Economic Effects of Temperatures on Household Electricity Consumption: A review of the empirical literature

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Abstract

This paper reviews the previous studies on the relationship between temperature and residential electricity consumption. In particular, we focus primarily on recent studies (2020~2022). The climate will affect household electricity use by altering residential responses to short-term weather shocks and long-term adaptation. Existing studies found a nonlinear (generally, U-shaped) response function with higher residential electricity consumption on very cold and hot days with threshold temperatures of about 50-77°F (10-25°C). In addition, it is necessary to study heterogeneity along different dimensions. A valuable direction for future research would be to see if short-term and long-term results hold each other. Another gap that needs to be filled is the analysis of the impact on a national and regional scale in Japan. Other household consumption may also be hit hard by temperature extremes, which could lead to new social problems under climate change. This is another fundamental issue that needs attention.

1. Introduction

The impact of temperature on household electricity consumption is an important topic to study as it has significant implications for energy policy and environmental sustainability. Temperature can impact household electricity consumption in different ways depending on whether it is hot or cold. During hot periods, households typically use more electricity to cool their homes, which leads to increased electricity consumption. On the other hand, during cold periods, households may use more electricity for heating purposes, which also contributes to increased electricity consumption. Understanding the impact of both hot and cold temperatures on household electricity consumption is essential for (1) promoting energy-efficient technologies and behaviors that reduce energy consumption, lower utility bills for households, and decrease greenhouse gas emissions; (2) slowing the pace of climate change since greater demand for electricity generation can result in higher greenhouse gas emissions and further exacerbate climate change; (3) improving the management of energy resources, particularly during periods of high demand; and (4) assisting public health and safety during periods of extreme temperatures, particularly for vulnerable populations such as the elderly and those with pre-existing health conditions. The purpose of this literature review is to summarize the existing research on the impact of both hot and cold temperatures on household electricity consumption and to identify areas for future research.

This paper proceeds as follows. In section 2, we brush up on methods for identifying the relationship between temperatures and household electricity consumption. Section 3 reviews the findings from the literature, especially the recent literature. Section 4 discusses the implications of the obtained findings for energy policy and environmental sustainability, identifies gaps in the literature, and suggests areas for future research. Section 5 concludes and suggests promising directions forward for the literature.

2. Methodology

This section discusses notable papers used to measure household electricity consumption from extreme temperatures. Auffhammer and Mansur (2014) and Dell et al. (2014) reviewed the extensive empirical literature on the impact of climate on energy consumption; we focus here on household electricity consumption.

2.1 Cross-sectional studies

A cross-sectional study is a type of observational research design that collects data at a point in time. Cross-sectional studies are a useful research tool because they are relatively quicker and more cost-effective than longitudinal studies, which require data collection over a longer period. Another advantage is that one can consider each unit (e.g., household) to be in its long-run equilibrium. The simple cross-sectional specification is as follows:

$$(1) \qquad y_i = \alpha + \beta T_i + c_s + \epsilon_i ,$$

where y_i is some outcome of interest for unit *i* (e.g., state, county, household), T_i is the average temperature (which can take many forms), and c_s is some other time-invariant factors that affect the outcome.

Zhang et al. (2022) used a repeated cross-sectional dataset to explore the impact of temperature on Chinese household electricity consumption. They studied households across 314 counties. These counties are highly geographically heterogeneous and thus better representative of China’s climatic patterns.

The cross-section approach has its drawbacks. A major problem is that it cannot account for temporal variation within a unit (such as households) and can only use interregional variation within a larger unit (such as a county). This is the classic omitted variable bias when such time-invariant factors are correlated with climate variables. Thus, panel analysis becomes more desirable as unobservable differences between units (e.g., households) are absorbed by unit (e.g., household) fixed effects.

2.2 Panel studies

Panel data analysis is a statistical method involving the analysis of multiple observations of the same individuals or entities over time. It typically entails the use of random effects or fixed effects models, which take into account individual-specific and time-invariant unobserved heterogeneity. The simple form of a panel analysis is:

$$y_{it} = \alpha + \beta T_{it} + c_i + \epsilon_{it}, \quad (2)$$

where t indexes time (e.g., year). All time-invariant factors are absorbed by the location fixed effects c_i, addressing the omitted variable concern in the cross-section model.

Auffhammer and Aroonruengsawat (2011) used panel data to study how household-level electricity consumption in California is affected by temperatures. Although the panel is limited to one state, the base dataset covers more than 300 million monthly household observations, allowing them to explore the relationship between temperature and electricity consumption in different climate zones in California. Using panel data from 278 cities in China, Du et al. (2020) studied the climatic impact on residential electricity consumption in China.

However, the year-to-year variation of the longitudinal data only allows us to explore the short-term weather impact. Although the panel design solves the identification problem in the cross-section approach, it may ignore the long-term response to climate at the cost of a poorer approximation of the idealized climate change experiment.

2.3 Time-series studies

A time series study is a type of observational study that focuses on analyzing changes in a specific variable over time. One of the main advantages of time series studies is that they can help identify patterns and trends in the data that may not be apparent in cross-sectional studies. The time-series specification is as follows:

(3) $$y_t = \alpha + \beta T_t + \epsilon_t .$$

Time series data is a sequence of observations for individuals or entities over time, while panel data is a set of observations for multiple individuals or entities over time.

While Auffhammer et al. (2017) did not focus on household electricity consumption, they used temperature variations in time series data. Using time series data, Zheng et al. (2020) quantified climate change's impact on electricity consumption at the regional scale, using Guangzhou, China as a case study.

Similar to panel analysis, time series study cannot address long-run adaptation. In addition, aggregate data may not be able to control for unobserved factors that are also changing over time, leading to omitted variable bias.

Although panel data can only capture short-run residential electricity consumption responses to changes in temperature, omitted variable bias is less likely to occur with panel data than with cross-sectional or time series data.

There are two common forms of temperature used in estimating temperature impact on electricity consumption: (1) Temperature Bin (e.g., Deschênes and Greenstone 2011; Davis and Gertler 2015; Zhang et al. 2022). Temperature bins are a way of categorizing temperature ranges to estimate the impact of temperature on electricity consumption. Temperature bins are used to group temperatures into ranges (e.g., 60-65°F, 65-70°F, 70-75°F, etc.); (2) Cooling Degree Days (CDD) and Heating Degree Days (HDD) (e.g., Ayyash et al. 1985; Li 2018; Du et al. 2020; Silva et al. 2020; Zhang et al. 2020; Zheng et al. 2020; Zhang et al. 2021). CDD and HDD are measures of the difference between the outdoor temperature and a reference temperature (usually 65°F), accumulated over some time. CDD is used to estimate the impact of warm weather on electricity consumption (in other words the need for cooling), while HDD is used to estimate the impact of cold weather on electricity consumption (in other words the need for heating). The degree-day method misses the convexity found in the non-parametric method, where the increase in energy demand due to temperature extremes is much stronger. The temperature bin method addresses this problem but reduces the degree of freedom in the estimation. However, this reduced degree of freedom may be acceptable, especially when analyzing large datasets.

3. Results

The effect of temperature on residential electricity consumption has been studied extensively. The following are some of the main findings of recent studies (see Table 1):

(1) non-linear (generally, U-shaped) response functions with higher residential electricity consumption on very cold and hot days; (2) threshold temperatures in the range of approximately 50-77°F (10-25°C); (3) many recent studies on the effect of temperature on residential electricity consumption have focused on case studies in China (based on *Energy Economics*, *Energy*, *Energy and Buildings*, *Energy Policy*, *Utility Policy*, *China Economic Review*, *PNAS*, and *Applied Energy*); (4) panel analysis seems preferable; and (5) both temperature bins and degree days (CDD/HDD) methods are widely used.

Even though in many cases a U-shaped relationship was found between temperature and household electricity consumption, in some cases the effect was significant only at high temperatures. Du et al. (2020) and Zhang et al. (2022) found that China's electricity consumption responds to extremely warm days, not cold days. A plausible explanation is that high HDDs are concentrated in the northern regions where most areas are served by central (district) coal-fired heating. This implies the importance of studying heterogeneity along different dimensions (e.g., north/south). Geographic heterogeneity in response to extreme temperatures has also been found in case studies in the United States (e.g., Deschênes and Greenstone 2011). Income level is also an essential component to further understand the distributional effects of extreme temperatures. High-income households appear to consume more electricity to relieve heat stress than low-income households (e.g., Du et al. 2020; Zhang et al. 2022). However, urban and rural areas are affected differently, with Zhang et al. (2020) showing that rural residents consume more electricity as income increases, while it is not true for urban residents. Similar results for urban areas can be found in Zhang et al. (2021). Households with or without children and elderly members (household composition), age, and air conditioning adoption are also important dimensions for studying the effects of heterogeneity.

Table 1

Findings of studies on the impact of temperature on residential electricity consumption

No.		Method/ Year Level of obs.	Change in consumption (%) with temperature change	Threshold temperature (*T*) (°F)	Reference
1	USA	Panel/ 1968-2002 State-year	1 extra day> 90°F: 0.4↑ 1 extra day< 20°F: 0.2-0.3↑	50-60	Deschênes and Greenstone 2011
2	Mexico	Panel/ 2009-2012 Household-month	1 extra day> 90°F: 3.2↑ 1 extra day< 50°F: near zero	65-70	Davis and Gertler 2015
3	China	Panel/ 2005-2015 City-year	1% increase in degree day> *T1*: 0.1↑ 1% increase in degree day< *T2*: −	*T1*= 77 *T2*= 55.4	Du et al. 2020
4	Portugal	Panel/ 2010-2017 Country-month	1 extra degree day exceeds *T1*: 0.1↑ 1 extra degree day below *T2*: 0.1↑	*T1*= 75.2 *T2*= 59	Silva et al. 2020
5	China	Rep. cross/ 2012-2014 Household-year	1 extra day> 89.6°F: 8.1-9.7↑ 1 extra day< 50°F: −	50-60.8	Zhang et al. 2022
6	Guangzhou, China	Time series/ 2004-2012 City-month	1 extra degree day exceeds *T*: 0.03↑	54.5	Zheng et al. 2020
7	YRDUA, China	Panel/ 2004-2015 City-year	1% increase in degree day> *T*: 10-20↑ 1% increase in degree day< *T*:11-13↑	64.4	Zhang et al. 2021

4. Discussion

Increased electricity consumption is not necessarily a bad thing; Deschênes and Greenstone (2011) argued that the weak relationship between mortality and temperature is due, at least in part, to self-protection by cooling from increased energy consumption. However, this will increase air pollution and carbon emissions. Therefore, it seems important for policymakers to place greater emphasis on renewable energy sources.

The vulnerability of households should also be taken into account when designing energy policies. Extreme temperatures, such as heat stress, may burden vulnerable households more. Therefore, governments may consider reducing the cost of acquiring air conditioning or heating equipment for vulnerable households. However, the provision of cooling or heating services alone may not demonstrate the effective impact of the policy, especially in the context of energy poverty. Reducing the operating costs of equipment is equally important.

Improving energy efficiency has also been mentioned in the previous literature. Improving energy efficiency has many benefits, including reducing energy consumption, lowering energy bills, and helping to slow the pace of climate change. Governments can provide financial incentives for consumers and businesses to invest in energy-efficient technologies and practices, such as rebates, tax credits, or low-interest loans. Governments can also invest in public education campaigns to raise awareness of the importance of energy efficiency and provide tips and guidance on how to reduce energy consumption. The thing is, while improving energy efficiency, they may face high initial costs to implement energy-efficient technologies and methods, which can be a barrier for households and businesses.

Most prior studies have investigated either short-term or long-term responses, and a useful direction for future research would be to see if the short-term and long-term results hold with each other. Ihara et al. (2008) and Hashimoto et al. (2019) estimated the sensitivity of electricity consumption to temperature using Tokyo and Osaka, Japan, as case studies, respectively. Because temperature conditions vary from region to region, applying their results to other regions may be difficult. It is important to analyze national and regional scales to improve the efficiency of policy implications.

Another issue is that increased electricity consumption may decrease other consumptions due to household budgets. Bhattacharya et al. (2003) found that in American families, both poor and wealthy households increased fuel costs in response to extreme cold weather. The poor reduced their food expenditures to the same extent as they increased their fuel expenditures, while the wealthy increased their food expenditures. This may suggest another social problem under climate change. Hirvonen (2016) found that extreme heat is likely to reduce total household consumption, but it is not known how it affects each type of consumption. Understanding how extreme temperatures will affect household consumption seems essential.

5. Conclusion

This paper reviews the literature on the relationship between temperature and residential electricity use. In particular, we focus primarily on recent studies. The climate will affect household electricity use by changing how residents respond to short-term weather shocks and how they adapt in the long term.

Global warming is a serious risk to our society, and extreme temperatures can increase the demand for residential electricity. A nonlinear (generally, U-shaped) response function was found with higher residential electricity consumption on very cold and hot days with a threshold temperature of about 50-77°F (10-25°C). Furthermore, it is necessary to study heterogeneity along different dimensions.

Increased demand for electricity is likely to increase air pollution and carbon dioxide emissions, which exacerbates climate change. Switching to renewable energy is one way to address this issue, but the initial investment can be expensive. While the long-term savings in energy costs can be significant, the upfront costs can be a barrier for many. Increasing access to energy and providing financial assistance may lift energy poverty, but political and technical barriers may prevent it. Improving energy efficiency is a key strategy for addressing climate change, reducing energy costs, and promoting sustainable economic growth, but high initial costs can be a barrier for households and businesses. To overcome these challenges, it is important to raise awareness and education about energy efficiency, provide financial incentives and support, develop and promote energy-efficient technologies, and implement supportive policies and regulations.

Since most of the previous studies focused on either the short or long-term, a useful direction for future research would be to see if the short and long-term results are consistent. Another gap that needs to be filled in is the analysis of national and regional scale impacts in Japan. Increased energy consumption can be seen as self-protective spending under the risk of climate change, but on the other hand, it may also lead to a decrease in other consumption concerning the household budget. According to the Agency for Natural Resources and Energy, Japan is gradually exceeding its maximum electricity demand in anticipation of a severe heat wave or cold snap. This means that other household consumption will also be hit hard, which could lead to new social problems under climate change. This is another essential issue that requires attention.

Overall, in the context of climate change and sustainability, studying the impact of temperature on household electricity use is crucial. It can help individuals and policymakers to develop strategies to reduce energy consumption and greenhouse gas emissions, promote renewable energy sources and contribute to a more sustainable future.

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