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Urban Heat Island and Household Energy Consumption in Bangkok, Thailand

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Abstract

This study focuses on the urban heat island (UHI) development and its impact on household energy consumption. Hourly air temperature data were used to study the characteristics and intensities of UHI in Bangkok area. A survey questionnaire of 400 randomly selected respondents is conducted to explain the relationship between UHI intensity and household energy consumption. Cooling Degree Days (CDD) index was used to establish the correlation between UHI and energy consumption. The result indicates that the presence of UHI in Bangkok plays a significant role in residential energy use, directly and indirectly. UHI is found to have association with the air conditioning equipment in Bangkok and increase the monthly electricity bill. Energy consumption is found to have positive association with CDD, which implies that UHI have significant influence on the household energy consumption. The study concludes that combining the concept of UHI mitigation and adaptation planning and energy-efficient housing design will contribute to better solutions for creating a more energy-efficient city.

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Keywords: household energy consumption; urban heat island; urban planning; sustainable urban development; cooling degree day

1. Introduction

Urban heat island (UHI) is defined as a phenomenon where temperatures of urban areas are higher than surrounding or rural areas [1]. A measure to quantify urban heat island usually uses the term Urban Heat Island Intensity (UHII), which is the maximum temperature difference between urban and rural air [2].

Generally, the largest urban heat island effect, or maximum urban-rural area temperature difference occurs most at night, three to five hours after sunset, because the roads and other surfaces absorbing solar

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radiation in daytime release heat in nighttime. Thus, the rural areas cool off faster than urban areas at night. UHIs can provide both negative and positive impacts for cities. As cities grow, the urbanization causes less tree and vegetation displaced by buildings and roads, more skyscrapers and streets trap the wind path, and more heat is released from vehicles and air-conditioners. Besides, UHI increases human discomfort and air pollution concentration. Moreover, higher temperatures in urban heat island increase energy use especially for air-conditioning in buildings [3]. This increases more air pollution and energy cost due to the use of more fuel.

The UHI conditions increase the risk of climatic and biophysical hazards in the urban environments including heat stress and heighten acute and chronic exposure to air pollutants. Climate change, which is caused by increased anthropogenic emission of carbon dioxide and other greenhouse gases, is a long-term effect with the potential to alter the intensity, temporal pattern, and spatial extent for the UHI in metropolitan regions [4]. On the contrary, urban heat island may be beneficial for reducing heat loads as a result of reduced energy use for heating consumption reduces. However, this benefit does not count for developing countries [5]. UHIs also have further impacts on global scale; it influences the long-term temperature record leading to difficulties to detect global climate changes.

Bangkok is the capital city of Thailand located in the central part of the country. It is the center of industries, manufacture, economy, commerce, and construction. This draws a large amount of people from all over the country into the city, leading to the high growth of urbanization and industrialization. This rapid urbanization has led to several environmental problems such as air pollution, water pollution, land subsidence as well as the problems from the presence of urban heat island such as temperature rise, high energy consumption, and biophysical hazards etc. In 2012, the maximum temperature difference between urban and rural area of Bangkok was 7°C, which higher than in the last 10 years.

Boonjawat et al [6] initially showed the presence of heat island in Bangkok. The urban heat island intensity (UHII) between Chulalongkorn University (urban area) and Asian Institute Technology (rural area) was observed to be 3.5°C during 6.00-7.00 a.m. This study also shows the substantial effect of sea breeze and solar radiation on UHI. Sea breeze decreases the air temperature in the southern part of Bangkok. Another study showed the effects of land cover on UHI in Bangkok. The study also showed inverse relationship among TVI, surface temperatures, and land applications. Green area had high TVI and low surface temperature, on the contrary the low TVI and high surface temperature corresponded to building area. This study also shows the substantial effect of sea breeze and solar radiation on UHI. Sea breeze decreases the air temperature in the southern part of Bangkok.

However, there are no further detail empirical evidences on the current status of UHIs effect to urban area in Bangkok, especially now that the city is in the process of implementing new master plan to guide its future development. Correspondingly, due to the appearance of urban heat island many problems arise, hence the impacts of urban heat island should be also taken into consideration. In case of Bangkok, the air conditioning load is considered to have the largest share (almost 60%) of electricity use [7]. Therefore, it is important to assess the impact of UHI to household energy consumption from the microclimate perspective.

2. Method

Cooling Degree Days (CDD) index was used to establish the correlation between UHI and energy consumption. The study also uses Cooling Degree Days (CDD) to investigate the effect of higher temperature on cooling energy consumption in Bangkok. The CDD profiles from 4 weather stations from 2013-2014, in addition to providing an energy audit database, are used in the OLS regression to examine the sensitivity of electricity consumption. The air temperature from 2008-2012 from all four stations are collected to understand the temperature variation trend in Bangkok in 5 years moving average. These data are also used to understand the daily and annual course of UHI.

Table 1. Weather station in the study

Name of Station	Type of Station	Data Collected
Bangkok Metropolis (BM)	Urban (inner Bangkok)	Hourly air temperature record from 2008-2012
Bangna (BN)	Urban (middle Bangkok)	Hourly air temperature record from 2008-2012
Don Muang airport (DM)	Urban (outer Bangkok)	Hourly air temperature record from 2008-2012
Pathumthani (PT)	Rural	Hourly air temperature record from 2008-2012

CDD is calculated from the following equation:

$$CDD, i, d = \sum_{m-1}^{24} \frac{(Tm - Tb)(Tm - Tb) > 0}{24} \quad (1)$$

Where CDDi is the cooling degree days for particular day (d), Tb is the base temperature 24°C and Tm is the mean air temperature, considering only the positive values. Four CDD profiles for each weather stations covering four different areas of Bangkok Metropolitan Area.

The study defines household energy consumption as the per-square meter of floor electricity consumption assuming that different types of house have the same amount of lighting, appliances and usage pattern. The benefit of the approach is that it is easier to give a simple and easy estimate of expected electricity consumption for different kind of housing types. However, the estimation will be very rough because in Bangkok, there are different typologies of housing that need to be considered. A survey questionnaire of 400 randomly selected respondents based on area sampling is conducted to explain the relationship between UHI intensity and household energy use. The questionnaire were designed based on the operational definitions of the variables and are tested with 20 households in the Bangkok area. The reliability of the questionnaire is tested with Cronbach's alpha with the score of 0.87.

Table 2. Variables used in the study

Variable	Description	Range
CDD	Monthly cooling degree days with base temperature 24°C in 2013	M = 152.68; SD = 32.11
Electricity	Monthly electricity bill in 2013 in THB	M = 854.35; SD = 431.178
Number of AC	Number of air conditioning unit owned in the house	Min = 0; max = 2
AC use	Frequency of using AC equipment in last month	0= no use; 1= just a few hours; 3 = few day and night; 4 = almost every day and night
Energy	monthly energy use for space cooling in 2013 (kWh/m2)	M = 2,136.04; SD = 2,103.65

Table 3 summarizes the variables used in the study. Variables that have not been found significant association with the household energy consumption are not included in the study. All variables in the study are analyzed whether they follow the normal distribution pattern.

To model the relationship between CDD and the household energy consumption, we use the linear regression following the equation below.

$$E = a + bCDD \quad (2)$$

Where E is the dependent variable of monthly energy use for space cooling per square meter, a represents the intercept and b is the slope and CDD is the predictor variable. We also use t-statistics to establish the simple association between two variables.

3. Result

3.1 UHI variation and CDD

The long-term annual air temperature record in Bangkok from 1980-2012 shows that the temperature had been cooler in cool season and warmer in hot season. For example, Bangkok Metropolis weather shows that the mean maximum and minimum annual air temperature from 1980-2012 was 33 °C and 24 °C respectively, and increasing linearly by 0.95 °C and 1.97 °C. One significant factor affecting this increase is probably the rapid urbanization in Bangkok. Using the data from the same weather station, the daily temperature from 2008-2012 is compared to Pathumthani weather station to understand the daily temperature variations between urban and non-urban area. The result shows that the temperature differences between each year are more obvious during winter. The temperature seems to be higher each year in the summer, and decrease during winter. In summer and in winter, 3 weather stations around the center is much warmer than its suburb (Pathumthani station). This is because they are located in the most densely build-up area which is surrounded by a number of buildings including hotels, hospitals, and government institutes while the Pathumthani station is situated away from the build-up area.

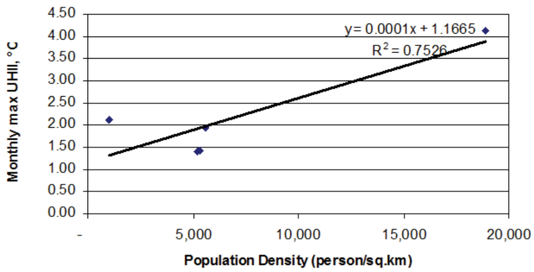

Fig 1. Relationship between population density and UHI variation

To show the relationship between population density and UHI magnitude, the population density data in district of those stations are presented and plotted in figure 3. The relationship between the population in city and the magnitude of heat island show the maximum urban heat island intensity in tropical hot and wet region is 4-9°C when the population is around 1 million to 10 million. The total population in Bangkok according to household registration was 5.78 million about 10% of the total population in Thailand. However, this does not include those who commute and live in Bangkok without registration. These numbers are estimated at around 3.2 million [8]. This makes the total population of Bangkok city to be almost 9 million. The Bangkok heat island magnitude should be approximately 6.5°C.

Monthly CDD profile for 4 weather station areas in 2013 is summarized in table 4. The highest number of CDD occurs in April and the lowest in January in the urban area. However, using the 24°C it seems that CDD occurs very little in sub-urban area (Pathumthani). The finding shows that UHI effect in Bangkok is higher compared to the sub-urban area.

Table 3. CDD profiles for four weather stations

	Jan	Feb	March	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Avg
BM	69	107	176	222	231	190	178	159	154	135	154	110	148.57
BN	106	156	115	230	122	220	234	181	169	149	148	136	151.92
DM	68	106	183	205	217	184	174	148	150	132	142	98	143.07
PT	46	5	0	0	0	0	0	0	0	0	0	10	6.57

3.2 Household Energy Consumption and CDD

A survey conducted by the National Statistical Office of Thailand [9] shows that the average energy expenditure is 2,084 THB or 10.9% of the total expenditure with the expenditure on electricity is 607 THB (29.1% of the total energy expenditure). The average electricity expenditure in Bangkok Metropolitan Area is 1,133 THB, higher than other region in the country. The number is slightly different with the result from the survey (854.35 THB for the electricity expenditure). 72% of households in the study has Air Conditioning (AC) equipment in their housing units. There is a positive correlation between income and the number of AC unit owned in the house (two-tailed *t-statistics,* $p < 0.0001$). This is because the higher the income, households tend to have bigger floor area in the house. The floor area of the house is also found to have a positive correlation with the frequency of AC use (two-tailed *t-statistics,* $p < 0.005$). Air Conditioning (AC) equipment ownership is the most fundamental factor in household space cooling consumption [8]. More than 80% of the respondents have AC equipment in their housing units. There is a positive relationship between the ownership of AC equipment and CDD ($F = 81.569$, $p < 0.001$). As expected, there is a positive correlation between household energy consumption and CDD. Regressing monthly energy use for space cooling per square meter (E) to CDD resulting in high coefficients of R2 (adj R2 = 0.881; std error = 1.046; p-value < 0.001). This finding implies that CDD and E values experience change in the same direction.

4. Concluding Remark

This study used hourly air temperature of Bangkok area (urban) and Pathumthani (non-urban) to estimate the urban heat island characteristics. The results from yearly data of air temperature shows the followings. During the last 30 year of air temperature observations (1980-2012), the mean, maximum, and minimum annual air temperature appear to have increased linearly by 1.74, 0.95, 1.97°C respectively. This shows a slight increase in maximum temperatures and a significant increase in minimum temperature. The UHI severity in Bangkok is found to be higher compared to other major cities with UHI problems such as Shanghai, San Diego, and San Francisco, and is of similar range to Tokyo.

The UHI effect is most pronounced during the night time. It begins to rise after sunset and reaches its maximum at about sunrise during 6-7 am. It continues to decrease to the lowest magnitude or often become cool island phenomenon around 3-6 pm. This development of UHIs is observed in all seasons. For seasonal variation, the UHI effect is most intensive during the dry season, followed by hot and wet season. The highest intensity can be observed in December (mid of cool season) around 5°C and in summer around 2-3°C. Unlike in winter and summer, the UHI intensity between the night time (7 pm-7 am) and morning time (7-12 am) during rainy season are almost the same.

The study shows that many factors govern the UHI variations including city structures, population, and weather. Precipitation is found to be inversely proportional to the UHI magnitude. The area with the maximum UHI intensity is corresponds to the most densely build-up area with highest building and population density among other stations used in the study. The maximum intensity could range from 8-10°C during the day time due to the surface materials such as road (concrete or asphalts), building walls, or paved surface warming faster than the surfaces in rural area, which normally are covered with green areas.

The study also examines the relationship between household energy consumption and UHI. The result shows that the higher the relationship is positive. It means that energy consumption is high in the area with high UHI variations and the other way around. This finding implies that if not UHI is not mitigated properly, Bangkok will experience a significant increase of household energy demand. The study concludes that combining the concept of UHI mitigation and adaptation planning and energy-efficient housing design will contribute to better solutions for creating a more energy-efficient city.

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