*, 2011). Thus, studies have focused on semiparametric and nonparametric models. They attempt to eliminate constraints from specific functional forms and assume the response function of energy consumption to climate change is unknown. To understand residents' temperature responses, Gupta (2012) and Davis and Gertler (2015) use semiparametric models to describe a linear combination of temperature response functions in India and Mexico, respectively. Harish *et al.* (2020) and Du *et al.* (2020b) also combine the simple additive structure of the parametric regression model with the flexibility of the nonparametric approach. However, their investigation emphasizes the nonlinear relationship between electricity demand and climate change.

Another strand of the literature generally analyzes the water–energy nexus. Most residents' electricity consumption is linked to water consumption (Dodder, 2014), such as cooking, showering and space cooling (Hussien *et al.*, 2017; Wang *et al.*, 2020). Binks *et al.* (2016) quantify residential water-related energy use and identify the driving factors. Based on sensitivity analysis of individual and combined parameters, Kenway *et al.* (2016) explore the activities associated with water-energy use at the end-use level. These studies track the water–electricity flows at the resident level and are focus on fully modeling the water–energy nexus. Matos *et al.* (2018) find that variation in water–energy factors in terms of individual behaviors and technology could result in heterogeneous water and energy use at the end-use level. Furthermore, some studies explore the mechanism of water-energy linkages. Chini *et al.* (2016) examine the water–energy nexus and evaluate the cost effect via a cost abatement analysis. Mounir *et al.* (2019) adopt water-limited regions and analyze the population effect in the nexus, supporting current efforts of local stakeholder engagement. Fang and Chen (2017) use the input–output model and linkage analysis to detect the synergetic effects of water and energy consumption and interactions among economic sectors. In addition, some scholars concentrate on the water-energy nexus in developing countries, such as Sub-Saharan African countries, India and South Africa (Ozturk, 2017; Mathetsa *et al.*, 2022; Mukherji, 2022). Thus, they broaden the discussion of the water–electricity nexus and are of great significance.

Overall, climate issues should neither be considered to belong only to agricultural or related sectors nor limited to temperature risks (Addoum *et al.*, 2020; Cao *et al.*, 2022). Studies on the temperature–electricity curve and water–energy nexus have contributed rich findings globally. Most studies only concentrate on production relationships or consumption habits. Few studies combine these factors to discuss the adaptive behaviors of the residential sector. Household consumption behaviors are essential to business cycles and macroeconomic policy (Lai *et al.*, 2022). As a common good of the residential sector, water goes hand in hand with electricity, the potential effects of which should be considered. Moreover, China is a developing country with considerable climate and economic differences across different provinces, even among cities (Li *et al.*, 2019). These differences may expand costs for the necessities of life, intensifying energy poverty. Exploring nonlinear substitution relationships is critical, which could provide a substitute response curve for long-term household consumption forecasts in developing countries. Therefore, this study fills these gaps in the literature by identifying the substitution role of water and heterogeneous adaptive behaviors in the residential sector.

## 3. Theoretical model and hypotheses

Research on climate change and consumption behaviors is mainly based on utility theory. Harrington and Portney (1987) first referred to Becker's health production function model, which incorporated health welfare into the consumer utility function. Deschênes and Greenstone (2011) incorporated temperature into the consumer utility function and proposed a set of behavioral impact analysis frameworks for climate change. This analytical framework has been widely used in numerous environmental impact studies. According to this framework, we assume that the individual utility function $U$ is a function of the individual survival rate $S$ and residential water consumption $X_w$, namely:

$$\mathrm{U} = \mathrm{U}(X_w, \mathrm{S}) \tag{1}$$

Suppose that survival rate $S$ is affected by temperature $T$ and residential electricity consumption $X_e$, namely:

$$\mathrm{S} = \mathrm{S}(X_e, \mathrm{T}) \tag{2}$$

Residential electricity consumption $X_e$ can improve individual survival in extreme weather, while individuals face income budget constraints:

$$\mathrm{I} - X_w - pX_e = 0 \tag{3}$$

where $I$ represents residential income. $p$ is the relative price of electricity to water. According to the utility maximization goal, when it is in equilibrium:

$$\frac{(\partial U/\partial S)(\partial S/\partial X_e)}{\partial U/\partial X_w} = p = MRS(X_e, X_w) \tag{4}$$

The maximum utility function is $\mathrm{V} = \mathrm{V}(\mathrm{I},\mathrm{T},p)$, namely, individuals will adjust their budgets according to changes in temperature owing to maintaining utility. When the price of electricity is constant, $\mathrm{V} = \mathrm{V}[\mathrm{I} \times (\mathrm{T}),\mathrm{T}]$. Meanwhile, by calculating the first derivative of $T$ with respect to $V$, the residential willingness to pay (WTP) for the temperature change can be obtained as follows:

$$\frac{dV}{dT} = \frac{\partial V}{\partial T} + \frac{\partial V}{\partial I}\frac{dI}{dT} = 0 \tag{5}$$

$$\frac{dI}{dT} = -\frac{\partial V/\partial T}{\partial V/\partial I} = \left(MRS(X_e, X_w)\frac{\partial X_e^*}{\partial T}\right) - \left(\frac{\partial U/\partial S}{\lambda} \times \frac{dS}{dT}\right) \tag{6}$$

$$MRS(X_e, X_w) = \frac{\left(\frac{dI}{dT} + \frac{\partial U/\partial S}{\lambda} \times \frac{dS}{dT}\right)}{\partial X_e^*/\partial T} \tag{7}$$

According to equation (7), the substitution effect between electricity and water consumption [$MRS(X_e,\ X_w)$] depends on the relationship between climate change and electricity consumption ($\frac{\partial X_e^*}{\partial T}$). Climate change stimulates rapid changes in electricity demand. When external factors change, residents will make adaptive consumption decisions (Moisander, 2007). Water is a necessary good for household consumption and brings residents the same utility of body comfort as electricity (Wang *et al.*, 2020; Wang *et al.*, 2021). Water helps people resist extreme weather without much use, directly acting on the human body, unlike air conditioning which changes the room temperature by indirect actions. Low consumption of water could substitute for the quantity of electricity used, which is cost-effective for households. Based on this, this study proposes the following hypothesis:

*H1*. Under the impact of climate change, water consumption has a substitution effect on electricity consumption.

In addition, according to equation (7), the substitution effect could impact consumers' WTP ($\frac{dI}{dT}$) and individual resilience to climate change ($\frac{\partial U/\partial S}{\lambda} \times \frac{dS}{dT}$), which reflects that the substitution effect is different among individuals with different attributes. Income level matters for consumption (Du *et al.*, 2020a), which could cause heterogeneity in the substitution effect. Although air conditioning meets the temperature needs of residents, this adaptation measure depends on households being able to afford the associated adaptation costs (Doremus *et al.*, 2022). Temperature shocks stimulate electricity consumption and increase living expenses through step tariffs (Zhang and Lin, 2018). Individuals have to consider their budget constraints and use water in a way that minimizes the impact on their normal life. Low-income individuals need to change their consumption bundles and lifestyle to maintain body comfort and avoid expensive expenditures. Water can bring them the same comfort utility as electricity without tiered charging, which saves their life costs and has a more significant substitution effect. Accordingly, this study proposes the following hypothesis:

*H2*. This substitution effect has heterogeneity among different income-level regions.

## 4. Methodology

The first objective of this study was to measure the impact of climate change on residential water and electricity consumption. Previous studies, such as Hekkenberg *et al.* (2009) and Fikru and Gautier (2015), have identified comfort zones where no heating or cooling is required. Song *et al.* (2017) and Cao *et al.* (2022) set reasonable thresholds for comfort zones that range between 18°C and 27°C in China.

Therefore, this study refers to the benchmark of thresholds and respectively constructs the indicators of heating degree days (HDD) and cooling degree days (CDD) as follows:

$$HDD_{it} = -\sum_{\tau=1}^{365} \min(0,\ Temp_{it\tau} - 18) \div 365 \tag{8}$$

$$CDD_{it} = \sum_{\tau=1}^{365} \max(0, \ Temp_{it\tau} - 27) \div 365 \tag{9}$$

where the subscripts $i$, $t$ and $\tau$ denote city, year and day, respectively. $Temp_{it\tau}$ indicates the outdoor temperature recorded every day in Celsius. HDD and CDD can measure residential electricity demand when heating or cooling buildings as a result of climate change. In addition, we refer to Li *et al.* (2018) to construct a mean temperature deviation (TDEV) indicator, which is the sum of HDD and CDD:

$$TDEV_{it} = (HDD_{it} + CDD_{it}) \tag{10}$$

The empirical estimation is conducted as follows. The first step is to estimate whether residential water consumption acts as a substitution effect and changes the impact of climate change on residential electricity consumption. According to Du and Li (2019), the baseline models are as follows:

Model 1:

$$ln(E_{it}) = \alpha + \beta_1 TDEV_{it} + \gamma_1 \ln(Water_{it}) + \theta_1[TDEV_{it} \times \ln(Water_{it})] + \lambda X_{it} + \mu_i + \varepsilon_{it} \tag{11}$$

Model 2:

$$\begin{aligned} ln(E_{it}) = \alpha + \beta_2 HDD_{it} + \beta_3 CDD_{it} + \gamma_2 \ln(Water_{it}) + \theta_2[HDD_{it} \times \ln(Water_{it})] + \\ \theta_3[CDD_{it} \times \ln(Water_{it})] + \lambda X_{it} + \mu_i + \varepsilon_{it} \end{aligned} \tag{12}$$

Here, $\ln(E_{it})$ is the natural logarithm of per-capita residential electricity consumption in city i and year t. $\ln(Water_{it})$ represents the natural logarithm of the per capita residential water consumption in city i and year t. $X_{it}$ is the matrix of control variable. In addition, $\mu_i$ denotes unobserved individual effects and $\varepsilon_{it}$ is a random error. The parameter $\theta$ ($\theta_1$, $\theta_2$ and $\theta_3$) measures the magnitude of the substitution effect of residential water consumption on the link between climate change and residential electricity consumption.

The aforementioned strategies indicate how the impact of climate change depends on residential water consumption. However, the link between climate change and residential electricity consumption is close to a nonlinear relationship. In this case, results from the linear model may influence the accuracy of identification. This study further introduces quantile regression and a partially linear functional-coefficient panel model into its estimation. The former regards the substitution effect as a linear approximation linkage (Lv, 2017), and it reveals these under different conditional quantiles. The latter is semiparametric (Du *et al.*, 2020a), and it assumes that the unknown response of residential electricity consumption is a function of the substitution effects represented by the logarithm of residential water consumption. These two models are close to the realistic adaptive behaviors of residents, which may reduce the risk of model misspecification and enable the detailed identification of the substitution mechanism of water between climate change and electricity demand. Thus, biased results may be overcome and the heterogeneity of the substitution effect of residential water consumption established. According to Cao *et al.* (2022a), the panel quantile regression model can be rewritten as:

Model 3:

$$Q_{ln(E_{it})}\left(\tau \mid X_{it}, \mu_i\right) = \alpha + \beta_{2\tau} HDD_{it} + \beta_{3\tau} CDD_{it} + \gamma_{2\tau}\ln(Water_{it}) + \theta_{2\tau}[HDD_{it} \times \ln(Water_{it})] + \theta_{3\tau}[CDD_{it} \times \ln(Water_{it})] + \lambda_\tau X_{it} + \mu_i + \varepsilon_{it} \tag{13}$$

where $\tau$ is a quantile in (0, 1) and $Q_{ln(E_{it})}\left(\tau|X_{it}, \mu_i\right)$ is the $\tau^{\text{th}}$ conditional quantile function. To optimize the estimation of parameters and the calculation of the covariance matrix (Wang *et al.*, 2013), we adopt the adaptive Markov chain Monte Carlo optimization procedure.

According to Du *et al.* (2020a), the partially linear functional–coefficient panel data model can be written as:

Model 4:

$$ln(E_{it}) = \alpha + G_2(\ln(Water_{it}))HDD_{it} + G_3(\ln(Water_{it}))CDD_{it} + \lambda X_{it} + \mu_i + \varepsilon_{it} \tag{14}$$

where $G(\ln(Water_{it}))$ is a function of the substitution effect represented by the logarithm of residential water consumption. Moreover, this model set means the response of residential electricity consumption varies with the change in temperature and residential water consumption. This accords with the nonlinear relationship and can verify heterogeneous substitution effects of residential water consumption. In addition, we refer to Du *et al.* (2020b) to estimate the aforementioned model.

## 5. Empirical study

### 5.1 Data

We compiled a city-level panel data set to precisely cope with the demand fluctuation dilemma in the residential sector. Some studies analyze the link between climate change and electricity demand at the provincial level (Fan *et al.*, 2019; Chen *et al.*, 2021b). The data set lacks representativeness and ignores dynamic changes in temperature and different geographic locations in China, which may lead to omission of heterogeneous characteristics of different terrains and climate zones.

Our panel data set covers 30 provinces and 295 cities in mainland China over 2004–2019 (excluding Tibet owing to missing data). The statistical descriptions of the variables are presented in Table 1. The explained variable is city-level per-capita residential electricity consumption (E) which is forward-looking to correlate with the key explanatory variables and the interaction terms of per-capita residential water consumption (Water) and key variables (TDEV). Raw daily temperature data are acquired from China's National Meteorological Information Center. Annual city-level residential electricity consumption data are from *China City Statistical Yearbook*.

The control variables (X) are selected and constructed as follows:

- *Water*. This study aims to identify the potential substitution effect and heterogeneity between *Water* and *TDEV*, which needs to control per-capita residential water consumption.
- *Income*. This is controlled because of its influence on electricity consumption (Bhattacharya *et al.*, 2021). On the one hand, income levels are unevenly distributed over China. On the other, different income levels may determine differences in

**Table 1.** Descriptive statistics of variables

| Variable | Description | Source | Unit | N | Mean | SD | Min | Max |
|---|---|---|---|---|---|---|---|---|
| E | Residential electricity consumption per capita | CCSYB | kWh | 4,431 | 21.73 | 19.8 | 0.008 | 332.8 |
| Water | Residential water consumption per capita | CCSYB | tons | 4,544 | 11.49 | 11.82 | 0.26 | 127.17 |
| cdd | cooling degree days | CMA | °C·d | 4,567 | 120.55 | 114.63 | 0 | 596 |
| hdd | heating degree days | CMA | °C·d | 4,566 | 2256.09 | 1422.54 | 0 | 7,163 |
| TDEV | Temperature deviation | CMA | °C·d | 4,566 | 6.51 | 3.68 | 0.32 | 19.62 |
| Income | GDP per capita | CMA | RMB | 4,559 | 21070.98 | 10520.21 | 0 | 71765.17 |
| Elecp | Electricity price | NDRC | RMB | 4,521 | 0.72 | 0.11 | 0.36 | 0.95 |
| Rhu | Relative humidity | CMA | % | 4,567 | 68.76 | 7.8 | 44 | 86 |
| Wins | Wind speed | CMA | m/s | 4,567 | 2.13 | 0.59 | 1 | 5 |
| Sunt | Sun time | CMA | hous | 4,567 | 1991.24 | 409.47 | 906 | 3,102 |
| Rain | Rain | CMA | mm | 4,567 | 1015.95 | 461.13 | 175 | 2,744 |

**Source:** CCSYB = China City Statistical Year Book; CMA = China Meteorological Administration; NDRC = National Development and Reform Commission consumption habits. Raw data are from the Wind database. *Income* is represented by real GDP per capita at the 2004 price level.

- Electricity price (*Elecp*). Electricity prices can impact the operating frequency of heating or cooling appliances for most residents to some extent (Pavanello *et al.*, 2021). The raw data were acquired from the National Development and Reform Commission. Owing to the lack of city-level data, we use the provincial average electricity selling price, represented at the 2004 price level.
- Other climatic factors. Li (2018) highlights that other climatic factors are especially responsive to residential electricity consumption in addition to temperature. He *et al.* (2022) highlight a synergistic and compound effect referring to two or more extremes occurring simultaneously that need to be taken into account. Therefore, we introduce relative humidity, wind speed, sun time and rain (denoted as *Rhu*, *Wins*, *Sunt* and *Rain*, respectively) into our models. These variables are taken from the China Meteorological Administration.

### *5.2 Baseline results*

The results of linear Models 1–2 are reported in Table 2. We focus on the coefficients of the interaction terms between water and climate variables to identify whether residential water consumption substitutes electricity consumption. Columns (1)–(3) indicate that the water substitution effect is insignificant. The coefficient is significant at the 5% level only without controlling the city and time-fixed effects. Columns (4)–(6) present the results of *hdd* and *cdd* that are divided by *TDEV*. The substitution effect of *hdd* is similar to *TDEV*, only significant at the 5% level when the control of the city and time-fixed effects is loosened.

Notably, the coefficients of *cdd* are positive and significant at the 1% level in Columns (4)–(6), which supports *H1*. This indicates that climate change significantly stimulates residential electricity consumption in hot weather, consistent with Zhang *et al.* (2021a, 2021b) and Zhang *et al.* (2022a, 2022b). Climate change has threatened the reliability of the electric power system (Brockway *et al.*, 2022). Extreme weather has become more frequent, and temperature levels have increased, leading to explosive electricity consumption growth (Zhang *et al.*, 2021a, 2021b). People have to consider other immediate and steady ways to deal with temperature demands. Regardless of whether we control the city or time-fixed effects, the substitution effect of *cdd* is significant and negative at the 1% level, which indicates that the substitution effect exists. The coefficient of the interaction term is approximately −0.223. In other words, residential water consumption can weaken the impact of cooling demand on residential electricity consumption. When *cdd* does not change, a 1% increase in residential water consumption could substitute residential electricity consumption by 22.3%. These results indicate that showering is a good alternative. Climate change has led residents to seek other reliable ways to keep the body comfortable.

### *5.3 Heterogeneity analysis*

The following analysis assumes that the substitution effects may have potential heterogeneous impacts. Resource endowments may influence residential preference. China is one of the world's poorest per-capita water resource countries and has disparate water resource endowments across the north and south (Fan *et al.*, 2020). People in water poor regions do not have adequate material conditions and their preferences may differ. In addition, the uneven development among China's cities may cause differences in terms of sensitivity. Compared to rich regions, residents in low-income regions have to make careful

**Table 2.** Estimation results of the linear panel model with interaction terms

| Variables | TDEV<br>(1) | (2) | (3) | hdd + cdd<br>(4) | (5) | (6) |
|---|---|---|---|---|---|---|
| TDEV × lnWater | −0.0124** (0.006) | −0.0070 (0.009) | −0.0047 (0.009) | | | |
| hdd × lnWater | | | | −0.0175** (0.007) | −0.0169* (0.010) | −0.0141 (0.010) |
| cdd × lnWater | | | | −0.1418* (0.073) | −0.2299*** (0.082) | −0.2226** (0.087) |
| lnWater | 0.4752*** (0.021) | 0.2833*** (0.031) | 0.2837*** (0.033) | 0.4631*** (0.022) | 0.2753*** (0.034) | 0.2783*** (0.036) |
| TDEV | 0.0161 (0.011) | 0.0280 (0.019) | 0.0304 (0.036) | | | |
| hdd | | | | 0.0298*** (0.009) | −0.0092 (0.018) | 0.0026 (0.035) |
| cdd | | | | 0.3381*** (0.079) | 0.5422*** (0.118) | 0.3403** (0.126) |
| Constant | −6.8616*** (0.662) | −6.6660*** (0.649) | −1.179 (1.653) | −6.7412*** (0.626) | −5.9952*** (0.597) | −1.2142 (1.632) |
| Controls | Yes | Yes | Yes | Yes | Yes | Yes |
| City FE | No | Yes | Yes | No | Yes | Yes |
| Time FE | No | No | Yes | No | No | Yes |
| Cluster | Province | Province | Province | Province | Province | Province |
| $N$ | 4,369 | 4,369 | 4,369 | 4,369 | 4,369 | 4,369 |
| adj. $R^2$ | 0.630 | 0.631 | 0.647 | 0.630 | 0.636 | 0.649 |

**Notes:** Standard errors are in parentheses; ***, ** and * indicate significance at the 1, 5 and 10% levels, respectively
**Source:** Created by author

calculations and engage in strict budgeting. They will pay more attention to consumption of life resources. Therefore, the results of dummy interaction terms and income heterogeneity tests are reported in Table 3. If the residential water consumption of the city is above the median level, the dummy variable is equal to 1, or 0.

In Columns (1) and (2), the coefficient of TDEV is insignificant, indicating no difference in sensitivity when climate change is measured by temperature deviation. The coefficients of $cdd \times Dum$ and $cdd$ are significant at the 10% and 5% levels, respectively. This indicates that there are differences in sensitivity between high and low water consumption cities when residents have cooling demands. Namely, around some high consumption regions, *cdd* has less impact on residential electricity consumption. Columns (3)–(6) report the results of further heterogeneity tests in terms of income. For high income levels, no matter coefficients of TDEV and TDEV × Dum or cdd and cdd × Dum are not significant, which suggests that rich people do not care so much about the method of pursuing body comfort. Conversely, as reported in Columns (5) and (6), residents in low-income levels have heterogeneous reactions. The coefficients of $cdd$ and $cdd \times Dum$ are still significant at the 1% and 5% levels, respectively, which supports *H2*. Additionally, the substitution effects are more evident among low-income residents who suffer from energy poverty easily. These residents need a comfortable living environment and to keep a balance of payments, which pushes them to adaptive and optimized actions in the face of climate change and variability.

In the above analysis, samples are separated according to the median water consumption level. In economic theory, the sample values near the split point are hard to interpret. If the observations near the split point suddenly change, finding a reasonable economic explanation will not be easy. The dummy interaction terms also have strict assumptions, possibly leading to biased estimation results and model misspecification. The substitute effects are regarded as a linear relationship, but many studies find that it is more likely to be nonlinear (Auffhammer and Mansur, 2014; Du *et al.*, 2020b). According to the linear approximation of quantile regression, it can be understood as a linear approximation of the conditional quantile function in the sense of least mean square error (Angrist *et al.*, 2006; Li *et al.*, 2016). In addition, the above results document that the substitution effects are not evident among *TDEV* and *hdd*, whether in the interaction or dummy interaction terms. When heatwaves occur, the water–electricity nexus is separated to some degree. Residents can feel comfortable directly through cold showers, which do not require electricity to heat the water as in winter. Therefore, this study further analyzes the substitution effects of water on the link between *cdd* and residential electricity consumption.

The variation in the interaction term of *cdd* over the quantiles in Model (3) is depicted in Figure 2. The substitution effects display a downward curve, indicating that they gradually increase as electricity consumption increases. Notably, the government regulates the electricity price (Liu *et al.*, 2019). The pricing mechanism is still not market-based, and the residential price of electricity will further increase. Although China has implemented a step tariff policy since 2012 (Wang *et al.*, 2020), the tiered electricity price policy has caused people with different electricity consumption levels to face different charge standards. Namely, residents need to pay more for electricity use from low to high quantiles. Alternatively, they have to use more water to meet cooling demand, which causes "chances" to adjust preferences and avoid energy poverty. Furthermore, this curve demonstrates the substitution effects of residential water consumption on the link between climate change and electricity consumption are linear approximation relationships.

**Table 3.**
Estimation results of the linear panel model with dummy interaction terms

| | DumWater | | High income | | Low income | |
|---|---|---|---|---|---|---|
| Variables | (1) | (2) | (3) | (4) | (5) | (6) |
| lnWater | 0.3105*** (0.034) | 0.3172*** (0.035) | 0.1636* (0.083) | 0.1754* (0.087) | 0.1895*** (0.031) | 0.1963*** (0.032) |
| TDEV | 0.0365 (0.036) | | −0.0042 (0.075) | | 0.0383 (0.033) | |
| TDEV × Dum | −0.0119*** (0.003) | | 0.0031 (0.010) | | −0.0093* (0.05) | |
| hdd | | 0.0076 (0.035) | | −0.0207 (0.062) | | 0.0137 (0.031) |
| hdd × Dum | | −0.0091** (0.002) | | 0.0074 (0.011) | | −0.0075 (0.004) |
| cdd | | 0.3104** (0.123) | | 0.1496 (0.232) | | 0.3055*** (0.091) |
| cdd × Dum | | −0.1356* (0.072) | | −0.1244 (0.134) | | −0.1115** (0.053) |
| Constant | −1.1384 (1.612) | −1.3035 (1.584) | 7.9662** (2.558) | 7.8227** (2.544) | −1.5091 (2.381) | −1.6424 (2.341) |
| Controls | Yes | Yes | Yes | Yes | Yes | Yes |
| City fixed effect | Yes | Yes | Yes | Yes | Yes | Yes |
| Time-fixed effect | Yes | Yes | Yes | Yes | Yes | Yes |
| Cluster | Province | Province | Province | Province | Province | Province |
| $N$ | 4,369 | 4,369 | 1,516 | 1,516 | 2,853 | 2,853 |
| adj. $R^2$ | 0.648 | 0.649 | 0.167 | 0.167 | 0.665 | 0.666 |

**Notes:** Standard errors are in parentheses; ***, ** and * indicate significance at the 1, 5 and 10% levels, respectively
**Source:** Created by author

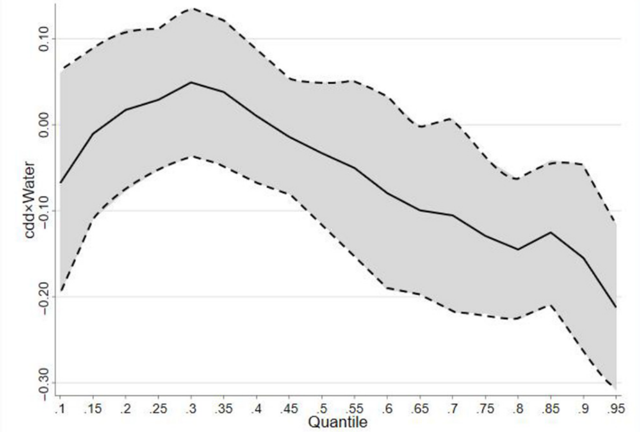


**Figure 2.**
Variation of interaction term of *cdd* over quantiles

**Note:** Horizontal lines represent ordinary least squares (OLS) estimates with a 95% confidence level
**Source:** Created by author

### *5.4 Robustness check for temperature bins*

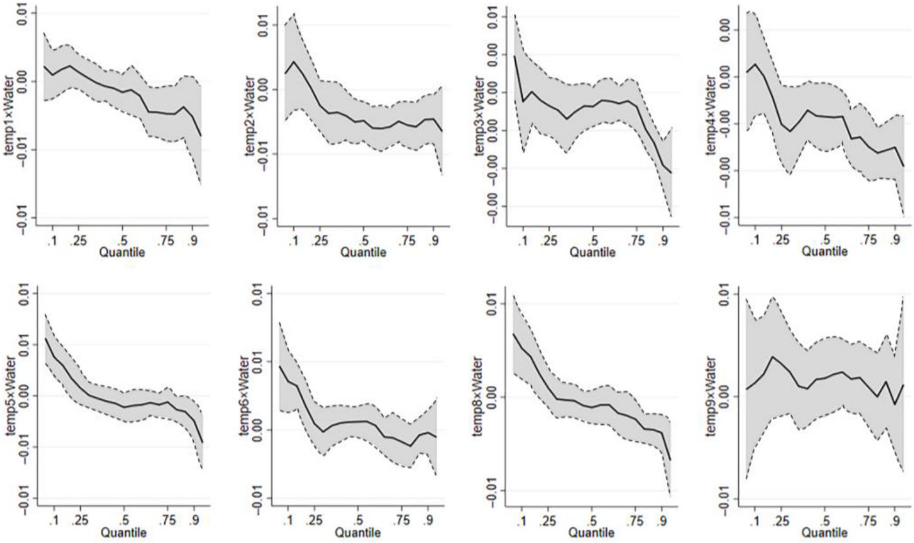
In this subsection, we conduct a robustness analysis using temperature bins. Referring to Deryugina and Hsiang (2014), we investigate temperature bin variables according to daily average temperature, calculating the number of days in a year when different temperatures fall into each bin. The panel quantile regression model can be rewritten as:

$$Q_{ln(E_{it})}(\tau|X_{it},\mu_i) = \alpha + \beta_{1\tau}Tempbin_{it}^{m} + \gamma_{1\tau}\ln(Water_{it}) + \theta_{1\tau}[Tempbin_{it}^{m} \times \ln(Water_{it})] + \lambda_{\tau}X_{it} + \mu_i + \varepsilon_{it} \tag{15}$$

where $Tempbin_{it}^{m}$ represents the total days in $m^{th}$ temperature bins of city $i$ and year $t$. Referring to Deryugina and Hsiang (2014), we divide the sample temperature intervals into nine temperature ranges based on the daily average temperature of 6°C, ([−38, −12], [12, −6), [−6, 0), [0, 6), [6, 12), [12, 18), [18, 24), [24, 30) and [30, 36]). To avoid multicollinearity, the temperature bin [18, 24] is set as the benchmark group.

The quantile regression results of temperature bins are illustrated in Figure 3, which show that the main findings remain unchanged. From *temp1* to *temp8*, the interaction terms are negative at high quantiles, meaning there are substitution effects of residential water consumption on the impact of climate change on electricity consumption. As quantiles increase, the substitution effects gradually transfer from positive to negative. This indicates that residential water consumption eliminates the synergistic effect of the water–electricity nexus. The substitution effects change, and the slopes are different among all quantiles from *temp1* to *temp8*, indicating heterogeneity due to climate variability. Hence, the results for the substitution effects are robust.

The interaction term of *temp9* is notable as, although its temperature range is the hottest, it reflects a weak substitution effect. On the one hand, the reason may be that there are few observations for [30, 36], which causes biased estimation results. On the other, hot weather



**Note:** Horizontal lines represent OLS estimates with a 95% confidence level
**Source:** Created by author

**Figure 3.**
Variation in interaction term of temperature bins over quantiles

can bring health risks and hamper normal life. Residents' body comfort reference may push them to ignore extra electricity consumption costs, which also impacts the substitution effects.

### *5.5 Further discussion*

The previous subsection analyzed the substitution effects of residential water consumption and heterogeneity under some restrictive assumptions. They are highly constrained by the given specific form and may suffer from model misspecification (Areosa *et al.*, 2011). We then relax the assumptions and discuss the nonlinear relationship via partially linear functional-coefficient models, which may match the actual energy behaviors of residents and precisely determine their temperature responses. The estimation results are reported in Figure 4.

Figure 4 depicts the functional-coefficient estimates of *cdd* in Model 4. The marginal effect climbs and then declines as residential water consumption increases. The inflection point is approximately 2.8 (i.e. residential water consumption per capita is 16.44 tons). That is, the substitution effects of water gradually appeared when residential water consumption per capita exceeds 16.44 tons. More specifically, residents need water to meet their basic life requirements. Subsequently, water usage changes and transfers to other effects when water consumption reaches a certain level (i.e. residential water consumption per capita is more than 16.44 tons). The marginal impact of *cdd* on residential electricity consumption will shrink under the influence of water. This demonstrates that the substitution effects become stronger as residential water consumption increases. When heatwave shocks occur, people have adaptive responses; they pursue body comfort and do not only rely on electric appliances and adjust their consumption structure and regard cold water as a good choice.

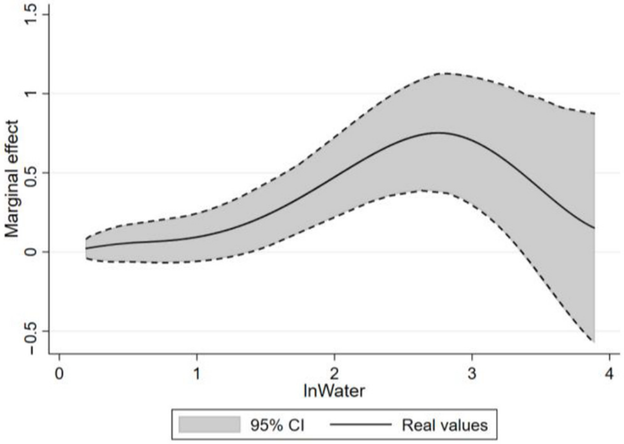


**Figure 4.**
Functional-coefficient estimates of lnWater

**Note:** The figure displays the estimated coefficients for values of lnWater ranging from the 2nd to 98th sample percentiles, with 95% confidence intervals shaded in gray
**Source:** Created by author

### *5.6 Policy implications*

This study presents several policy implications. For policymakers, the government could introduce policies to improve resource allocation efficiency and energy poverty issues. During heatwaves, the government may need to guide the price of water and no longer rely on the step tariff policy to suppress demand. Price signals will lead to people's preference to pursue body comfort. Electricity and water incorporations and investors could gradually arrange production projects and prevent business risks according to residential adaptive behaviors. The substitution effect of water provides forward-thinking expectations. When extreme weather shocks occur, residential demand fluctuations for water and electricity are known well in advance, which provides sufficient time to smooth production and resist operational risk. For the residential sector, people may need a new plan for budget management in case of energy poverty. Climate change brings more energy demand and results in sharp increases in electricity bills. Their original life budget and consumption habits experience shocks. Residents could adjust their consumption structure in a timely manner according to their lifestyle habits and preferences, thus avoiding overspending and the inconvenience caused by climatic shocks.

## 6. Conclusion

Climate change shocks normal residential life and incentivizes adaptive behavior. More frequent temperature fluctuations and extreme weather may push people to rely on air conditioning appliances to maintain comfortable indoor temperatures, leading to increased residential electricity consumption. Residents face higher energy bills and energy poverty risk. Using water for showers is an alternative choice that could bring about the same temperature utility, which may substitute for electricity consumption, bringing electricity conservation and budget balance for residents. However, few studies investigate the substitution role of residential water consumption between climate change and electricity use and do not mention the nonlinear association between them. Furthermore, this substitution effect may be heterogeneous. Different income levels and tiered electricity pricing policies in China may trigger heterogeneity.

To fill this gap, this study used panel data from 30 provinces and 295 cities in mainland China over the period 2004–2019 to identify the substitution effect. Moreover, we considered several empirical strategies to explore the potential heterogeneity of the substitution effect. The results reveal the following conclusions. First, residential water consumption could weaken the impact of cooling demand on residential electricity consumption. People prefer using water to prevent temperature shocks when heatwaves occur rather than during cold waves. Second, regions with high-water consumption or low-income levels have heterogeneous reactions. Owing to the extra electronic appliance use and tiered electricity pricing, residents in these regions need to maintain a balance of payments while keeping a comfortable living environment, which pushes them to optimize actions and aggravates energy poverty risks among poor regions when climate change and variability occur. Third, residents exhibit adaptive asymmetry behaviors when they suffer climate-related issues. As the electricity consumption level rises, the substitution effect gradually becomes stronger. The substitution effect of water appears gradually when residential water consumption per capita exceeds 16.44 tons, which is the level of basic life guarantee. Therefore, the substitution effects will not always be highly responsive to the impact of climate change on residential electricity consumption. Furthermore, this study presents some policy implications that may be beneficial for stakeholders in the case of climate risks.

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