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Equivalent full-load hours for assessing climate change impact on building cooling and heating energy consumption in large Asian cities

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HIGHLIGHTS

- EFLH for estimating cooling/heating energy demand in Asian buildings are provided.
- Net increases in building energy consumption over the next 30 years are predicted.
- Switching to more efficient AC devices can offset much of the increases.

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ABSTRACT

Estimating cooling and heating energy requirements is an integral part of designing and managing buildings. Further, as buildings are among the largest energy consumers in cities, the estimates are important for formulating effective energy conservation strategies. Where complex hourly simulation models are not favored, such estimates may be derived by simplified methods that are less computationally intensive but still provide results that are reasonably close to those obtained from the more complicated approach. The equivalent full load hours (EFLH) method is a simplified energy estimation method that has recently gained popularity. It offers a straightforward means of evaluating energy efficiency programs. However, to date, easily accessible EFLH data exist only for a very limited number of countries in North America and Europe, but not Asia. This current work provides previously unavailable monthly EFLH data for building cooling and heating in three large Asian cities, viz. Hong Kong, Seoul and Tokyo. To assess the effects of changing temperature over the course of decades on building cooling and heating energy consumption, EFLH data are calculated for three time periods: past (1983–2005), present (2006–2014) and future (2015–2044). The projections for the future time period are based on the climate scenarios Representative Concentration Pathways (RCPs) 4.5 and 8.5 of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report. RCP-4.5 assumes a stabilization of future greenhouse gas (GHG) emissions followed by a reduction, while RCP-8.5 assumes their further increase. From the EFLH data, considering just the effects of ambient temperature changes, it is projected the total energy required to heat and/or cool residential dwellings in Hong Kong, Seoul and Tokyo to increase by 18.3%, 4% and 10.4%, respectively over 62 years from 1983 to 2044 in the case of RCP-4.5, and by 23.3%, 9.3% and 15.8%, respectively in the case of RCP-8.5. This shows that even with future stabilization and reduction of GHG emissions, as per scenario RCP-4.5, the energy needs of the three cities for building heating and cooling combined can be expected to increase over the next few decades. This has significant implications, namely increased demands for additional primary energy, which will result in further GHG emissions. These effects, however, can be controlled with adjustments to the electricity fuel mix of each location, and also by use of more efficient heating, ventilation and air-conditioning (HVAC) devices.

1. Introduction

A key factor in building management is the estimation of the energy needs of its heating, ventilating and air conditioning (HVAC) system to optimize energy consumption and operating cost. At the city level, the heating and cooling of buildings constitute a major source of energy use and generation of greenhouse gas (GHG) emissions. Thus, the ability to estimate present and future building energy requirements allows for the development of improved energy policies, including conservation strategies, that are necessary for preparing for and mitigating the effects of climate change.

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Traditionally, estimations of cooling and heating energy requirements for the built environment have been conducted either by use of sophisticated building energy simulations [1–4] or simplified techniques [2,5–11]. The former offer a high level of accuracy, but are usually time-consuming and computationally expensive. The latter are more direct and simple, but have limited accuracy. Recently, Papakostas et al. [12] developed a simplified method based on ambient temperature bins to calculate location-specific equivalent full load hours (EFLH), which are the number of hours a cooling or heating system would need to operate at full load to consume the same amount of energy it consumes on average in a year. Once the EFLH data for a location are known, it is straightforward to conduct building energy analyses involving estimation of building cooling and heating energy demands, e.g. analyses to evaluate energy efficiency standards for HVAC systems.

To date, the use of EFLH is uncommon as the conventional approach to derive the data is tedious and the data produced often inaccurate. However, with the development of the method presented in [12], hereafter referred to as the "temperature bin-based EFLH method", EFLH data are now significantly simpler to derive. Additionally, the method is able to account for hour-to-hour variances in outdoor environmental conditions, and differences in building characteristics and occupancy pattern, thereby adding greater accuracy to the results.

Location-specific EFLH are presently available for only a limited number of cities in North America [13] and Europe [12]. There is currently no such data for Asia, where there has been rapid population growth and urbanization leading to increased cooling and heating demands in many of the region's cities. This paper aims to fill this gap by developing and providing for the first time tabulated monthly EFLH data for three large Asian cities, namely Hong Kong, Seoul and Tokyo, using the temperature bin-based EFLH method. This paper also seeks to derive the cooling and heating demands of real buildings from the EFLH data, and to use the estimates to further prove the validity of the said method by comparing the estimates against real building data. (To the best of knowledge, validation of the method is still scarce in the literature.) Moreover, from the EFLH data, this paper predicts and discusses the impacts of temperature changes due to climate change on building cooling and heating demands for the three cities and their implications. It is hoped that the results will be of interest to energy policy-makers in Asia and elsewhere.

While the EFLH data developed in this study are applicable to buildings of all types, much of the ensuing discussions are focused on residential buildings. This is due to the fact that in Asia, as in every other continent, residential buildings surpass non-residential buildings in energy consumption, and that worldwide, the residential sector constitutes the third largest energy consumer [14]. In addition, the sector has been identified as having a greater potential for improved energy efficiency [15].

2. Background

2.1. Building energy consumption in Hong Kong, Seoul and Tokyo

On a global average, buildings are responsible for approximately 40% of total energy use and 33% of total GHG emissions [16]. However, in certain highly urbanized centers in Asia, the percentages are even higher. In Hong Kong, there has been a steady increase in energy consumption over the past several years. Residential and commercial buildings in the city combined account for about 92% of total electricity demand [17]. Hong Kong has a subtropical climate. Thus, space cooling is the city's single largest energy consumer, more so than cooking, lighting, industrial processes, and transportation; at the city level, it accounts for 16% of total energy use. Space heating is also a large energy consumer as 23% of total energy consumption in residential buildings and 25% in commercial buildings are due to it [17].

In South Korea, 10.3% of total electricity use occurs in the capital city, Seoul [18]. Seoul is a vibrant city that has witnessed tremendously rapid growth since the 1960s [19]. Today, its 650,000 buildings (75% of which are residential) account for 56% of the city's total energy consumption [19], which, like for the case of Hong Kong, has continuously increased over the years [18]. The Seoul Metropolitan Government has set the goal of reducing the city's GHG emissions by 6.06 million tonnes of CO_2 equivalent. Towards this, reducing building energy consumption has been identified as a top priority [18]. In residential buildings, heating is the largest contributor to energy consumption, whereas in commercial buildings, it is cooling that is the largest contributor [20].

In Japan, national mandates enforcing energy-saving measures have succeeded in reducing energy consumption and GHG emissions [21,22]. However, the city of Tokyo alone, with a population of 13 million, still consumes more energy and generates more GHG emissions than whole countries. In Tokyo, as in Hong Kong and Seoul, buildings are the largest consumer of energy, and collectively, are responsible for 67% of total energy use [23]. Space cooling is a major contributor to the typical household's energy consumption, accounting for 25.5% of total energy use [24].

In summary, Hong Kong, Seoul and Tokyo are major urban centers with huge energy demands largely due to building cooling and/or heating. Thus, the monthly EFLH data and resulting building energy consumption estimates for the past, present and future that this paper aims to provide offer an additional and straightforward tool for local agencies to design effective energy adaptation policies in view of climate change.

2.2. Methods for estimating building cooling and heating energy demands

There are several methods for estimating the cooling and heating energy requirements of buildings [25,26]. These rely on either detailed simulations [2,3] or simpler calculations [2,27,6]. Methods of the former kind seek to predict the hour by hour heat transfer across a building's envelope by considering the dynamic behavior of heating and cooling equipment, and assuming predefined conditions and building parameters. Characteristic examples of detailed building energy simulation models are Building Load and Analysis and System Thermodynamics (BLAST) developed by the United States (US) Army Construction Engineering Research Laboratory and the University of Illinois at Urbana-Champaign, and Energy Plus [3] and DOE-2/DOE-2.2 [1] developed by the US Department of Energy. Related studies in the field are usually about employing simulation models deemed most suitable for specific buildings, or developing and improving widely applicable universal models. Recently, Cui et al. [28] proposed an expert system based on meta-learning to identify the model most appropriate for representing a building given its unique physical characteristics.

However, these models are complex, requiring sophisticated software, extensive computing hours and a high level of human expertise. Where such resources are unavailable, simpler, more direct methods are favored. These simpler methods typically assume a steady-state system with zero energy accumulation over the examined period of time. They also usually assume that energy loads are proportional to the difference between indoor and outdoor temperatures [12]. While they are less comprehensive compared to the methods based on detailed simulations, they are still useful for deriving trends and to compare between alternatives [2]. Despite their relative simplicity, they have been found to generate predictions that are reasonably close to results obtained by detailed simulations [29,30].

Among the more common of simplified methods are the degree-days and temperature bin methods, and their variations. The degree-days method [2,10,9] is based on the premise that over the long term, on average, solar and internal heat gains counterbalance heat losses when the mean daily ambient temperature is 18.3 °C (65°F) [2], and thus, at that temperature, no energy is required for heating. In the same manner, when the mean daily ambient temperature is 23.8 °C (75°F), no energy is required for cooling. When the temperature is any other value, the energy consumption of a building is considered to be linear to the difference between that value and the 18.3 °C baseline if for heating, and the 23.8 °C baseline if for cooling. While 18.3 °C and 23.8 °C are the most widely accepted values for defining the baselines, other values have been used depending on the location. A variation of the degree-days method is the variable degree-days method [11], which does not use standard base temperatures, but uses instead temperature-balance points, which not only represent the range of outdoor temperatures within which a building needs neither heating nor cooling, but are also specific to the building considering its construction, structure, and occupation pattern in addition to its location. The degree-days and variable degree-days methods are often used for estimating the cooling or heating requirements of small buildings, and for comparing the requirements among different locations [2,8].

A major limitation of the degree-days approach is that it is based on the mean of the temperature extremes of the day and ignores the effects of same-day fluctuations. This can lead to situations where the cooling or heating degree days are zero, but the building does in fact require cooling or heating [5]. To circumvent this limitation, the temperature bin method [6,7,31–33] divides the hours throughout the day according to the ambient dry-bulb temperature into several intervals, or temperature bins. By considering the temporal variation in outdoor temperature in this manner, the method adds accuracy to building energy estimates. The original bin method does not consider solar effects, which has led to the development of a modified bin method [34]. Both these versions base their calculations on hourly ambient dry-bulb temperature measurements. However, an alternative method for generating bin data, proposed by Erbs et al. [31,32,35] requires mainly monthly averages of the ambient dry-bulb temperature and the solar clearness index, which greatly reduces the necessary input data, thus improving the accessibility of the temperature bin method.

Another method to estimate building energy consumption is to use EFLH [12,36,37], which are the number of hours a cooling or heating system would need to operate at full load to consume the same amount of energy it consumes on average in a year. This method has been used to compare the effectiveness of energy efficiency standards of appliances [36]. The EFLH of a heating or cooling system are typically obtained by dividing total energy use by peak load [38]. However, this restricts the use of EFLH to cases where detailed information from electric utility companies is available, and often requires additional surveys of individual buildings to account for differences in occupation pattern. Further, EFLH calculations are typically limited to large centralized systems as the energy consumption of small individual room units are often unavailable since they are usually not measured separately.

With the recent development of the temperature bin-based EFLH method [12] (as mentioned in Section 1), computation of location-specific EFLH from just weather data, i.e., monthly or annual ambient temperature bin data, is now possible. This is an advantage over the conventional approach of computing EFLH from total energy use and peak load as the use of bin data enables the explicit consideration of hour-to-hour variances in outdoor environmental conditions (as in the case of the temperature bin method). The method yields the output of monthly or annual EFLH that can then be used to estimate building cooling or heating needs given the building occupation pattern and type, which affect internal heat gains and the indoor design temperature. Employing different balance point temperatures for different buildings in calculations accounts for variations due to these factors. As the temperature bin-based EFLH method takes into account all these complexities, it can be considered to be more accurate than the other simplified methods, and thus, has been selected for use in this present paper to generate the required EFLH data.

2.3. Climate change impacts on building cooling and heating energy consumption

There is a strong correlation between energy use and climate change [39], which has led to numerous studies to estimate future climate impacts on building energy. See Li et al. [40] and Wang and Chen [41] for detailed reviews of studies on identifying and measuring such impacts for various regions around the world. Most of the studies have predicted reductions in heating energy but increases in cooling energy, and that, in general, the impacts will be most severe in climate zones with hot summers and warm winters. While the majority of the studies were made using building energy simulation models [40–52], there are also numerous studies based on simplified methods [27,8,53–61] such as the degree-days and temperature bin methods.

A recent example of a study based on building simulations is the study by Dirks et al. [42], who used the Building Energy Demand (BEND) model to assess the climate change impacts on peak and annual building energy consumption across the Eastern Interconnection in the US. In many of the studies based on building simulations, there tends to be a greater focus on non-residential buildings as compared to residential buildings [40]. This is possibly due to the greater complexity of non-residential settings which necessitates the use of complex simulation models to adequately capture essential details. For instance, when modeling large commercial buildings such as malls, it is often necessary to conduct hourly energy usage simulations to adequately capture the building occupancy pattern, which can deviate quite markedly from standard patterns. As for examples of simulation-based studies focusing exclusively on residential buildings, see [43–47]. In these studies, building simulation models were used to study the effects of modifying building characteristics to assess the effectiveness of climate mitigation measures involving changes in building shading, ventilation and insulation.

Despite their greater accuracy, the high computational demands of building simulation models render them inaccessible in many cases. When this is true, simplified methods are favored. Among simplified methods, the degree-days method is the most commonly applied, e.g. Zhou et al. [59] and Petri and Caldeira [27] used degree-days to assess the effects of climate change on US buildings. Unlike simulation-based studies, studies based on simplified methods show no obvious bias for any particular building type. Also unlike the former, the latter are mostly focused on the implications of changes in climate parameters (rather than the effects of altering building characteristics). However, the main weakness of studies based on simplified methods, of which the bulk rely almost exclusively on the degree-days method, is the limited reliability of the results due to the incapacity of the degree-days method to capture the effects of same-day fluctuations (as discussed in Section 2.2). To the best of knowledge, there is still a lack of studies utilizing EFLH to evaluate the impacts of climate change on building heating and cooling energy. This current paper is the first, or at least among the first, to do so. The use of EFLH for the said purpose, especially if derived using the temperature bin-based ELFH method [12], promises more reliable results given the reasons described in Section 2.2 above.

3. Methods and data

To estimate EFLH data for Hong Kong, Seoul and Tokyo, ambient temperature bin data in the required form are first generated using the method of Erbs et al. [35]. (Fig. 1 shows the geographic locations of the three cities.) This method is selected as it requires less input data while producing results that are very similar to other more data-intensive methods. The main inputs to the method are the monthly average, minimum and maximum ambient dry-bulb temperatures for a given location, together with the monthly averages of the solar clearness index [62]. The latter is the ratio of solar global radiation on a horizontal surface to extraterrestrial radiation [63]. For every month, from the solar clearness index and the monthly average temperature, the average temperature of each hour of the month is derived, and from there, it can be approximated the number of hours in the month where the ambient temperature is below a prespecified reference temperature. This is repeated for multiple reference temperatures, the smallest being the minimum temperature for the month and the largest the maximum. Finally, the number of hours the ambient temperature lies within an interval, or bin, is calculated by the difference between the number of hours it is below the reference temperature at the lower end of the bin and the one that is below its upper end. For a detailed description of the method, refer to Papakostas et al. [31] and Peng et al. [32].

In this present work, the bins are 2 °C wide and the day is divided into six 4-h shifts. This is consistent with similar past studies where bins are typically spaced 2.8 °C (5°F) or 2 °C (3.6°F) apart [6,7,31,32]. The division of time into six 4-h shifts facilitates the consideration of variations in occupation pattern depending on building type. For example, for a residential building, it can be assumed that a cooling system operates for 12 h, and for a hospital, 24 h [12]. In the first case, to calculate the EFLH, only bins for three out of the six shifts need be considered, while in the second case, bins for all six shifts.

Bin data are derived for three time periods, past (1983–2005), present (2006–2014) and future (2015–2044). To achieve this, temperature data for the past and present periods are obtained from Hong Kong Observatory [64], Korea Meteorological Administration [65], and Japan Meteorological Agency [66]. Temperatures for the future period are based on projections for East Asia by climate models of the Coordinated Regional Climate Downscaling Experiment [67], a project sponsored by the World Climate Research Program. Projections for two scenarios are considered, the scenarios Representative Concentration Pathways (RCPs) 4.5 and 8.5 of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report [68], or in short, RCP-4.5 and RCP-8.5. RCP-4.5 assumes the stabilization of radiative forcing at 4.5 W/m^2 before 2100, which would require the successful implementation of policies and technologies for reducing GHG emissions [69]. RCP-8.5 assumes the failure to curb GHG emissions leading to rising levels of radiative forcing that will reach 8.5 W/m^2 by 2100 and greater thereafter [70].

Fig. 1. Geographic locations of Hong Kong, Seoul and Tokyo in East Asia.

For all locations, monthly averages of the solar clearness index for the past time period (1983–2005) are obtained from the Atmospheric Science Data Center (ADSC) of the National Aeronautics and Space Administration (NASA) of the US [71]. For the other two time periods, they are estimated assuming the values during those periods mirror the past (real data for the present and future time periods are unavailable).

From the temperature bin data, the temperature bin-based EFLH method [12] is then used to compute EFLH data for the three cities. This method is favored because it requires neither past records from electric utilities nor hourly measurements of temperature, but only weather data that can be easily accessed or approximated. In addition, the method may be applied to any size and type of heating or cooling unit, and is able to take into account differences in building occupation pattern. The EFLH data are computed according to equations (1) and (2) below [12]:

$$E_{\mathrm{c}} = \frac{\sum_{i=1}^{m} N_{\mathrm{bin},i}(T_{\mathrm{o},i} - T_{\mathrm{bal,c}})}{(T_{\mathrm{ODC}} - T_{\mathrm{bal,c}})} \tag{1}$$

$$E_{\mathrm{h}} = \frac{\sum_{i=1}^{m} N_{\mathrm{bin},i}(T_{\mathrm{bal,h}} - T_{\mathrm{o},i})}{(T_{\mathrm{bal,h}} - T_{\mathrm{ODH}})} \tag{2}$$

E_{c} and E_{h} are the cooling and heating EFLH, respectively for a particular month. m is the total number of bins depending on the minimum and maximum temperatures of the month. $N_{\mathrm{bin},i}$ is the total number of hours with a dry-bulb temperature that is within bin i, as estimated by the method of Erbs et al. [35] described above. $T_{\mathrm{o},i}$ is the midpoint of bin i. $T_{\mathrm{bal,c}}$ is the building balance-point temperature for cooling, and $T_{\mathrm{bal,h}}$ for heating. For the same location, building balance-point temperature, whether for cooling or heating, is influenced by building type and construction, indoor temperature, internal heat gains and occupation pattern. In this study, it is assumed that the buildings modeled are "typical", and therefore, their balance-point temperatures are equal to standard cooling and heating base temperatures for their locations. For Hong Kong, the standard base temperatures for cooling and heating are taken as 26 °C and 18 °C, respectively as specified by the Ministry of Housing and Urban-Rural Development of China [72]. The same temperatures are assumed for Seoul [73,74], while for Tokyo, a standard base temperature of 22 °C is assumed for cooling, and 14 °C for heating [75].

Other key parameters for estimating EFLH are cooling and heating outdoor design temperatures, T_{ODC} and T_{ODH}. (The former is the outdoor temperature that is exceeded only 1% of all hours in a year; it is also known as the 1% design temperature. Similarly, the heating outdoor design temperature, or the 99% design temperature, is the outdoor temperature that is exceeded 99% of all hours.) The outdoor design temperatures used in this study are taken from the 2009 edition of the Handbook of Fundamentals of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [26]. A comparison of these and earlier values [76] shows the changes in the outdoor design temperatures with time to be insignificant and therefore, for this study, they are assumed to remain unchanged over the years.

Table 1 summarizes basic location information for the three cities of interest. It also describes the data sources used.

Finally, from the EFLH estimates obtained using Eqs. (1) and (2), the energy requirements of a building for cooling, C and heating, H (in kWh) are estimated as follows [12]:

$$C = Q_{DC}E_c \tag{3}$$

$$H = Q_{DH}E_h \tag{4}$$

where Q_{DC} and Q_{DH} are the building's design cooling and heating loads (in kW), respectively.

The EFLH data are also used as a tool for comparison of energy efficiency standards for air-conditioners (ACs). To estimate the annual energy savings that can occur from using an AC model with a higher efficiency compared to a baseline model, the equation below is applied [38]:

$$E_{saved} = Cap\left(\frac{1}{EER_{base}} - \frac{1}{EER_{std}}\right)E_c \tag{5}$$

E_{saved} is the energy saved (in kWh), Cap is the cooling capacity of the AC unit (in kW), and EER_{base} and EER_{std} are the energy efficiency ratios (EERs) (in W/W) of the baseline model and the more efficient model, respectively.

4. Temperature bin and EFLH data

Using the bin method of Erbs et al. [35], as described above, monthly ambient temperature bin data are generated for three time periods, past (1983–2005), present (2006–2014) and future (2015–2044) for Hong Kong, Seoul and Tokyo. Due to space limitations, only the bin data for Hong Kong are presented in this section; see Tables 2 and 3 for the derived bin data, $N_{bin,i}$ for the city. See also Appendix A for the bin data for Seoul and Tokyo. Note that for the case of Hong Kong, only bin data for the cooling months of May to October are provided, as buildings in Hong Kong are not typically equipped with central heating. Note also that in Tables 2 and 3, as well as the tables in Appendix A, the temperature ranges are non-uniform across the present, past and future periods. This is due to differences in the minimum and maximum temperatures (either reported or projected) between the time periods.

Table 4 shows the EFLH estimates for cooling and heating for the past, present, and future periods for Hong Kong, Seoul and Tokyo. The data are estimated from Eqs. (1) and (2) and are based on the monthly bin data for each city. As before, for Hong Kong, only EFLH data for the cooling months are provided; for Seoul

Table 1
Location information and sources of data for the 3 cities examined in this study.

City	Longitude (E°)	Latitude (N°)	Elevation (m)	Population (million)	Temperature data sources[a]	Solar clearness index data source[b]	T_{ODC}/T_{ODH} source[c]
Hong Kong	114°17′	22°30′	33	7.2	HKO [64], CORDEX East Asia [67]	NASA ADSC [71]	ASHRAE [26]
Seoul	126°97′	37°57′	85.9	10.3	KMA [65], CORDEX East Asia [67]	NASA ADSC [71]	ASHRAE [26]
Tokyo	139°45′	35°41′	37	13	JMA [66], CORDEX East Asia [67]	NASA ADSC [71]	ASHRAE [26]

[a] HKO: Hong Kong Observatory; KMA: Korea Meteorological Administration; JMA: Japan Meteorological Agency; CORDEX: Coordinated Regional Climate Downscaling Experiment.
[b] NASA ADSC: Atmospheric Science Data Center of the US National Aeronautics and Space Administration.
[c] ASHARE: American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

Table 2
Monthly $N_{bin,i}$ values (hours per month) in six daily 4-h intervals for the past (1983–2005) and present (2006–2014) periods for months in the cooling season in Hong Kong.

	$N_{bin,i}$ values in six daily 4-hour intervals														
	Past period (1983–2005)								Present period (2006–2014)						
Month	Temperature range (°C)	1:00 – 4:59	5:00 – 8:59	9:00 – 12:59	13:00 – 16:59	17:00 – 20:59	21:00 – 00:59	Total	Temperature range (°C)	1:00 – 4:59	5:00 – 8:59	9:00 – 12:59	13:00 – 16:59	17:00 – 20:59	21:00 – 00:59	Total
May	24.3/26.3	32	29	29	10	22	37	159	24.1/26.1	33	31	27	8	20	37	156
	26.3/28.3	13	11	34	34	38	23	153	26.1/28.1	14	12	35	32	37	25	155
	28.3/30.3	3	3	16	36	22	6	86	28.1/30.1	4	3	17	38	24	8	94
									30.1/32.1	1	1	4	13	6	2	27
June	26.3/28.3	34	31	28	7	20	40	160	26.2/28.2	34	31	28	7	20	40	160
	28.3/30.3	12	10	37	33	40	24	156	28.2/30.2	12	10	37	33	40	24	156
	30.3/32.3	2	2	16	42	24	6	92	30.2/32.2	2	2	16	42	24	6	92
									32.2/34.2	0	0	3	12	5	1	21
July	26.8/28.8	31	27	24	3	15	40	140	26.9/28.9	30	28	23	2	14	40	137
	28.8/30.8	10	8	36	18	37	25	134	28.9/30.9	11	9	36	17	36	26	135
	30.8/32.8	2	2	21	48	31	6	110	30.9/32.9	2	2	23	48	33	6	114
August	26.6/28.6	34	31	25	4	17	40	151	26.8/28.8	34	31	25	4	17	40	151
	28.6/30.6	12	10	37	25	39	26	149	28.8/30.8	12	10	37	25	39	26	149
	30.6/32.6	2	2	20	47	29	6	106	30.8/32.8	2	2	20	47	29	6	106
September	24.3/26.3	38	37	12	1	5	26	119	24.1/26.1	34	36	8	0	3	19	100
	26.3/28.3	25	22	30	6	22	38	143	26.1/28.1	32	28	24	3	16	39	142
	28.3/30.3	7	6	34	31	39	18	135	28.1/30.1	11	9	36	21	37	25	139
	30.3/32.3	1	1	15	43	23	4	87	30.1/32.1	2	2	21	47	30	6	108
October	23.7/25.7	23	19	24	3	16	35	120	24/26	24	20	23	3	15	36	121
	25.7/27.7	8	6	31	17	33	20	115	26/28	8	7	31	16	33	21	116
	27.7/29.7	2	2	20	42	29	6	101	28/30	2	2	21	42	30	6	103

and Tokyo, data for both the cooling (June-September) and heating months (January-March and November-December) are provided. The "24 h data" are generated considering all the six daily 4-h intervals defining the bin data, while the "12 h data" are obtained considering only the three intervals between 9 am and 9 pm. This distinction is useful for differentiating between buildings with different occupation patterns. The use of "12 h data" can be considered as the general standard for modeling residential or office buildings, while "24 h data" are generally more suitable for modeling certain special-use buildings, such as hospitals [12].

Table 3
Monthly $N_{\mathrm{bin},i}$ values (hours per month) in six daily 4-h intervals for the future (2015–2044) period for months in the cooling season in Hong Kong under scenarios RCP-4.5 and RCP-8.5.

	$N_{\mathrm{bin},i}$ values in six daily 4-hour intervals															
	Future period (2015–2044), scenario RCP-4.5								Future period (2015–2044), scenario RCP-8.5							
Month	Temperature range (°C)	1:00–4:59	5:00–8:59	9:00–12:59	13:00–16:59	17:00–20:59	21:00–00:59	Total	Temperature range (°C)	1:00–4:59	5:00–8:59	9:00–12:59	13:00–16:59	17:00–20:59	21:00–00:59	Total
May	25.7/27.7	35	32	27	8	20	39	161	25.9/27.9	35	33	27	7	20	39	161
	27.7/29.7	14	12	36	33	39	26	160	27.9/29.9	14	12	37	33	40	26	162
	29.7/31.7	3	3	17	40	24	7	94	29.9/31.9	3	3	17	41	24	7	95
June	26.8/28.8	36	32	27	6	19	41	161	26.8/28.8	36	32	27	6	19	41	161
	28.8/30.8	12	10	38	31	41	26	158	28.8/30.8	12	10	38	31	41	26	158
	30.8/32.8	2	2	17	44	25	6	96	30.8/32.8	2	2	17	44	25	6	96
July	26.7/28.7	32	28	23	2	14	39	138	26.8/28.8	33	28	23	2	14	39	139
	28.7/30.7	11	9	36	17	36	26	135	28.8/30.8	11	9	36	17	36	26	135
	30.7/32.7	2	2	23	48	33	7	115	30.8/32.8	2	2	23	48	33	6	114
August	26.5/28.5	36	33	23	3	14	39	148	26.6/28.6	36	33	23	3	14	39	148
	28.5/30.5	14	12	37	21	38	29	151	28.6/30.6	14	11	37	21	38	29	150
	30.5/32.5	3	2	22	47	31	8	113	30.6/32.6	3	2	22	48	31	7	113
September	26.1/28.1	33	29	23	3	14	39	141	26.2/28.2	32	30	23	3	14	39	141
	28.1/30.1	12	9	36	19	36	26	138	28.2/30.2	12	9	36	19	37	26	139
	30.1/32.1	2	2	22	47	32	7	112	30.2/32.2	2	2	22	48	32	7	113
October	24.2/26.2	26	22	22	2	14	36	122	24.5/26.5	26	22	22	2	14	36	122
	26.2/28.2	9	7	32	13	32	23	116	26.5/28.5	9	7	32	13	32	23	116
	28.2/30.2	2	2	23	41	32	7	107	28.5/30.5	2	2	23	41	32	7	107

Table 4
24 h and 12 h cooling and/or heating EFLH data for Hong Kong, Seoul and Tokyo for the past and present periods, and for the future period under scenarios RCP-4.5 and RCP-8.5.

City	EFLH type	Month	24 h data				12 h data			
			1983–2005	2006–2014	2015–2044 (RCP-4.5)	2015–2044 (RCP-8.5)	1983–2005	2006–2014	2015–2044 (RCP-4.5)	2015–2044 (RCP-8.5)
Hong Kong	Cooling	May	61	74	173	192	47	58	125	138
		June	216	236	259	259	155	177	180	180
		July	250	261	248	254	179	185	177	181
		August	245	259	249	252	174	183	171	174
		September	195	204	206	215	151	150	151	156
		October	63	76	84	98	54	64	70	81
		Total	1030	1110	1219	1270	760	817	874	910
Seoul	Cooling	June	37	52	71	84	32	45	60	70
		July	126	124	148	181	91	91	106	128
		August	162	182	193	227	123	140	143	163
		September	16	33	36	50	14	30	32	45
		Total	341	391	448	542	260	306	341	406
	Heating	January	220	218	217	215	111	111	104	103
		February	229	218	201	206	121	117	98	101
		March	166	164	164	165	83	83	74	75
		November	153	142	139	146	75	70	68	61
		December	194	207	208	189	102	99	99	100
		Total	962	949	929	921	492	480	443	440
Tokyo	Cooling	June	53	72	97	116	39	52	67	79
		July	210	250	280	300	137	161	175	186
		August	285	319	329	344	186	208	208	217
		September	119	147	179	215	83	99	116	136
		Total	667	788	885	975	445	520	566	618
	Heating	January	190	187	193	200	88	90	82	85
		February	189	181	183	175	87	86	77	73
		March	132	114	84	79	57	46	28	26
		November	32	24	14	16	10	7	3	3
		December	132	124	144	139	57	55	58	55
		Total	675	630	618	609	299	284	248	242

In the case of Hong Kong, considering the 24 h data, the number of cooling EFLH is highest in July for the past, present and future under scenario RCP-8.5, and in August for the future under scenario RCP-4.5. When considering the 12 h data, it is highest, again in July for all periods and scenarios. Based on both the 12 h and 24 h data, the number of cooling EFLH is least in either the starting or ending month of the cooling period, i.e., May for the past and present, and October for the future. For Seoul, in all cases, the cooling EFLH peak in August and are minimum in September, while the heating EFLH peak in February for the past and the present and in January for the future, and are minimum in November. As for Tokyo, for all time periods and according to both the 12 h and 24 h data, the number of cooling EFLH is greatest in August and least in June, and the number of heating EFLH highest in January and least in November.

For all three locations, it can be observed a tendency for the annual cooling EFLH (i.e., the sum of all monthly cooling EFLH over the cooling period) to increase from the past period to the present to the future, and for the annual heating EFLH (i.e., the sum of all monthly heating EFLH over the heating period) to decrease. Generally, for the future period, when scenario RCP-8.5 is applied, the increases in annual cooling EFLH and decreases in annual heating EFLH are greater than when scenario RCP-4.5 is applied. At the monthly level, no dominant trends can be observed due to month-to-month and city-to-city variations in the results.

5. Residential building energy consumption estimation

5.1. Validation of temperature bin-based EFLH method

In this section, the annual energy requirements for cooling and heating, on a per unit floor area basis, are estimated for representative residential dwellings in the three cities. The results are obtained by multiplying the EFLH data in Table 4 (E_c and E_h) with the maximum cooling and heating loads of the dwellings (Q_{DC} and Q_{DH}) according to Eqs. (3) and (4). The Hong Kong dwelling is selected from a case study by Bojic et al. [77], who gave its maximum cooling load per floor area as 0.12 kW/m^2. The Seoul dwelling is taken from another case study by Cho et al. [78]; its maximum cooling and heating loads per floor area are 0.08 and 0.1 kW/m^2, respectively. For Tokyo, a “representative” apartment is defined by averaging the heating and cooling design loads (on a per floor area basis) of a group of apartments in the city’s Shinjuku district, one of Japan’s busiest areas [79]. The apartment’s maximum cooling load, per unit of space, is 0.06 kW/m^2 and maximum heating load 0.08 kW/m^2.

Fig. 2 gives the estimated heating and cooling demands of the representative dwellings. Two sets of results are provided. One is derived from the 24 h EFLH data in Table 4, and the other from the 12 h data. (As explained above, switching between the two datasets allows for representation of different building types.) The results are consistent with published numbers obtained using building simulation modeling (as outlined in the following paragraph). This validates the accuracy of the EFLH data in Table 4, and substantiates the reliability of the EFLH method for estimating building heating and cooling loads. To the best of knowledge, the findings represent the first validation of EFLH data derived from the temperature bin-based method [12] against real buildings.

The 12 h data-based cooling demand for the Hong Kong dwelling for the past period in Fig. 2 (95.63 kWh/m^2) matches the estimate (94.04 kWh/m^2) of Bojic et al. [77] for the same property with an accuracy of 98%. Additionally, past estimates of residential building heating and cooling requirements for Seoul [80] and Tokyo [81] are close to the 12 h data-based results for the past and present periods in Fig. 2. The 24 h data-based cooling and/or heating demands for the present and future periods are close to previously reported values for non-residential buildings in Hong Kong [82], and residential buildings in Seoul [83]. (24 h EFLH data are usually applied to non-residential buildings, while 12 h data to

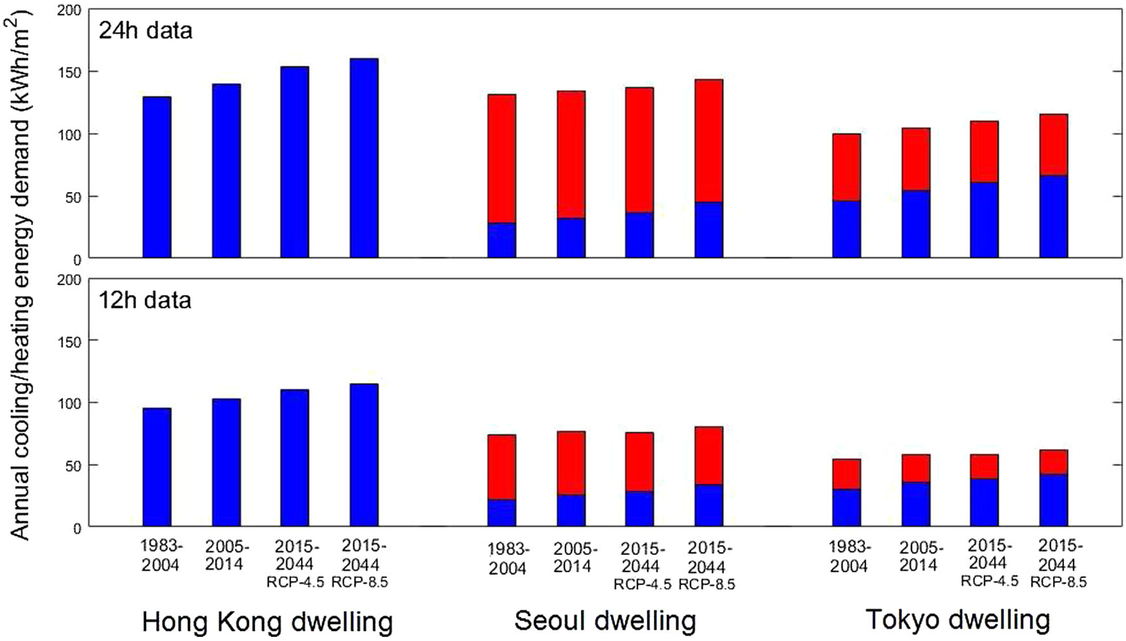

Fig. 2. Annual energy demands (in kWh/m^2) for cooling (blue) and heating (red) of representative residential dwellings in Hong Kong, Seoul and Tokyo for three time periods (past, present and future) estimated using 24 h (top) and 12 h (bottom) EFLH data. The results are based on the EFLH data in Table 4, and the maximum cooling and heating loads of the dwellings, and obtained by applying Eqs. (3) and (4).

residential buildings. However, this is not a strict rule depending on occupant behavior patterns.)

5.2. Projected changes in building heating and cooling loads due to climate change

Future changes in building cooling and heating energy depends on the complex interplay between multiple parameters including climate, building characteristics, and energy system setup and operation. However, considering the focus of this paper on human-induced climate change, the results in this section considers only the effects of changes in ambient temperature as projected by regional climate models.

For the dwelling in Hong Kong, Fig. 2 predicts a future increase in cooling energy demand if considering solely the effects of temperature change due to climate change. According to the 24 h data, it is predicted an 18.3% increase from 1983 to 2044 if scenario RCP-4.5 is true, and a 23.3% increase if scenario RCP-8.5 is true. According to the 12 h data, the respective increases are 15% and 19.7%. The results for the residential dwelling in Seoul show the required cooling energy to increase in the future but the required heating energy to decrease. However, the latter is insufficient to counterbalance the former and therefore, it can be expected a net increase in building heating and cooling energy, i.e. by 4% under scenario RCP-4.5, and 9.3% under scenario RCP-8.5 considering the 24 h data, and by 2% and 8.7% respectively considering the 12 h data. Similarly, in the case of the Tokyo dwelling, as presented in Fig. 2, it is forecasted a net future increase in the combined demand for cooling and heating energy even though the demand for heating alone is expected to decrease. Based on the 24 h data, it is predicted an increase in total energy load of 10.4% over 62 years from 1983 to 2044 given scenario RCP-4.5, and 15.8% given scenario RCP-8.5; based on the 12 h data the increases are 7.7% and 13.3%, respectively.

In summary, Hong Kong can be expected to witness a higher percent increase in building energy consumption for temperature control in the future due to climate change. This is because of the warmer weather there that makes the demand for heating relatively insignificant compared to Seoul and Tokyo, and thus, the city's low potential for any substantial offset of the future increase in cooling energy by a reduction in heating energy. The results for Seoul and Tokyo exhibit similar trends. In both cities, it can be expected an increase in the future demand for cooling energy and a decrease for heating energy such that the total demand will rise but the rise, in terms of percentage, will be smaller than in Hong Kong. Note also that of the three dwellings, the Tokyo one consumes the least energy on the overall. This has been attributed to behavioral and cultural preferences in Tokyo, where residents often cool or heat only parts of their apartments, or seek alternative sources of thermal comfort [24].

The trends forecasted here of future increases in cooling energy use and decreases in heating energy use in buildings are in line with predictions for other cities around the world [40]. Specifically for Hong Kong, residential cooling energy use has been projected to increase in the future by up to approximately 25% [47,48], which is in range with the results of this present study. For Seoul, similar to this present study, it has also been projected by [60] an increase in building cooling energy and a decrease in building heating energy. As for Tokyo, there is a lack of studies of this kind to compare the results here against. The previous studies cited were conducted using either the degree-days method or building energy simulation techniques [40]. This present study, however, has taken an alternative approach and is the first effort to use EFLH data based on temperature bins to predict future building energy trends. The temperature bin-based EFLH approach offers the benefit of a simplified method that despite its ease of use, is reliable and capable of accommodating different building types and occupation patterns.

5.3. Energy and environmental policy implications

In this section, based on the results in Fig. 2, implications of the predicted climate change induced future increases in energy consumption for primary energy supply and GHG emissions are quantified and discussed. To do so, the energy sources for residential cooling and/or heating in the three cities are considered. At this point it, should be noted that while the "representative" apartment in Tokyo is based on the design loads and floor areas of a number of apartments in the city's Shinjuku district which is served by the Shinjuku District heating and cooling system (DHC) [84], for subsequent calculations, it is treated as a typical Tokyo apartment with energy sources similar to averages for the city as a whole. This is an appropriate assumption given the city-level scope of this section.

The energy implications of the trends of increasing cooling loads and in most cases, decreasing heating loads with time are important for formulating effective energy policies for the future. As cooling energy in the three cities is mostly provided by electricity, it is expected that the demand for it will rise, and as heating energy is provided mostly by direct use of fossil fuels, their demand will fall. In addition, should the penetration of heat pumps in the Korean and Japanese markets increase [85], the use of electricity can be expected to increase even further. As electricity becomes more important, changes to its fuel mix in future decades can play a significant role in managing the environmental effects of increased energy use for temperature control. Table 5 summarizes

Table 5
Current electricity fuel mixes of Hong Kong, South Korea and Japan, and suggested future percentages; the source or generation method with the highest percentage in each row is bolded.

Country	Period	Gas	Oil	Nuclear	Coal	Renewables	Others	Source
Hong Kong	Current	22%		23%	**53%**	2%[a]		[86]
	Future	**60%**		20%	20%[a,b]			
South Korea	Current	22%	4%[c]	30%	**44%**			[88,89]
	Future	24.7%	4.2%	18.5%	**32.2%**	4.6%	15.8%[d]	
Japan	Current	**43.2%**	13.7%	1%	30.3%	10.7%[e]	1.1%	[91]
	Future	**27%**	1%	20–22%	26%	22–24%[f]		

[a] Mostly solar and wind.
[b] 20% shared between coal and renewable sources.
[c] 4% shared between oil and renewable sources.
[d] Includes 5.8% from combined heat and power (CHP).
[e] Mostly hydroelectric.
[f] Mostly hydroelectric, solar, wind and geothermal.

the current electricity fuel mixes of Hong Kong, South Korea and Japan, together with targeted future adjustments [86].

In Hong Kong, the heating energy demand is relatively insignificant and thus, not explicitly considered in this study. Currently, Hong Kong's main electricity fuel source is coal, followed by natural gas, then nuclear power. For the future, the government has proposed adjusting the fuel mix to reduce the city's GHG emissions. One of the suggested options is to significantly increase the percentage of natural gas and slightly reduce that of nuclear [86]. In Seoul, heating in residential apartments is primarily supplied by gas and secondarily by electricity [20]. Gas is the main energy source of Ondol, a traditional Korean underfloor heating system which remains popular until today [87]. Nationwide, approximately two-thirds of electricity comes from coal and gas, and one-third from nuclear [88]. Recent governmental plans for a 2030 mix included a further increase in the use of nuclear, but latest updates have adjusted the percentage of nuclear back to the original level, and instead, increased the percentages of gas and renewables [89]. In Japan, almost 60% of residential heating is supplied by petroleum products, a quarter by electricity, and the remaining by gas [90]. Electricity in the country is generated mostly from natural gas and coal. The percentage of nuclear energy is now much smaller than in previous years because of the Fukushima disaster in 2011. However, the government is targeting a new mix by 2030 which will return the percentage of nuclear back to near the pre-Fukushima value (though this can be expected to spark controversy considering the Fukushima disaster), and increase the utilization of renewables [91].

The energy generation efficiencies of different power plants and fuel types are relevant too when estimating the environmental implications of increased building heating and cooling loads. Depending on data availability, country-specific efficiency levels [92] or world averages [93] are used. To calculate additional total GHG emission due to the increased loads, the emissions from direct combustion of fossil fuels in buildings and from electricity generation [94,95] are considered. Fig. 3 below shows the additional annual primary energy supplies that would be needed and the additional GHG emissions that would be generated from the projected increases in the energy loads of the three representative dwellings (as given in Fig. 2). The results represent the additional primary energy supplies and GHG emissions in 2044 over 2014 levels. Results based on both the 24 h and 12 h EFLH data are provided, and are for four scenarios: (i) scenario S1, which assumes the climate scenario RCP-4.5 is true and which applies the current electricity fuel mixes of the three cities; (ii) scenario S2, which assumes RCP-8.5 is true and which applies the current fuel mixes; (iii) scenario S3, which assumes RCP-4.5 is true and which applies the targeted future electricity fuel mixes of the three cities; and finally (iv) scenario S4, which assumes RCP-8.5 is true and which applies the future fuel mixes. Note that in the calculations, the ratios of electricity to fossil fuels (for direct combustion) for building heating and cooling are fixed at current values, and it is only the future changes in the electricity fuel mixes that are considered.

Based on both the 24 h and 12 h data, under all scenarios S1–S4, on a per unit area basis, it is the Hong Kong dwelling that will require the largest increase in primary energy supply and that will release the most new GHG emissions. This is driven by increases in Hong Kong's 24 h and 12 h EFLH from 2014 to 2044 which are larger than Tokyo's and Seoul's. It is also evident that switching from scenarios S1 and S2 to scenarios S3 and S4 reduces the GHG emissions of all three cities. For Hong Kong and Seoul, switching to the new target mixes also reduces the required primary energy. Whether switching from scenario S1 to S3 or from scenario S2 to S4, for the Hong Kong dwelling, the percent reduction is approximately 1.3%. For the Seoul dwelling, the percent reduction is 24% when switching from scenario S1 to S3, and 20% when switching from scenario S2 to S4. The reductions are due to the smaller percentages of coal and higher percentages of gas in the new mixes.

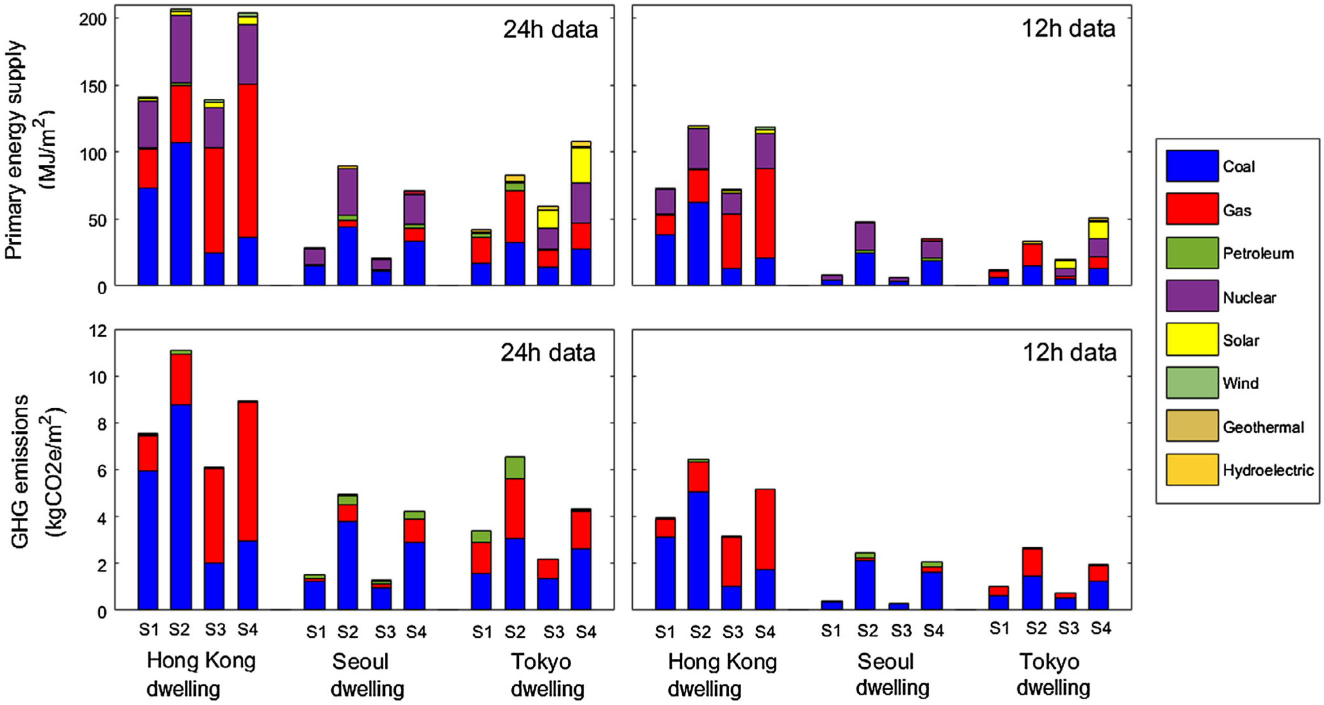

Fig. 3. Additional annual primary energy supplies (top row) and GHG emissions (bottom row) required to satisfy the projected increases in the energy demands for the cooling and/or heating of the three representative residential dwellings in Hong Kong, Seoul and Tokyo in 2044 over 2014 levels. The results are based on 24 h EFLH (left column) and 12 h EFLH (right column) data and are for scenarios S1 to S4. The results show the breakdowns of the additional primary energy supplies and GHG emissions by source.

Table 6
Percentages of the projected increases in the three representative dwellings' cooling energy demands that can be counterbalanced by switching from AC models with the current minimum or average EER to models with the maximum EER in each market.

City	EFLH data type	Future climate scenario	Additional cooling energy demand (kWh/m^2)	Baseline EER (W/W)	Maximum EER (W/W)	Offset of additional cooling energy demand (%)
Hong Kong	24 h data	RCP-4.5	13.71	Minimum: 2.03	6.6	100
			13.71	Average: 3.12		100
		RCP-8.5	20.13	Minimum: 2.03	6.6	100
			20.13	Average: 3.12		83.7
	12 h data	RCP-4.5	7.17	Minimum: 2.03	6.6	100
			7.17	Average: 3.12		100
		RCP-8.5	11.70	Minimum: 2.03	6.6	100
			11.70	Average: 3.12		100
Seoul	24 h data	RCP-4.5	4.70	Minimum: 3.05	5.73	72.7
			4.70	Average: 3.78		42.7
		RCP-8.5	12.45	Minimum: 3.05	5.73	33.2
			12.45	Average: 3.78		19.5
	12 h data	RCP-4.5	2.97	Minimum: 3.05	5.73	87.9
			2.97	Average: 3.78		51.6
		RCP-8.5	8.25	Minimum: 3.05	5.73	37.5
			8.25	Average: 3.78		22
Tokyo	24 h data	RCP-4.5	6.63	Minimum: 2.37	6.67	100
			6.63	Average: 4.10		86.2
		RCP-8.5	12.78	Minimum: 2.37	6.67	100
			12.78	Average: 4.10		49.3
	12 h data	RCP-4.5	3.14	Minimum: 2.37	6.67	100
			3.14	Average: 4.10		100
		RCP-8.5	6.69	Minimum: 2.37	6.67	100
			6.69	Average: 4.10		59.6

(Gas-fired power stations have efficiency rates close to coal-fired plants, but the combustion of gas leads to emissions with lower global warming potential than coal.) In the case of the Tokyo dwelling, switching to the new target mix increases the required amount of primary energy. This is because in the new mix, the percentages of all fossil fuels are reduced, while the percentages of nuclear and renewables increased. (Generally, nuclear and renewable energy plants have lower efficiency rates than fossil fuel-fired ones.) This increase in the required primary energy supply is despite the accompanying reduction in GHG emissions. In fact, the expected percent reduction in Tokyo's GHG emissions is largest (approximately 35%), compared to Hong Kong's (19.5%) and Seoul's (approximately 15%). The results apply whether switching from scenario S1 to S3 or scenario S2 to S4. The predicted reduction in GHG emissions for the Hong Kong dwelling meets the governmental target of a 19–33% decrease from 2005 emissions by 2020 [86]. However, the reduction for the Seoul dwelling is only about half the national target of a 30% cut by 2020 [96]. In contrast, the predicted reduction for the Tokyo dwelling exceeds the national target of a 26% decrease by 2030 [97].

5.4. Role of appliance energy efficiency standards

To rapidly counterbalance the expected rises in energy consumption (and ensuing GHG emissions) for building cooling and heating in the three cities due to climate change, appropriate measures need be employed. While improving energy generation efficiencies on the supply side can be expected to lead to reductions in the long term, for more immediate results, improvements in demand side efficiencies are imperative. To this end, higher energy efficiency standards of domestic appliances and incentives to encourage modifications in consumer energy behaviors when using them are recommended. It has been estimated energy-related behavioral changes to have the potential to yield reductions in energy use from 20% [98] up to 50% [99]. Thus, given that it will be the increases in cooling energy demand that will dominate, a key product to target for energy reductions are AC devices.

In this section, the potential of stricter energy efficiency standards for domestic ACs to counterbalance the projected increases in cooling energy demands of the three representative dwellings over the next 30 years is quantified. The calculations are made following Eq. (5) given the EFLH data in Table 4. The results are obtained considering the increases in cooling EFLH from the present to the future periods, and assuming typical AC efficiencies based on existing models in the Hong Kong, Korean and Japanese markets [100,101]. To obtain the results, the Hong Kong, Seoul and Tokyo dwellings are assumed equipped with ACs with the total cooling capacities of 0.078 kW/m^2, 0.049 kW/m^2 and 0.068 kW/m^2 respectively based on the sizes of the dwellings [102], which are as follows: the Hong Kong dwelling is 44.66 m^2, the Seoul dwelling 200 m^2 and the Tokyo dwelling 59.7 m^2. Note that as the Tokyo dwelling is defined by averaging the design loads of a number of apartments, its size is taken as the average size of apartments in Tokyo [103].

Table 6 shows the percentages of the projected climate change-driven increases in the three dwellings' energy use that can be offset by switching from AC units with the current minimum or average EER to units with the maximum EER available, which differs from location to location. The results show that for all three cities, a simple change from using AC models of minimum or average efficiency to models that are most efficient would significantly counterbalance the projected increases in cooling energy. For the Hong Kong dwelling, in all scenarios considered except one, the additional demand for energy would be fully offset. As for the Tokyo dwelling, switching from the minimum efficiency to the maximum would also fully offset the expected increase in cooling energy use, though switching from the average to the maximum would offset it by only 49.3–100% depending on the future climate scenario and EFLH data type (12 or 24 h) assumed. For the Seoul dwelling, switching to the most efficient model would lead to an offset of 19.5–87.9%. These offsets can be immediately realized as models with the assumed maximum EERs are already available, but will require behavioral modifications on the part of consumers. To encourage residential users to switch to more efficient models, proper implementation of appropriate policy tools, e.g. incentive and reward programs is essential.

6. Conclusions

The EFLH method offers a simplified and straightforward means of estimating energy demands for building cooling and heating. The method requires minimal resources and computational power, and can assist decision makers develop location-specific energy solutions. However, to date, easily accessible tabulated EFLH data exist only for very few locations in North America and Europe. In Asia, where there are numerous large and high energy consuming cities, EFLH data are non-existent. This paper aims at filling this gap by providing for the first time tabulated monthly EFLH data for three large Asian cities, namely Hong Kong, Tokyo and Seoul. The EFLH data are calculated from location-specific temperature bin and solar radiation data following the temperature bin-based EFLH method [12]. The EFLH values are useful for predicting building cooling and heating demands by simply multiplying the values with a building's design cooling and heating loads. Further, comparing the EFLH data for different time periods, as done in this study, yields valuable insights into the impacts of climate change on building energy consumption.

For the three cities of interest, this paper presents monthly and annual EFLH values calculated from temperature bin data for three different periods: past (1983–2005), present (2006–2014) and future (2015–2044). The future temperature bins are based on temperature projections obtained from regional climate models of CORDEX-East Asia for two future emission scenarios, the RCP-4.5 scenario which assumes the successful employment of strategies to reduce GHG emissions, and the RCP-8.5 scenario which assumes the continuous increase of GHG emissions with time. For each city, the EFLH data are used to assess the annual cooling and/or heating demands of a representative residential dwelling for the three time periods.

The implications of the projections are also quantified and discussed. From analyses of the results, the following conclusions can be drawn:

(1) In Hong Kong, the cooling EFLH are predicted to peak in July for all cases; the only exception is the future period under scenario RCP-4.5 when 24 h data are considered, where they peak in August. The cooling EFLH of the city are expected to be lowest in May for the past and present, but October for the future. In Seoul, in all cases, the maximum cooling EFLH occur in August and the minimum in September, while the maximum heating EFLH in February (past, present) or January (future), and the minimum in November. As for Tokyo, the number of cooling EFLH is highest in August and least in June, while the number of heating EFLH is highest in January and least in November. This is true for all three time periods and both future climate scenarios.

(2) At the annual level, for all three cities, total cooling EFLH are predicted to increase from the past time period to the future, while total heating EFLH to decrease. It is also predicted the magnitudes of the changes to be greater under the future scenario RCP-8.5 than under RCP-4.5.

(3) On the overall, the increases in cooling EFLH outweigh the decreases in heating EFLH such that the total energy demands of the three representative dwellings for cooling and heating combined show an increasing trend from the past time period to the present, and onwards to the future. Depending on the future climate scenario and EFLH data type (12 or 24 h) assumed, the energy demand of the Hong Kong dwelling is expected to grow by 15–23.3%, the Seoul dwelling by 2–9.3%, and the Tokyo dwelling by 7.7–15.8%. Thus, as cooling is mostly by electricity (as opposed to direct combustion of fossil fuels), it can be expected the dependence on electricity and consequently, the significance of future electricity mix policies to rise in the future. This is even more true considering the growing use of heat pumps in Japan and Korea.

(4) The predicted increases in energy demands are expected to lead to additional GHG emissions and consumption of primary energy, even after adjusting the electricity fuel mixes of the cities to new percentages targeted by current governmental plans. The predicted additional amounts of primary energy and GHG emissions, in terms of percentage, for the Hong Kong dwelling are the largest among the three cities. The results (see Fig. 3) predict that moving from the current to the target fuel mixes will reduce GHG emissions by 19% in the case of the Hong Kong dwelling, 15% Seoul dwelling and 35% Tokyo dwelling, and primary energy demand of the Hong Kong dwelling by 1.3% and the Seoul dwelling 22%. (For the Tokyo dwelling, the target mix is predicted to increase primary energy demand.)

(5) To immediately offset the additional energy demands, adoption of AC devices with higher energy efficiencies is recommended. Based on the estimates in Table 6, it is shown that switching from devices with the minimum or average efficiency to devices with the maximum efficiency is in most scenarios sufficient to fully offset the additional cooling energy that will be needed by the Hong Kong dwelling. Switching to the maximum efficiency is predicted lead to offsets of 19.5–87.9% and 49.3–100% in the cases of the Seoul and Tokyo dwellings respectively. These changes are technically feasible as AC models with the required efficiencies are already available. However, to improve the adoption of higher EER devices, policies to encourage consumer behavioral changes are necessary.

This paper has demonstrated that, even after accounting for the possibility of reductions in GHG emissions that is likely only possible in the long term (as per scenario RCP-4.5), the energy required for the cooling and heating of residential buildings (which surpass non-residential buildings in energy consumption) can be expected to still increase in the short term. This in turn will lead to increased primary energy use and further GHG emissions. As the time before these changes will take effect is not long, quick action leading to immediate reductions in energy demand and GHG emissions is key. Thus, without neglecting efforts to advance energy supply side technologies, a stronger focus on demand side management, including programs to rapidly transform consumer energy behaviors is strongly recommended.

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Appendix A

See Tables A.1–A.8 for monthly temperature bin, $N_{bin,i}$ values (hours per month) in six daily 4-h intervals for cooling and heating months in Seoul and Tokyo for the three time periods examined in this study.

Table A.1
Monthly $N_{bin,i}$ values (hours per month) in six daily 4-h intervals for the past (1983–2005) and present (2006–2014) periods for months in the cooling season Seoul.

	$N_{bin,i}$ values in six daily 4-hour intervals															
	Past period (1983–2005)								Present period (2006–2014)							
Month	Temperature range (°C)	1:00 – 4:59	5:00 – 8:59	9:00 – 12:59	13:00 – 16:59	17:00 – 20:59	21:00 – 00:59	Total	Temperature range (°C)	1:00 – 4:59	5:00 – 8:59	9:00 – 12:59	13:00 – 16:59	17:00 – 20:59	21:00 – 00:59	Total
June	18/20	28	29	9	1	5	17	89	19/21	30	31	10	1	5	20	97
	20/22	30	28	22	6	16	32	134	2/23	28	26	24	7	18	33	136
	22/24	15	13	31	21	31	26	137	2/25	12	11	31	25	33	23	135
	24/26	5	4	22	38	28	10	107	25/27	4	3	19	38	26	8	98
	26/28	1	1	8	23	11	3	47	27/29	1	1	6	19	9	2	38
July	21.9/23.9	34	34	16	4	11	26	125	22/24	34	34	18	5	12	28	131
	23.9/25.9	28	25	33	19	30	35	170	24/26	26	24	34	21	32	34	171
	25.9/27.9	10	9	29	40	34	18	140	26/28	9	8	27	40	33	16	133
	27.9/29.9	2	2	10	25	14	5	58	28/30	2	2	9	22	13	4	52
August	22.4/24.4	35	34	13	1	7	27	117	23/25	35	34	15	2	8	30	124
	24.4/26.4	24	20	29	8	23	35	139	25/27	21	18	31	10	26	34	140
	26.4/28.4	8	6	31	31	36	17	129	27/29	6	5	30	36	36	15	127
	28.4/30.4	2	1	14	39	21	4	81	29/31	1	1	12	36	18	3	71
September	16.9/18.9	29	30	9	1	4	20	93	17.8/19.8	30	30	10	1	5	21	97
	18.9/20.9	26	23	21	4	14	31	119	19.8/21.8	25	22	22	4	16	32	121
	20.9/22.9	12	10	29	16	28	23	118	21.8/23.8	10	9	29	17	30	22	117
	22.9/24.9	4	3	22	35	29	9	102	23.8/25.8	3	3	21	37	28	8	100
	24.9/26.9	1	1	9	29	14	3	57	25.8/27.8	1	1	8	27	12	2	51

Table A.2
Monthly $N_{bin,i}$ values (hours per month) in six daily 4-h intervals for the future (2015–2044) period for months in the cooling season in Seoul under scenarios RCP-4.5 and RCP-8.5.

	$N_{bin,i}$ values in six daily 4-hour intervals															
	Future period (2015–2044), scenario RCP-4.5								Future period (2015–2044), scenario RCP-4.5							
Month	Temperature range (°C)	1:00 – 4:59	5:00 – 8:59	9:00 – 12:59	13:00 – 16:59	17:00 – 20:59	21:00 – 00:59	Total	Temperature range (°C)	1:00 – 4:59	5:00 – 8:59	9:00 – 12:59	13:00 – 16:59	17:00 – 20:59	21:00 – 00:59	Total
June	19.2/21.2	28	30	8	1	4	17	88	19.5/21.5	28	30	8	1	4	17	88
	21.2/23.2	31	29	22	5	15	33	135	21.5/23.5	32	29	22	5	15	33	136
	23.2/25.2	15	13	32	20	32	27	139	23.5/25.5	15	13	32	20	32	27	139
	25.2/27.2	4	4	22	39	30	10	109	25.5/27.5	4	4	22	40	30	10	110
	27.2/29.2	1	1	7	24	11	2	46	27.5/29.5	1	1	7	24	11	2	46
July	22.3/24.3	34	35	16	4	11	27	127	22.9/24.9	35	35	16	4	11	27	128
	24.3/26.3	28	25	34	19	31	35	172	24.9/26.9	28	25	34	19	31	36	173
	26.3/28.3	10	8	28	40	34	17	137	26.9/28.9	9	8	29	41	35	17	139
	28.3/30.3	2	2	10	24	14	4	56	28.9/30.9	2	2	10	24	14	4	56
August	22.9/24.9	35	35	12	1	6	26	115	23.4/25.4	36	36	12	1	6	26	117
	24.9/26.9	25	21	29	7	22	36	140	25.4/27.4	25	22	29	7	22	37	142
	26.9/28.9	8	7	32	30	37	18	132	27.4/29.4	8	6	33	30	37	18	132
	28.9/30.9	2	1	15	41	23	5	87	29.4/31.4	2	1	15	41	23	4	86
September	17.7/19.7	29	30	8	1	4	18	90	18.3/20.3	30	31	8	1	3	18	91
	19.7/21.7	27	24	20	3	13	32	119	20.3/22.3	28	25	20	3	13	32	121
	21.7/23.7	13	10	29	14	28	25	119	22.3/24.3	12	10	30	13	28	25	118
	23.7/25.7	4	3	24	35	30	10	106	24.3/26.3	4	3	24	35	31	10	107
	25.7/27.7	1	1	9	31	15	3	60	26.3/28.3	1	1	9	31	15	3	60

Table A.3
Monthly $N_{\text{bin},i}$ values (hours per month) in six daily 4-h intervals for the past (1983–2005) and present (2006–2014) periods for months in the heating season in Seoul.

Month	$N_{\text{bin},i}$ values in six daily 4-hour intervals															
	Past period (1983–2005)								Present period (2006–2014)							
	Temperature range (°C)	1:00 – 4:59	5:00 – 8:59	9:00 – 12:59	13:00 – 16:59	17:00 – 20:59	21:00 – 00:59	Total	Temperature range (°C)	1:00 – 4:59	5:00 – 8:59	9:00 – 12:59	13:00 – 16:59	17:00 – 20:59	21:00 – 00:59	Total
January	−6.3/−4.3	17	16	11	3	8	17	72	−6.1/−4.1	17	16	11	3	8	17	72
	−4.3/−2.3	14	12	15	7	13	18	79	−4.1/−2.1	13	12	16	7	13	18	79
	−2.3/−0.3	9	8	17	12	17	14	77	−2.1/−0.1	8	7	17	13	17	14	76
	−0.3/1.7	5	4	15	18	18	9	69	−0.1/1.9	5	4	15	19	18	9	70
February	−3.9/−1.9	19	18	11	2	7	18	75	−3/−1	19	18	11	2	7	18	75
	−1.9/0.1	15	13	16	5	13	20	82	−1/1	14	13	16	6	13	20	82
	0.1/2.1	9	8	18	12	18	16	81	1/3	9	7	19	12	19	15	81
	2.1/4.1	5	4	17	19	20	10	75	3/5	4	4	17	20	20	9	74
	4.1/ 6.1	2	2	11	22	16	5	58	5/7	2	2	11	23	15	5	58
March	1.5/3.5	20	20	10	2	6	18	76	1.6/3.6	20	20	11	2	7	18	78
	3.5/5.5	17	15	16	5	13	21	87	3.6/5.6	17	15	16	5	13	21	87
	5.5/7.5	10	9	20	12	19	17	87	5.6/7.6	10	9	20	12	19	17	87
	7.5/9.5	5	5	18	21	21	11	81	7.6/9.6	5	4	18	21	21	10	79
	9.5/11.5	2	2	12	24	16	5	61	9.6/11.6	2	2	12	24	16	5	61
November	3/5	21	21	10	2	7	18	79	3.7/5.7	22	21	11	2	7	19	82
	5/7	18	17	17	6	13	22	93	5.7/7.7	18	16	18	6	14	22	94
	7/9	11	10	21	13	20	18	93	7.7/9.7	11	9	21	14	21	18	94
	9/11	6	5	19	23	22	11	86	9.7/11.7	5	4	18	24	22	10	83
	11/13	2	2	12	24	16	5	61	11.7/13.7	2	2	11	24	15	5	59
December	−3.1/−1.1	18	17	12	4	9	18	78	−4.4/−2.4	18	18	11	3	7	17	74
	−1.1/0.9	13	12	17	8	15	18	83	−2.4/−0.4	15	14	15	6	13	19	82
	0.9/2.9	8	7	18	15	19	14	81	−0.4/1.6	10	9	18	12	18	16	83
	2.9/4.9	4	4	15	21	18	8	70	1.6/3.6	6	5	16	19	19	10	75

Table A.4
Monthly $N_{\text{bin},i}$ values (hours per month) in six daily 4-h intervals for the future (2015–2044) period for months in the heating season in Seoul under scenarios RCP-4.5 and RCP-8.5.

Month	$N_{\text{bin},i}$ values in six daily 4-hour intervals															
	Future period (2015–2044), scenario RCP-4.5								Future period (2015–2044), scenario RCP-8.5							
	Temperature range (°C)	1:00 – 4:59	5:00 – 8:59	9:00 – 12:59	13:00 – 16:59	17:00 – 20:59	21:00 – 00:59	Total	Temperature range (°C)	1:00 – 4:59	5:00 – 8:59	9:00 – 12:59	13:00 – 16:59	17:00 – 20:59	21:00 – 00:59	Total
January	−6/−4	17	17	10	3	7	16	70	−5.8/−3.8	18	17	10	3	7	16	71
	−4/−2	15	13	15	6	12	18	79	−3.8/−1.8	15	13	15	6	12	18	79
	−2/0	10	8	17	11	17	15	78	−1.8/0.2	10	8	17	11	17	15	78
	0/2	6	5	16	18	18	10	73	0.2/2.2	5	5	16	18	18	10	72
February	−3.9/−1.9	19	18	11	2	7	18	75	−4.4/−2.4	19	18	11	2	7	18	75
	−1.9/0.1	15	13	16	5	13	19	81	−2.4/−0.4	15	13	16	6	13	19	82
	0.1/2.1	9	8	18	12	18	16	81	−0.4/1.6	9	8	18	12	18	15	80
	2.1/4.1	5	4	17	19	20	9	74	1.6/3.6	5	4	16	19	19	9	72
	4.1/6.1	2	2	11	22	15	5	57	3.6/5.6	2	2	11	22	15	5	57
March	1.3/3.3	20	20	10	3	7	16	76	1.2/3.2	20	20	10	3	7	16	76
	3.3/5.3	20	19	16	7	13	21	96	3.2/5.2	20	19	16	7	13	21	96
	5.3/7.3	14	13	21	15	20	19	102	5.2/7.2	14	13	21	15	20	19	102
	7.3/9.3	8	7	19	22	21	13	90	7.2/9.2	8	7	19	22	21	13	90
	9.3/11.3	4	3	12	22	16	6	63	9.2/11.2	4	3	12	22	16	6	63
November	4/6	22	21	11	2	7	18	81	3.5/5.5	22	21	11	2	7	18	81
	6/8	18	17	17	6	14	23	95	5.5/7.5	18	17	17	6	14	22	94
	8/10	11	10	21	13	21	18	94	7.5/9.5	11	10	21	14	21	18	95
	10/12	5	4	19	23	22	10	83	9.5/11.5	5	5	18	23	22	10	83
	12/14	2	2	11	25	16	5	61	11.5/13.5	2	2	11	24	16	5	60
December	−2.5/−0.5	18	17	13	4	9	18	79	−2.7/−0.7	18	17	13	4	9	18	79
	0.5/1.5	13	12	17	8	15	18	83	−0.7/1.3	13	12	17	8	15	18	83
	1.5/3.5	8	7	18	15	19	14	81	1.3/3.3	8	7	18	15	19	14	81
	3.5/5.5	4	4	15	21	18	8	70	3.3/5.3	4	4	15	21	18	8	70
	55/7.5	2	2	9	20	13	4	50								

Table A.5
Monthly $N_{\mathrm{bin},i}$ values (hours per month) in six daily 4-h intervals for the past (1983–2005) and present (2006–2014) periods for months in the cooling season in Tokyo.

	$N_{\mathrm{bin},i}$ values in six daily 4-hour intervals															
	Past period (1983–2005)								Present period (2006–2014)							
Month	Temperature range (°C)	1:00 – 4:59	5:00 – 8:59	9:00 – 12:59	13:00 – 16:59	17:00 – 20:59	21:00 – 00:59	Total	Temperature range (°C)	1:00 – 4:59	5:00 – 8:59	9:00 – 12:59	13:00 – 16:59	17:00 – 20:59	21:00 – 00:59	Total
June	19.1/21.1	31	32	17	6	13	26	125	19.8/21.8	33	33	19	7	14	28	134
	21.1/23.1	27	25	32	22	30	32	168	21.8/23.8	25	23	33	24	32	32	169
	23.1/25.1	11	10	26	37	31	17	132	23.8/25.8	9	8	25	37	30	15	124
	25.1/27.1	3	3	10	22	14	5	57	25.8/27.8	2	2	9	20	12	4	49
July	22.9/24.9	36	35	17	4	11	29	132	23.8/25.8	37	36	18	4	11	31	137
	24.9/26.9	24	22	34	18	31	35	164	25.8/27.8	23	21	35	19	33	35	166
	26.9/28.9	8	6	28	41	34	15	132	27.8/29.8	7	6	27	43	34	14	131
	28.9/30.9	2	1	9	25	14	4	55	29.8/31.8	1	1	8	24	12	3	49
August	24.5/26.5	37	36	16	2	9	31	130	25.3/27.3	38	36	17	2	9	33	135
	26.5/28.5	21	17	33	11	29	35	146	27.3/29.3	19	16	34	12	30	35	146
	28.5/30.5	5	4	30	40	37	13	129	29.3/31.3	5	4	29	42	37	12	129
	30.5/32.5	1	1	10	34	16	3	65	31.3/33.3	1	1	9	33	15	2	61
September	21.1/23.1	34	34	19	6	13	29	135	21.6/23.6	34	35	18	5	12	28	132
	23.1/25.1	25	22	34	23	32	33	169	23.6/25.6	26	23	34	21	32	34	170
	25.1/27.1	8	7	25	39	31	15	125	25.6/27.6	9	8	27	40	33	16	133
	27.1/29.1	2	2	9	21	12	4	50	27.6/29.6	2	2	9	22	13	4	52

Table A.6
Monthly $N_{\mathrm{bin},i}$ values (hours per month) in six daily 4-h intervals for the future (2015–2044) period for months in the cooling season in Tokyo under scenarios RCP-4.5 and RCP-8.5.

	$N_{\mathrm{bin},i}$ values in six daily 4-hour intervals															
	Future period (2015–2044), scenario RCP-4.5								Future period (2015–2044), scenario RCP-8.5							
Month	Temperature range (°C)	1:00 – 4:59	5:00 – 8:59	9:00 – 12:59	13:00 – 16:59	17:00 – 20:59	21:00 – 00:59	Total	Temperature range (°C)	1:00 – 4:59	5:00 – 8:59	9:00 – 12:59	13:00 – 16:59	17:00 – 20:59	21:00 – 00:59	Total
June	20.1/22.1	31	32	15	5	10	24	117	20.6/22.6	32	32	15	4	10	24	117
	22.1/24.1	29	27	32	19	28	35	170	22.6/24.6	30	28	32	19	29	35	173
	24.1/26.1	12	11	29	38	34	20	144	24.6/26.6	12	11	29	38	34	20	144
	26.1/28.1	3	3	12	25	16	6	65	26.6/28.6	3	3	11	25	15	6	63
July	24.1/26.1	37	37	15	3	9	28	129	24.5/26.5	37	37	15	2	9	28	128
	26.1/28.1	27	24	34	15	30	37	167	26.5/28.5	27	24	34	15	30	38	168
	28.1/30.1	8	7	30	42	37	16	140	28.5/30.5	8	7	31	43	38	16	143
	30.1/32.1	2	1	10	29	15	4	61	30.5/32.5	2	1	10	29	15	4	61
August	25.1/27.1	38	38	14	1	7	29	127	25.4/27.4	39	38	14	1	6	29	127
	27.1/29.1	24	20	32	8	26	38	148	27.4/29.4	24	20	32	8	26	38	148
	29.1/31.1	6	5	33	37	39	16	136	29.4/31.4	6	5	33	37	40	16	137
	31.1/33.1	1	1	12	39	19	3	75	31.4/33.4	1	1	12	39	19	3	75
September	22/24	34	35	16	4	10	26	125	22.8/24.8	35	35	15	4	10	26	125
	24/26	28	26	33	19	30	36	172	24.8/26.8	29	26	34	18	31	37	175
	26/28	10	9	29	40	35	18	141	26.8/28.8	10	8	30	42	36	18	144
	28/30	2	2	10	25	14	5	58	28.8/30.8	2	2	10	25	14	4	57

Table A.7
Monthly $N_{\mathrm{bin},i}$ values (hours per month) in six daily 4-h intervals for the past (1983–2005) and present (2006–2014) periods for months in the heating season in Tokyo.

Month	$N_{\mathrm{bin},i}$ values in six daily 4-hour intervals															
	Past period (1983–2005)								Present period (2006–2014)							
	Temperature range (°C)	1:00–4:59	5:00–8:59	9:00–12:59	13:00–16:59	17:00–20:59	21:00–00:59	Total	Temperature range (°C)	1:00–4:59	5:00–8:59	9:00–12:59	13:00–16:59	17:00–20:59	21:00–00:59	Total
January	2.5/4.5	20	19	11	2	7	19	78	2.6/4.6	19	18	12	2	8	20	79
	4.5/6.5	15	13	17	5	14	21	85	4.6/6.6	14	12	17	6	14	20	83
	6.5/8.5	8	7	20	12	20	16	83	6.6/8.6	8	7	20	13	20	15	83
	8.5/10.5	4	3	17	21	21	9	75	8.6/10.6	4	3	17	22	20	8	74
February	2.9/4.9	21	20	12	2	7	20	82	3.2/5.2	21	20	12	2	8	21	84
	4.9/6.9	16	14	18	5	14	22	89	5.2/7.2	15	13	18	6	15	22	89
	6.9/8.9	8	7	21	13	21	16	86	7.2/9.2	8	7	21	14	22	15	87
	8.9/10.9	4	3	18	23	22	9	79	9.2/11.2	4	3	17	24	21	8	77
March	5.5/7.5	22	22	12	3	8	19	86	6.1/8.1	23	22	11	2	7	19	84
	7.5/9.5	18	17	19	8	16	23	101	8.1/10.1	19	18	19	7	15	23	101
	9.5/11.5	11	9	22	17	23	18	100	10.1/12.1	11	10	22	16	23	19	101
	11.5/13.5	5	4	17	26	21	10	83	12.1/14.1	5	5	18	26	22	10	86
November	9.9/11.9	25	23	13	2	8	22	93	10.4/12.4	25	23	13	2	8	23	94
	11.9/13.9	18	16	21	7	17	25	104	12.4/14.4	17	15	22	8	18	25	105
	13.9/15.9	9	7	24	19	25	17	101	14.4/16.4	8	7	24	19	26	16	100
	15.9/17.9	3	3	17	29	22	8	82	16.4/18.4	3	3	17	30	22	7	82
December	4.9/6.9	21	19	11	2	7	20	80	5.2/7.2	20	19	12	2	7	21	81
	6.9/8.9	15	13	17	5	14	22	86	7.2/9.2	14	12	18	5	14	21	84
	8.9/10.9	8	7	20	12	21	16	84	9.2/11.2	7	6	20	13	21	15	82
	10.9/12.9	4	3	18	22	22	8	77	11.2/13.2	3	3	17	23	21	8	75

Table A.8
Monthly $N_{\mathrm{bin},i}$ values (hours per month) in six daily 4-h intervals for the future (2015–2044) period for months in the heating season in Tokyo under scenarios RCP-4.5 and RCP-8.5.

Month	$N_{\mathrm{bin},i}$ values in six daily 4-hour intervals															
	Future period (2015–2044), scenario RCP-4.5								Future period (2015–2044), scenario RCP-8.5							
	Temperature range (°C)	1:00–4:59	5:00–8:59	9:00–12:59	13:00–16:59	17:00–20:59	21:00–00:59	Total	Temperature range (°C)	1:00–4:59	5:00–8:59	9:00–12:59	13:00–16:59	17:00–20:59	21:00–00:59	Total
January	2.3/4.3	21	20	10	1	6	18	76	2/4	20	20	10	1	6	18	75
	4.3/6.3	17	15	16	4	11	21	84	4/6	17	15	15	4	11	21	83
	6.3/8.3	10	8	19	9	18	18	82	6/8	10	9	19	10	18	18	84
	8.3/10.3	5	4	19	19	21	11	79	8/10	5	4	18	19	21	11	78
February	3/5	22	21	10	1	6	19	79	3.4/5.4	22	21	10	1	6	19	79
	5/7	18	16	17	4	12	23	90	5.4/7.4	18	16	17	4	12	23	90
	7/9	10	8	21	11	20	18	88	7.4/9.4	10	8	21	11	20	18	88
	9/11	5	4	19	21	23	10	82	9.4/11.4	5	4	19	21	23	10	82
March	7.1/9.1	23	23	10	2	6	17	81	7.3/9.3	23	23	10	2	6	17	81
	9.1/11.1	21	19	17	5	13	24	99	9.3/11.3	21	20	17	5	13	24	100
	11.1/13.1	13	11	23	14	22	21	104	11.3/13.3	13	11	23	14	22	21	104
	13.1/15.1	6	5	20	25	24	12	92	13.3/15.3	6	5	20	25	24	12	92
November	11/13	26	25	10	1	6	20	88	10.8/13	26	25	11	1	6	20	89
	13/15	21	19	19	5	15	27	106	12.8/14.8	21	19	19	5	15	26	105
	15/17	11	9	25	15	25	20	105	14.8/16.8	11	9	25	15	25	20	105
	17/19	4	4	20	29	25	9	91	16.8/18.8	4	4	20	29	25	9	91
December	4.3/6.3	21	20	10	1	5	18	75	4.5/6.5	21	20	10	1	5	18	75
	6.3/8.3	17	15	16	4	12	22	86	6.5/8.5	17	15	16	3	12	22	85
	8.3/10.3	10	8	20	9	19	18	84	8.5/10.5	10	8	20	9	19	18	84
	10.3/12.3	5	4	19	19	22	10	79	10.5/12.5	5	4	19	19	22	10	79

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