The Effects of Extreme High Temperature Day Off on Electricity Conservation

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ABSTRACT: The continuously increasing temperatures worldwide indicate that the frequently extreme heat in summer will become a new normal. The extreme high temperature (EHT) could be dangerous to human health, especially for outdoor workers or commuters, and could increase the risk of grid collapse. Thus, the possibility of a day off due to EHT has started to be discussed in Taiwan, based on the experience of typhoon day off, but discussions have not yet concluded. In this study, the effects of the EHT day off on electricity consumption in the industrial, service, and residential sectors were investigated through two determinants: First, high temperature would increase the electricity consumption in space cooling. Second, a day off would change people’s behavior of electricity consumption from workday to nonworkday modes. Combining the effects of cooling hours and nonworkdays, the net influence of the EHT day off on electricity consumption can be evaluated. Estimated results indicated that an EHT day off can reduce aggregate electricity consumption by between 0.41% and 1.08%. The reduction of electricity consumption due to the off day offsets the increase driven by high temperatures. Thus, an EHT day off will mitigate the pressure on the power grid and benefit electricity conservation.

KEYWORDS: Social science; Asia; Regression analysis; Temperature conservation.

1. Introduction

The speed of global warming has been faster in the past three decades than it has been in the past 100 years (Meehl and Tebaldi 2004). The average temperature worldwide increased by 0.07°C every 10 years between 1880 and 2018, and this number jumped to 0.18°C between 1989 and 2018, based on the National Oceanic and Atmospheric Administration (NOAA) in the United States. The trend of warming is more severe in Taiwan (Wu et al. 2009; Cheng et al. 2004). The average temperature in Taiwan increased by 0.1°C every 10 years from 1880 to 2018, and this number boosted to 0.24°C from 1990 to 2018, based on the Central Weather Bureau (CWB).

The temperatures are forecast to increase worldwide in the future. According to the Intergovernmental Panel on Climate Change (IPCC 2018), human activities are estimated to have caused 1°C of global warming above preindustrial levels. If global warming continues to increase at the current rate, it will reach 1.5°C in 2030 at the earliest and increase the probability of extreme weather, especially for the extreme heat in inhabited regions. Extreme high temperatures (EHT) will not only increase the risk of heat-related illness but also strain the electricity grid. Since the extreme weather seems to be irreversible, adapting to it is crucial and urgent.

In Taiwan, the number of days with maximum temperature above 36°C rose form 15 days in 2010 to 38 days in 2018, based on the CWB. Since 2018, a heat warning is issued by the CWB to the public when regional temperatures are higher than 36°C. Considering the EHT could be a danger to human health, especially for outdoor workers or commuters, the possibility of a day off because of EHT has been discussed in Taiwan. However, no conclusion has yet been reached.

In addition, extreme weather affects all components of the electric grid system, from generation to end use (Dumas et al. 2019). Sending people home from work due to the EHT may change their electricity consumption behavior. If the EHT day off increases the electricity demand, which strains the power grid further, grid collapse and blackout would cause great damage to human health and welfare. On the contrary, if the EHT day off decreases the electricity demand, which mitigates the risk of power outage, this policy tool will be worth considering by policy makers. In other words, the government cannot change the weather but can send people home from work to decrease the risk of power grid collapse. Therefore, the effect of the EHT day off on electricity consumption is estimated in this study to provide a new perspective from energy conservation.

The electricity demand in the industrial, service, and residential sectors was estimated separately using panel data models among 19 cities and counties between January 2012 and December 2018 in Taiwan. The number of nonworkdays was used as a proxy variable to control the change of electricity consumption behavior between workdays and nonworkdays. The cooling hour was employed to evaluate the influence of high temperatures. Estimated results indicated that an EHT day off can reduce the electricity consumption in the industrial, service, and residential sectors due to consumers change behavior from workday to nonworkday modes. The reduction of electricity consumption due to behavior changes can also offset the increase driven by high temperatures. Overall, an EHT day off can save electricity by between 0.41% and 1.08%.

The remainder of this paper is organized as follows: section 2 introduces the background of EHT, weather effects, and the

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concept of the EHT day off in Taiwan. Section 3 introduces the method, data, and models. Section 4 reports the estimated results of electricity demand in the industrial, service, and residential sectors. The related policy implication of the EHT day off on electricity consumption is also discussed in this section. Section 5 concludes this paper.

2. Background

a. Extreme high temperatures

A heat wave, based on the National Weather Service of the United States, is defined as a period of abnormally and uncomfortably hot and humid weather lasting two or more days. For workplaces, a heat wave is specifically defined when the daily maximum temperature exceeds 35°C (95°F), according to the National Institute for Occupational Safety and Health of the United States (NIOSH). Senior citizens, children, and those who are sick, overweight, or work outdoors are at a higher risk of heat-related illness, such as heat stroke, hyperthermia, heat exhaustion, or excess mortality (Koppe et al. 2004). Thus, the engineering and administrative controls, preventing heat-related illness and reducing the heat stress, were provided by the NIOSH. When engineering controls, such as air conditioning or cooling fans, are not enough to keep workers’ exposure below the limit, administrative controls, such as scheduling work earlier or later or using work/rest schedules, were suggested (Jacklitsch et al. 2016).

Extreme weather events also strain the electricity grid from power generation to end use (Dumas et al. 2019; Ke et al. 2016; Campbell and Lowry 2012; Shahid 2012; Miller et al. 2008). Abnormally hot temperatures will raise the electricity demand in ventilation and air conditioning (VAC) systems in building constructions that could increase the risk of power outage in summer (Baniassadi et al. 2018; Castillo 2014). Extreme weather changes the behavior of electricity consumption; however, little research has been conducted to examine the effects of behavior changes.

The extreme high temperatures have become more frequent in Taiwan. The deviation of days with maximum temperature above 35°C in Taipei1 from 1968 to 2019 was shown in Fig. 1, based on the CWB. Even though these numbers fluctuated, most of the positive deviations occurred in the past 20 years. The number of days with maximum temperature above 35°C reached a record high of 77 days in 2016. The 10-yr average of deviations also rose dramatically from −12.1 in the 1970s to 22.0 in the 2010s. Studies have also shown that the extreme heat increased mortality risk in Taiwan (Sung et al. 2013). It seems to be inevitable and irreversible that the frequently extreme

1 A heat wave for workplaces is also defined when the daily maximum temperature exceeds 32°C (90°F) and is 5°C (9°F) or more above the maximum reached on the preceding days, based on the NIOSH.

2 Taipei is the capital city of Taiwan. Approximately 30% of households of Taiwan lived in Taipei in 2019, based on DGBAS.

b. Effects of temperatures

The high temperature in summer has positive impacts on the electricity demand. This weather effect is linked to the electric cooling appliances or systems used by firms, stores, or households (Moral-Carcedo and Pérez-García 2015). In previous studies, high temperatures in summer, usually represented by cooling degree-days or cooling hours, will increase electricity demand at the aggregate level (Tung et al. 2013; Ahmed et al. 2012; Hekkenberg et al. 2009; Mirasgedis et al. 2006). The size of the effects, however, depends on the climate zone. Areas located in the low-latitude regions or relying on VAC systems had higher temperature effects (Damm et al. 2017; De Felice et al. 2013; Eskeland and Mideksa 2010; Pilli-Sihvola et al. 2010; Bessec and Fouquau 2008).

The sectoral breakdown of the temperature effect on electricity demand has also been studied in previous research, and the positive effect of summer temperature mainly came from the service sector (Hong et al. 2013; Lam et al. 2008; Zachariadis and Pashourtidou 2007) and the residential sector (Rhodes et al. 2014; Sandels et al. 2014; Xu and Ang 2014; Dergiades and Tsoulfidis 2008). A large amount of electricity is used in space cooling or air conditioning in these two sectors. Comparatively, electricity demand of industrial activities was slightly affected by temperatures due to the automated and consistent production process (Vassileva et al. 2012; Asadourian et al. 2008; Bessec and Fouquau 2008; Zachariadis and Pashourtidou 2007).

The effect of temperatures on electricity consumption in Taiwan was significantly positive in the industrial and service sectors (Su 2018) and residential sector (Su 2020; Hung and Huang 2015; Holtedahl and Joutz 2004). The relationship between cooling hours above 28°C and sectoral electricity consumption from January 2012 to December 2019 was shown in Fig. 2. Taiwan, located in the boundary between the tropical and subtropical climate zone, is warm and humid almost all year, so the electricity was mainly consumed in space cooling instead of heating. Patterns were quite consistent between cooling hours and electricity consumption in the service and residential sectors, and the annual peaks occurred in July and August. Comparatively, the annual peaks of industrial electricity consumption were sometimes ahead of the annual peak
of cooling hours, representing the influence of temperatures in the industrial sector could be weak. Thus, the temperature effect could be different among the three sectors and should be estimated separately.

The electricity consumption behavior in the industrial, service, and residential sectors, covering 91% of aggregate electricity consumption in total, were investigated in this paper. The structure of electricity consumption in summer and nonsummer months in Taiwan in 2018 was shown in Fig. 3 according to the Taiwan Power Company (Taipower). In summer, 24,189 GW·h of electricity was consumed per month, and approximately 53.4% of electricity were consumed by the industrial sector, followed by the residential sector (19.3%) and service sector (18.6%). For nonsummer months, not only the monthly electricity consumption (21,202 GW·h) but also the percentages of the residential (16.6%) and service sectors (17.2%) shrunk. Therefore, the increase of electricity consumption in summer mainly came from the service and residential sectors, when compared with that in nonsummer months.

c. Effects of the EHT day off

Considering the extreme heat could be dangerous to human health, especially for outdoor workers or commuters, the feasibility of the EHT day off has been discussed in Taiwan for years, but these discussions have not yet concluded. The concept of the EHT day off is similar to the so-called typhoon day off, which already has been implemented in Taiwan since 2000. The government of Taiwan has established a standard process for evaluating the impact of natural disasters, especially for typhoons, and for announcing a day off to prevent people from the danger of outdoor work or commuting between home and workplaces. Based on the CWB, 3.4 typhoons on average interacted with Taiwan between June and September annually. Unlike typhoons, however, extreme heat may only last for several hours around noon and may have little influence on indoor office workers. Little research has been done to investigate the influence of the EHT day off. Even though people have started to discuss this topic, no conclusion can be reached without sufficient evidence.

In this study, the effect of the EHT day off on sectoral electricity consumption was estimated from the viewpoint of energy economics. For the EHT day off, two possible determinants would affect the electricity consumption: First is the weather effect. In other words, high temperatures would directly increase the electricity demand through VAC systems. Second, a day off would change people’s behavior of electricity consumption from workday to nonworkday modes. Specifically, electricity consumption in the industrial and service sectors would decrease because some firms or stores would be closed on the nonworkday. At the same time, some people may choose to stay at home and increase the residential electricity consumption, but some of them may go out to enjoy outdoor activities and reduce residential electricity consumption. Moreover, employees or workers may have less incentive to save electricity since it is the responsibility of companies. On the contrary, people would be more willing to save electricity when they were sent home from work and paid the electricity bill by themselves.

The net effect of EHT day off on electricity consumption was defined as the summation of the marginal effect of the nonworkday and corresponding effects of cooling hours. This net effect would largely depend on the changes of electricity consumption in summer and nonsummer months.

FIG. 2. Monthly cooling hours above 28°C and electricity consumption in the industrial, service, and residential sectors in Taiwan [January 2012 (2012m1)–December 2019 (2019m12)].

FIG. 3. Structure of electricity consumption in (a) summer and (b) nonsummer months in Taiwan (2018).
consumption behavior between workday and nonworkday. If a day off can reduce the aggregate electricity demand and this reduction offsets the increase of electricity consumption due to high temperatures, the benefit of energy conservation of the EHT day off can be concluded. Therefore, it will be a useful policy tool to mitigate the risk of power outage under extreme weather.

3. Method and data

a. Panel data models

The electricity consumption in region $i$ at time $t$, $y_{it}$, is expressed as

$$ y_{it} = f(x_{it}, \beta) + u_{it}, \tag{1} $$

where $x_{it}$ is the vector of explanatory variables, such as the electricity price, income, or weather, and $\beta$ is the coefficient vector. The $u_{it}$ denotes an error term, which is the summation of an unobserved area-specific variable $c_i$ and idiosyncratic error $\varepsilon_{it}$.

The pooled ordinary least squares (OLS) regression was estimated initially. The Breusch–Pagan test (B-P; Breusch and Pagan 1980; Cook and Weisberg 1983) was then employed to examine the heteroscedasticity of the error term. When the null hypothesis is rejected (i.e., $\varepsilon_{it} \neq 0$) causing the problems of inefficient and biased estimators, panel data models should be used. Panel data models consider time-invariant factors ($c_i$) by extending the time span, which cope with heteroscedasticity and omitted variables.

For panel data models, two assumptions can be made based on data characteristics. First, the fixed effect (FE) model assumes that the area-specific variable ($c_i$) is a constant and can be estimated for each area. Second, the random effect (RE) model further assumes that $c_i$ satisfies a normal distribution. In other words, the FE estimator used the orthogonality condition that regressors are uncorrelated with the idiosyncratic error. Comparatively, the RE estimator used the additional orthogonality condition that regressors are uncorrelated with the area-specific constant. This additional overidentifying restriction of the RE can be tested using the Hausman test (Hausman 1978) to determine which model is more accurate. Details of panel data models and related tests were provided by Wooldridge (2010).

b. Data

The descriptive statistics were listed in Table 1. The data employed in this study are all publicly available. Observations are strongly balanced panel data, covering 19 cities and counties in Taiwan from January 2012 to December 2018. The electricity demand in the industrial, service, and residential sectors were modeled separately to investigate the influences of the temperature and the electricity consumption behavior of nonworkdays.

Dependent variables are the monthly electricity consumption in the industrial (EI$_{it}$), service (ES$_{it}$), and residential (ER$_{it}$) sectors. These three data came from the Taipower Company. A month was the smallest time interval for the public data of electricity consumption because of the restriction of data privacy.

The number of nonworkdays per month (NW$_{it}$) is the key explanatory variable to understand the effect of an additional day off on electricity demand. This discrete variable was weekends plus national holiday, which was shown in Fig. 4. This variable has decent variation for two reasons: First, some months have more weekends due to the idiosyncratic variation in the calendar. In other words, some months have four weekends, while others have five. Second, holidays based on the lunar calendar have a moving-holiday effect (Liu 1980, 1986). In Taiwan, the official statistics are compiled according to the Gregorian calendar; however, the main traditional holidays are set on the basis of the lunar calendar. Because of the parallel use of these two calendars, traditional holidays fall during different Gregorian calendar month from year to year. For example, the Lunar New Year is on the first of the first month based on the lunar calendar, but it may fall in either January or February according to the Gregorian calendar. This moving-holiday effect contributes the exogenous variation for identification of the effect of nonworkdays. In addition, this

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**Table 1. Descriptive statistics.**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
<th>Obs</th>
<th>Mean</th>
<th>Std dev</th>
<th>Min</th>
<th>Max</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dependent variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EI</td>
<td>Electricity consumption in the industrial sector</td>
<td>GW h</td>
<td>1596</td>
<td>474</td>
<td>529</td>
<td>5</td>
<td>1743</td>
<td>Taipower</td>
</tr>
<tr>
<td>ES</td>
<td>Electricity consumption in the service sector</td>
<td>GW h</td>
<td>1596</td>
<td>197</td>
<td>221</td>
<td>21</td>
<td>995</td>
<td>Taipower</td>
</tr>
<tr>
<td>ER</td>
<td>Electricity consumption in the residential sector</td>
<td>GW h</td>
<td>1596</td>
<td>197</td>
<td>194</td>
<td>23</td>
<td>1003</td>
<td>Taipower</td>
</tr>
<tr>
<td><strong>Explanatory variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NW</td>
<td>Nonworking days per month</td>
<td>Day</td>
<td>1596</td>
<td>10</td>
<td>1</td>
<td>7</td>
<td>14</td>
<td>This study</td>
</tr>
<tr>
<td>CH</td>
<td>Cooling hours (above 28°C) per month</td>
<td>h</td>
<td>1596</td>
<td>170</td>
<td>176</td>
<td>0</td>
<td>567</td>
<td>BOE; CWB</td>
</tr>
<tr>
<td>PC</td>
<td>Residential electricity price</td>
<td>TWD (kW h)$^{-1}$</td>
<td>1596</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>Taipower</td>
</tr>
<tr>
<td>PR</td>
<td>Industrial electricity price</td>
<td>TWD (kW h)$^{-1}$</td>
<td>1596</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>Taipower</td>
</tr>
<tr>
<td>IA</td>
<td>Median of household disposable income per year</td>
<td>1000 TWD</td>
<td>1596</td>
<td>912</td>
<td>171</td>
<td>636</td>
<td>1379</td>
<td>DGBAS</td>
</tr>
<tr>
<td>IM</td>
<td>Mean of household disposable income per year</td>
<td>1000 TWD</td>
<td>1596</td>
<td>782</td>
<td>157</td>
<td>456</td>
<td>1181</td>
<td>DGBAS</td>
</tr>
<tr>
<td>HH</td>
<td>No. of households at the end of year</td>
<td>1000 households</td>
<td>1596</td>
<td>441</td>
<td>412</td>
<td>81</td>
<td>1562</td>
<td>DGBAS</td>
</tr>
<tr>
<td>T</td>
<td>Time trend</td>
<td>—</td>
<td>1596</td>
<td>43</td>
<td>24</td>
<td>1</td>
<td>84</td>
<td>This study</td>
</tr>
</tbody>
</table>

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variable is at the national level (i.e., NW\textsubscript{i} = NW\textsubscript{t} for all i) since every city or county faces the same weekends and national holidays.

The influence of nonworkdays was expected to be negative for the industrial and service sectors because the electricity for production or commercial use would decrease when some companies do not operate. For the residential sector, however, the direction of the effect was not clear yet. The residential electricity demand may rise because more people stay at home and consume electricity in their off day; nevertheless, it may drop when people choose to go shopping or enjoy outdoor recreation. Moreover, people may be more willing to save electricity when they are sent home from work and paid the electricity bill by themselves. Thus, the net effect depends on the electricity consumption behavior of households in the off day.

The cooling hours above 28°C per month (CH\textsubscript{it}) is employed to control weather conditions, especially for the extremely high temperature in summer. Electric power is consumed to adapt to the increase of temperatures in terms of adjusting cooling needs. It was assumed that people turn on their air conditioners when the temperature is higher than 28°C. Thus, the effect of cooling hours on the electricity demand was expected to be positive. To explain the weather variation at the regional level, this variable was calculated according to monthly cooling hours at the national level weighted by monthly temperatures at the regional level. These two data were shown in Fig. 5. The national cooling hours came from the Bureau of Energy (BOE), while the regional temperature was collected from the CWB in Taiwan.

Prices are important factors affecting the willingness of purchase and use of electric power based on the demand theory. The commercial electricity prices (PC\textsubscript{t}) were used to explain the price effect for the industrial and service sectors, while the residential electricity prices (PR\textsubscript{it}) were employed to explain that for the residential sector. The price effect was expected to be negative, according to the law of demand. In addition, as a state-owned electricity utility, the Taipower Company monopolizes Taiwan’s electricity market. Any adjustments of electricity prices must be proposed by the Taipower Company under the supervision of the Ministry of Economic Affairs in the purpose of maintaining the stability of prices. As price takers, companies and households rarely affect the final electricity prices, so the endogeneity of prices with respect to quantity is not a problem in the short term. In the long term, the endogeneity problem may exist. However, this problem is not serious in this study since the time span, from 2012 to 2018, was short, and the standard deviations of the electricity prices in Table 1 were low. A check of the estimates with the electricity prices excluded in section 4a will also assuage the concern of endogeneity. Price variables are at the national level (i.e., PC\textsubscript{it} = PC\textsubscript{t} and PR\textsubscript{it} = PR\textsubscript{t} for all i) since every city or county faces the same electricity prices announced by the Taipower.

The income effect was controlled by the household disposable income, came from the Directorate-General of Budget, Accounting and Statistics (DGBAS). For the industrial and service sectors, the mean income (IA\textsubscript{it}) was used as a proxy variable describing the production values of city or county \textit{i} in year \textit{t}. The income approach was used because the data of regional value added, based on the output approach, are not available. For the residential sector, the median income (IM\textsubscript{it}) was employed due to the robustness against outliers. More electric power will be consumed when more goods are produced, more services are provided, or households’ income is higher; thus, the income effects were expected to be positive.

<table>
<thead>
<tr>
<th>NW</th>
<th>CH</th>
<th>lnPC</th>
<th>lnIA</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH</td>
<td>-0.262</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>lnPC</td>
<td>-0.030</td>
<td>-0.021</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>lnIA</td>
<td>0.009</td>
<td>0.015</td>
<td>-0.113</td>
<td>1</td>
</tr>
<tr>
<td>T</td>
<td>-0.001</td>
<td>0.095</td>
<td>-0.524</td>
<td>0.163</td>
</tr>
</tbody>
</table>
The number of households at the end of year (HH\textsubscript{it}) was additionally used to control the increasing trend of households in estimating the residential electricity demand. More households will increase the demand for electricity, so the effect of the number of households was expected to be positive.

The time trend (T\textsubscript{it}) was employed to control the aggregated unobservable trends, for example, the nationwide adaption of energy efficient appliances or electricity consumption behavior changes. For panel data models, omitted variables may exist in two dimensions: One is the cross-sectional time-invariant variables, which can be controlled by the area-specific factors (c\textsubscript{i}). The other is time-varying variables. Thus, the monthly trend variable T\textsubscript{it} was used to absorb the trend effect.

The correlation coefficients are listed in Tables 2 and 3. There is no high correlation between any two explanatory variables.

c. Modeling the electricity demand

The electricity demand in the industrial and service sectors are respectively expressed as

\[
\ln EI_{it} = \beta_0^I + \beta_1^I NW_{it} + \beta_2^I CH_{it} + \beta_3^I \ln PC_{it} + \beta_4^I \ln IA_{it} \\
\quad + \beta_5^I T_{it} + c_i^{I} + \epsilon_i^{I},
\]

and the electricity demand in the residential sector is expressed as

\[
\ln ER_{it} = \beta_0^R + \beta_1^R NW_{it} + \beta_2^R CH_{it} + \beta_3^R \ln PC_{it} + \beta_4^R \ln IM_{it} \\
\quad + \beta_5^R \ln HH_{it} + \beta_6^R T_{it} + c_i^{R} + \epsilon_i^{R},
\]

where the superscripts \textit{I}, \textit{S}, and \textit{R} on the \(\beta\)s are for industrial, service, and residential sectors, respectively. Moreover, \(\beta_1s\) and \(\beta_2s\) represent the marginal effects of nonworkdays (NW\textsubscript{t}) and cooling hours (CH\textsubscript{it}), respectively, on the percentage change of sectoral electricity consumption. Other parameters represent the elasticities due to the log–log formula, except the parameter of the time trend \(T\textsubscript{it}\), which represents the monthly growth rate of the sectoral electricity consumption. The formula was chosen based on the interpretability of the variables.

The net influence of the EHT day off on electricity consumption was calculated on the basis of the parameters of nonworkdays (\(\beta_1\)) and cooling hours (\(\beta_2\)) in Eqs. (2), (3), and (4). For an additional EHT day off with cooling hour \(h\),
0 \leq h \leq 24$, the percentage change of electricity consumption in sector $k$ ($k = I$ for the industrial sector, $k = S$ for the service sector, and $k = R$ for the residential sector) was specified as

$$\beta_k^i + \beta_k^h h.$$  \hspace{1cm} (5)

Combining the effects of the industrial, service, and residential sectors, the overall effect of the EHT day off on aggregate electricity consumption can be calculated. If this effect is negative, it represents an EHT day off will relieve the burden of the boosting electricity demand, and vice versa.

4. Results

a. Main estimation

The estimated results of electricity demand in the industrial, service, and residential sectors are listed in Tables 4–6, respectively. For each sector, the main estimation consists of three stages: First, the basic panel data models without time trend were estimated for reference (model 1 and 2). Second, the time trend was added to control the time-varying factors (model 3 and 4). Third, the electricity prices were excluded to confirm that the endogeneity problem was slight (model 5 and 6). Three models for each stage were estimated: the pooled OLS, FE, and RE panel data models. However, the estimated results of pooled OLS models were skipped due to the existence of variable heteroscedasticity according to the B-P test results. Thus, only the panel data models were listed. Based on the Hausman test results, models I4, S3, and R3 for the industrial, service, and residential sectors were chosen.

For model I4, the effect of nonworkdays was $-0.0071$, meaning additional one day off will reduce the monthly industrial electricity consumption by nearly 0.71%. The negative sign, as expected, represents that the electricity consumption in the industrial sector would decrease in the nonworkdays. On the other hand, the effect of cooling hours was 0.0002, representing additional one cooling hour will increase the industrial electricity consumption by 0.02%. In other words, the weather effect in the industrial sector was positive as expected. Based on Eq. (5), the percentage change of monthly electricity consumption in the industrial sector for additional one EHT day off was between $-0.23\%$ and $-0.71\%$ with cooling hours from 0 to 24. For the industrial sector, an EHT day off can reduce electricity consumption, and this reduction offsets the increase of electricity consumption driven by high temperatures. Thus, the EHT day off can save electricity in the industrial sector.

For model S3, the effect of nonworkdays was $-0.0164$, representing the electricity consumption in the service sector would reduce by 1.64% in the nonworkday. The effect of cooling hours was 0.0003, representing that additional one cooling hour will increase the monthly electricity consumption in the service sector by 0.03%. Based on Eq. (5), the percentage change of electricity consumption in the EHT day off was between $-0.44\%$ and $-1.64\%$ in the service sector.
The decrease of electricity consumption due to additional one EHT day off offsets the increase driven by high temperatures. Thus, an EHT day off is helpful in energy saving in the service sector.

For model R3, the effect of nonworkdays was $-0.0204$, while the effect of cooling hours was $0.0004$. The results represent that the electricity consumption will decrease by 2.04% in the nonworkday, and additional one cooling hour will offset the decrease by 0.04% in the residential sector. The residential electricity consumption in the EHT day off reduced for two reasons: First, not all of the people who were sent home from work stayed at home. Some of them may choose to go out, causing the residential electricity consumption to drop. Second is the behavior changes. People may be more willing to save electricity when they are sent home and pay the electricity bill by themselves. Based on Eq. (5), the percentage change of monthly electricity consumption in the residential sector for the EHT day off was between $-1.08\%$ and $-2.04\%$. An additional EHT day off will reduce the residential electricity consumption and this reduction offsets the increase one driven by the high temperatures. Thus, the influence of the EHT day off on residential electricity consumption was negative.

In comparing the results of models with electricity prices (model 3 and 4) with those without them (model 5 and 6), it can be seen that the marginal effects of explanatory variables were very consistent. Thus, we can confirm that the endogeneity problem of electricity prices was slight and could be ignored. In the industrial sector (model I4), the price elasticity was $0.0896$, and the income elasticity was 0.2531. In the service sector (model S3), the income elasticity was 0.201, while the price elasticity was not statistically significant, representing the electricity demand in the service sector was mainly driven by production, instead of the electricity prices. In the residential sector (model R3), the price and income elasticities were $0.2723$ and $0.1276$, respectively. In addition, when the number of households increases by 1%, the residential electricity consumption will increase by $1.0173\%$.

Moreover, the monthly growth rate of electricity consumption was $0.05\%$, $0.14\%$, and $0.36\%$ in the industrial, service, and residential sectors, respectively, based on the estimated results. These positive parameters of time trends represent that the overall electricity consumption still rose in the past seven years when other possible influences were excluded. This increase may come from the change of electricity consumption behaviors. People may demand a higher quality of life through using more appliances or consuming more electricity. It is also a warning that the strain on the electricity grid will increase as this trend continues.

### b. Aggregation and robustness

Considering that some of the explanatory variables were at the national level, the aggregation model that aggregates the regional variables to the national level was estimated to check if the simple aggregation model yields the similar results to the panel data models. The regional electricity consumption ($E_{IT}$, $E_{ST}$, and $E_{RT}$), income ($IA_{IT}$ and $IM_{IT}$), and number of households ($HH_{IT}$) were
aggregated, and the cooling hours (CH_{t}) were averaged to the national level. The estimated results of aggregation models in the industrial, service, and residential sectors were listed in Table 7.

The two main explanatory variables, nonworkdays and cooling hours, had different marginal effects between aggregating and panel data models, but the panel data models had higher variability explained by the regressions. On the one hand, the effects of nonworkdays were all smaller for the aggregating models. The results represent the variation of regional reaction to the day off were offset in the aggregation model, rendering the national effects limited or insignificant. On the other hand, the effects of cooling hours were similar between models using national and regional data. Taiwan is a small island, so the regional temperatures may be different but still share similar seasonal variation (see Fig. 5). Overall, the panel data models reveal more information of regional electricity consumption when considering the effects of nonworkdays and cooling hours at the same time.

The robustness was checked in Tables 8–10 for the industrial, service, and residential sectors, respectively. Six models were estimated based on the subsamples of the urban and rural areas^4 (models 7 and 8), and northern, central, southern, and eastern areas (models 9–12) in Taiwan. These models were chosen based on the results of B-P and Hausman tests. Even though the parameters varied in these three tables, the direction of effects of nonworkdays and cooling hours were quite consistent among different areas. In addition, the interaction terms of four areas with nonworkdays and with cooling hours were estimated separately to check the regional impacts on electricity consumption. Almost all regions were significant. The estimated results indicate that the influences of nonworkdays and cooling hours were not driven by any particular areas. The results of the interaction terms were similar to that of regional robustness check in Tables 8–10, so only the latter was listed.

c. Policy implications

On an extremely hot day, an EHT day off can reduce electricity consumption in the industrial, service, and residential sectors because consumers change their behavior from workday to nonworkday modes. Not only was the electricity reduced due to behavior changes, but the reduction also offset the increase of electricity consumption driven by high temperatures. The effect of the EHT day off on the aggregate electricity consumption can be calculated through the average of effects weighted by sectoral electricity consumption. The marginal effects of nonworkdays and cooling hours, and corresponding weights, were listed in Table 11.

The influences of nonworkdays were negative, while the influences of cooling hours were positive in Table 11. The absolute values of the parameters in the industrial sector were relatively smaller than that in other two sectors, representing that the electricity consumption in the industrial sector was less sensitive to the changes of nonworkday and temperature. The industrial sector has some automated production lines that are more weather insensitive. The effects of cooling hours that represent the electricity savings were higher than that in the industrial sector. The service and residential sectors were more weather sensitive. The effects of cooling hours that offset part of the electricity savings were higher than that in the industrial sector. The service and residential sectors have more people flow so the effects of behavior changes were also more obvious.

Even though the actual cooling hours in an extremely hot day are unknown, the range of effects can be pinned down.

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Table 7. Aggregation results. Standard deviations are in parentheses. One, two, and three asterisks denote significance at the 10%, 5% and 1% statistical levels, respectively. The B-P test tests for heteroskedasticity.

<table>
<thead>
<tr>
<th></th>
<th>Model A1 (Industrial)</th>
<th>Model A2 (Service)</th>
<th>Model A3 (Residential)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW_{t}</td>
<td>-0.0052* (0.0031)</td>
<td>-0.0115* (0.0069)</td>
<td>0.0057 (0.0093)</td>
</tr>
<tr>
<td>CH_{t}</td>
<td>0.0002*** (0.0000)</td>
<td>0.0005*** (0.001)</td>
<td>0.0004*** (0.0001)</td>
</tr>
<tr>
<td>lnPC_{t}</td>
<td>-0.0301 (0.0872)</td>
<td>-0.4026** (0.1934)</td>
<td></td>
</tr>
<tr>
<td>lnPR_{t}</td>
<td>-0.5779 (0.5823)</td>
<td>5.0915*** (1.2915)</td>
<td>0.4124 (0.2741)</td>
</tr>
<tr>
<td>lnIA_{t}</td>
<td></td>
<td></td>
<td>1.1983 (1.1386)</td>
</tr>
<tr>
<td>lnIM_{t}</td>
<td></td>
<td></td>
<td>34.9710*** (4.4552)</td>
</tr>
<tr>
<td>lnHH_{t}</td>
<td></td>
<td></td>
<td>0.0115* (0.0069)</td>
</tr>
<tr>
<td>T</td>
<td>0.0022*** (0.0007)</td>
<td>0.0065*** (0.0015)</td>
<td>0.0322*** (0.0038)</td>
</tr>
<tr>
<td>Constant</td>
<td>21.6017*** (5.7008)</td>
<td>64.9690*** (12.6442)</td>
<td>559.1926*** (67.7549)</td>
</tr>
<tr>
<td>B-P test</td>
<td>11.76***</td>
<td>0.16</td>
<td>1.21***</td>
</tr>
<tr>
<td>R^{2}</td>
<td>0.6979</td>
<td>0.6175</td>
<td>0.6444</td>
</tr>
<tr>
<td>Obs</td>
<td>83</td>
<td>83</td>
<td>83</td>
</tr>
</tbody>
</table>

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^4 Six urban areas are Taipei, New Taipei, Taoyuan, Taichung, Tainan, and Kaohsiung. The other 13 counties and small cities (Yilan, Hsinchu County, Miaoli, Changhua, Nantou, Yunlin, Chiayi County, Pingtung, Taitung, Hualien, Keelung, Hsinchu City, and Chiayi City) belong to the rural areas. Even though the six main cities accounted for only 30% of the area of Taiwan, nearly 70% of households lived and 70% of the electrical power was consumed in the urban areas in 2019, based on the DGBAS and Taipower Company.
<table>
<thead>
<tr>
<th>Model I7 (urban area)</th>
<th>Model I8 (rural area)</th>
<th>Model I9 (northern Taiwan)</th>
<th>Model I10 (central Taiwan)</th>
<th>Model I11 (southern Taiwan)</th>
<th>Model I12 (eastern Taiwan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW_t</td>
<td>-0.0097*** (0.0023)</td>
<td>-0.0067*** (0.0015)</td>
<td>-0.0069*** (0.0020)</td>
<td>-0.0086*** (0.0022)</td>
<td>-0.0078** (0.0032)</td>
</tr>
<tr>
<td>CH_t</td>
<td>0.0002*** (0.0000)</td>
<td>0.0002*** (0.0000)</td>
<td>0.0003*** (0.0000)</td>
<td>0.0002*** (0.0000)</td>
<td>0.0002*** (0.0000)</td>
</tr>
<tr>
<td>lnPC_t</td>
<td>-0.0535 (0.0529)</td>
<td>-0.1356*** (0.0364)</td>
<td>-0.1046*** (0.0465)</td>
<td>-0.1490*** (0.0519)</td>
<td>-0.0577 (0.0824)</td>
</tr>
<tr>
<td>lnIA_t</td>
<td>1.2784*** (0.1704)</td>
<td>0.1532*** (0.0503)</td>
<td>0.0538 (0.0717)</td>
<td>0.5103*** (0.0799)</td>
<td>0.4300* (0.2194)</td>
</tr>
<tr>
<td>T</td>
<td>-0.0012*** (0.0003)</td>
<td>0.0005*** (0.0001)</td>
<td>0.0002 (0.0002)</td>
<td>0.0015*** (0.0002)</td>
<td>0.0006 (0.0004)</td>
</tr>
<tr>
<td>Constant</td>
<td>4.6674*** (1.1631)</td>
<td>10.4001*** (0.5387)</td>
<td>11.9933*** (0.8379)</td>
<td>8.2428*** (0.9725)</td>
<td>10.3136*** (1.4995)</td>
</tr>
<tr>
<td>Hausman test</td>
<td>9.54***</td>
<td>1.68</td>
<td>0.05</td>
<td>0.06</td>
<td>2.75*</td>
</tr>
<tr>
<td>R²</td>
<td>0.4818</td>
<td>1.68</td>
<td>0.05</td>
<td>0.06</td>
<td>2.75*</td>
</tr>
<tr>
<td>Chi²</td>
<td>498</td>
<td>1079</td>
<td>383</td>
<td>480</td>
<td>729</td>
</tr>
</tbody>
</table>

Table 8. Robustness check of the industrial sector. Standard deviations are in parentheses. One, two and three asterisks denote significance at the 10%, 5%, and 1% statistical levels, respectively. The Hausman test tests for overidentifying restrictions of random effect.

<table>
<thead>
<tr>
<th>Model S7 (urban area)</th>
<th>Model S8 (rural area)</th>
<th>Model S9 (northern Taiwan)</th>
<th>Model S10 (central Taiwan)</th>
<th>Model S11 (southern Taiwan)</th>
<th>Model S12 (eastern Taiwan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NW_t</td>
<td>-0.0155*** (0.0003)</td>
<td>-0.0163*** (0.0020)</td>
<td>-0.0170*** (0.0030)</td>
<td>-0.0157*** (0.0028)</td>
<td>-0.0151*** (0.0037)</td>
</tr>
<tr>
<td>CH_t</td>
<td>0.0005*** (0.0000)</td>
<td>0.0004*** (0.0000)</td>
<td>0.0005*** (0.0000)</td>
<td>0.0004*** (0.0000)</td>
<td>0.0004*** (0.0000)</td>
</tr>
<tr>
<td>lnPC_t</td>
<td>0.0431 (0.0697)</td>
<td>0.0437 (0.0483)</td>
<td>0.0464 (0.0706)</td>
<td>0.0596 (0.0673)</td>
<td>-0.1251 (0.0957)</td>
</tr>
<tr>
<td>lnIA_t</td>
<td>0.9752*** (0.2246)</td>
<td>0.1214* (0.0664)</td>
<td>0.1939* (0.1089)</td>
<td>0.0491 (0.1034)</td>
<td>0.8451*** (0.2549)</td>
</tr>
<tr>
<td>T</td>
<td>0.0027*** (0.0004)</td>
<td>0.0013*** (0.0001)</td>
<td>0.0013*** (0.0002)</td>
<td>0.0013*** (0.0002)</td>
<td>0.0002*** (0.0005)</td>
</tr>
<tr>
<td>Constant</td>
<td>19.6674*** (1.5337)</td>
<td>11.8120*** (0.4701)</td>
<td>13.3086*** (0.8598)</td>
<td>11.6977*** (0.7955)</td>
<td>18.0565*** (1.7419)</td>
</tr>
<tr>
<td>Hausman test</td>
<td>1.02**</td>
<td>2.29</td>
<td>2.49</td>
<td>1.59</td>
<td>36.41***</td>
</tr>
<tr>
<td>R²</td>
<td>0.5416</td>
<td>1.100</td>
<td>603</td>
<td>493</td>
<td>5615</td>
</tr>
<tr>
<td>Chi²</td>
<td>498</td>
<td>1079</td>
<td>383</td>
<td>480</td>
<td>729</td>
</tr>
</tbody>
</table>

Table 9. Robustness check of the service sector. Standard deviations are in parentheses. One and three asterisks denote significance at the 10% and 1% statistical levels, respectively. The Hausman test tests for overidentifying restrictions of random effect.
Given that the cooling hours in one day are always within 24 h, the electricity conservation rates and cooling hours in an EHT day off were shown in Fig. 6. Overall, the electricity conservation rates were between 20.41% and 21.08%. The higher the cooling hour was, the lower the electricity conservation would be. For an EHT day off, more electricity would be saved in the residential sector than in the other two sectors. The electricity conservation rates were relatively small in the service sector because some stores may still operate in public holidays. Commercial buildings may still consume electricity even though they are unoccupied or with very low occupancy. In addition, although the industrial sector had the smallest absolute value of elasticities, its electricity conservation rates were still large due to the highest share of electricity consumption. This change of electricity consumption behavior may be triggered by the moral hazard. Specifically, employees or workers have less incentive to save electricity in the workplaces since it is the responsibility of companies. In other words, people would have higher incentive to save electricity when they were sent home from work and paid the electricity bill by themselves.

Considering the EHT could be dangerous to human health, the topic of the EHT day off has been discussed in Taiwan for years, but no conclusion has been reached. In this study, the benefit of the EHT day off on electricity conservation has been proved. The EHT day off would reduce the risk of power shortage in summer caused by abnormally hot temperatures. Therefore, the results suggest that the EHT day off is one of the effective policies in conserving electricity and avoiding power outage.

Several limitations of the study are noted. First, the time interval of observations was month due to the availability of public data. It would be more precise to study behavior changes if the daily or hourly data were obtained. The proxy variable of behavior changes was used in this study, but it could be simply replaced by dummy variables when analyzing the detailed time series data. Second, the sectoral structures of electricity consumption were assumed to be constant at the values in 2018 when calculating the rate of aggregate electricity conservation. This rate could be different if the sectoral structures change. The share of electricity consumption in the industrial sector, for example, has increased smoothly over the last 10 years. If this trend continues, the estimated electricity conservation may decrease due to the less sensitive effect of the electricity consumption behavior in the industrial sector.
Moreover, the changes of electricity consumption due to the EHT day off in the energy, agriculture, and transport sectors were skipped because their percentages of the aggregate electricity consumption were relatively small and constant.

5. Conclusions

The extreme weather seems to be irreversible worldwide, and the role of policy makers is guiding people to adapt to it. The concept of EHT day off, covering the weather effects and changes of electricity consumption behavior in the non-workdays, was discussed in this study. Taiwan’s electricity demand in the industrial, service, and residential sectors was estimated using panel data models. Data consist of 19 cities and counties in Taiwan between January 2012 and December 2018. The number of nonworkdays was employed as a proxy variable of electricity consumption behavior in nonworkdays. The cooling hour was used to estimate the effect of high temperatures. Combining these two determinants, the net influence of the EHT day off on electricity consumption in the industrial, service, and residential sectors in Taiwan were thus investigated.

Estimated results indicated that an EHT day off can reduce the electricity consumption in the industrial, service, and residential sectors due to consumers’ change of the behavior from workday to nonworkday modes. This reduction can also offset the increase of electricity consumption driven by high temperatures. The change of electricity consumption in the industrial sector for an additional EHT day off was between −0.23% and −0.71%. This range was between −0.44% and −1.64% in the service sector, and between −1.08% and −2.04% in the residential sector. More electricity would be saved in the EHT day off in the residential sector, relative to other two sectors. People would be more willing to save electricity when they were sent home from work and paid the electricity bill by themselves. The electricity consumption in the industrial sector was less sensitive than other two sectors to the changes of nonworkday and temperature; however, the electricity conservation rates of the EHT day off in the industrial sector were still large because it has the highest percentage of electricity consumption. The electricity conservation rates were relatively small in the service sector because some stores or commercial buildings may still operate or have with low occupancy on the off day.

Overall, an EHT day off can conserve electricity by 0.41%–1.08% in Taiwan. The electricity conservation would be lower when cooling hours increase, but the benefit of saving electricity of the EHT day off is still confirmed in this study. This result also indicated that the EHT day off would be one of the potential effective policies in saving energy and avoiding power outage.

Further research into the EHT day off will provide a more complete picture of policy discussions and implications. In an economic aspect, a day off may have instant impacts on production, but the potential costs of labor health and system maintenance could be avoided due to an EHT day off. The trade-off between these two effects needs further research. In addition, how to establish a standard process for evaluating the impact of EHT and for announcing a day off needs further study with regard to the aspect of policy design.

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