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The Combined Impacts of Climate Change and Urban Expansion on Energy Consumption for Different Types of Buildings

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Abstract: The impacts of climate change and urban expansion (expressed as increase of building area) on heating/cooling energy consumption of commercial, office and residential buildings in a large city in Northern China, were determined. The results showed that climate change and urban expansion have different impacts on the building energy consumption at the city scale. In the case of without considering urban expansion impact on energy consumption (i.e., unit area energy consumption), heating energy consumption was dominantly affected by dry bulb temperate. In contrast of heating consumption, wet bulb temperature had the dominant effect on cooling energy consumption for commercial and office buildings. If the urban expansion impact on the total energy consumption at the city scale was considered the climate change impact became weaker. For the total heating energy consumption (unit area energy consumption multiplied by building area), climate change is the dominant impacting factor for total heating energy consumption of commercial or office buildings, whereas urban expansion has the dominant impact on the cooling energy consumption, with no (commercial building) or small (office building) impacts by climate change. The results indicates, although the total energy consumption at the city scale is less affected by climate change, especially for the cities with rapid expansion, efficient measures for energy saving should be made according to the impact of climate parameters due to the apparent impacts of climate change on unit area energy consumption. In particular, the rapid warming of climate in winter should be fully considered to promoting energy efficiency for heating of buildings.

Keywords: Building Energy Consumption, Climate Change, Different Buildings, Cooling, Heating, Urbanization

1. Introduction

Approximately 16 billion tons of standard coal represents the total national building energy consumption (TNBEC) in China every year, accounting for 25% of the total end energy consumption and likely increasing to 35% by 2020 [1-3]. As a dominant portion of building energy consumption, 65% of the energy is used for building heating or cooling [1]. The continuous increase in building energy consumption is closely related to the fast urbanization together with the improvement of living standards for the people in China, especially in large cities such as Beijing, Shanghai and Tianjin [4]. Over the last two decades, China's urbanization ratio rose from approximately 20% in the early 1980s to 45% in 2007 [4]. In addition, climate conditions are a basic factor influencing building energy consumption. The global climate change is significantly warming the whole world, which had a substantial impact on building energy usage [5-7].

To curb the rapid growing of building energy consumption, China has been executing a great effort. Standard systems, design guides and design codes have been established and implemented during the past decade [1-2]. However, the energy consumed for heating or air-conditioning per square meter of buildings in northern China is much higher than that in western European or North American countries with similar climate conditions [4]. Additionally, people in northern China have less thermal comfort despite the higher energy consumption. This is, to some extent, due to the lack of detailed and precise information on the impacts of climate change on the building energy consumption under the conditions of rapid urbanization [2]. Therefore, targeted adaptation measures could not be efficiently established. It is necessary to determine the impacts of both urbanization and changing climate on energy consumption in buildings, especially for buildings in large cities.

The previous studies on building cooling and heating energy demand are mainly based on simplified analyses using constant increases in the annual average temperature or changes in cooling or heating degree-days [8-11]. These studies may usually ignore the impacts of other climate parameters, e.g., humidity, solar radiation and wind speed, on the energy consumption in buildings and therefore cannot make targeted or efficient adaptation technologies for promoting the energy efficiency of buildings. In addition, some researchers also used energy consumption data collected from the China Statistical Yearbook or Energy Statistics Yearbook [12]. However, it is difficult to remove the impacts of economic growth or urbanization from the energy consumption.

The transient systems simulation program (TRNSYS), as a useful tool for simulating energy consumption, has been widely used in many previous related studies [3, 13-14]. For a given building, the heating or cooling energy consumption per unit area is generally considered be related to the climate change [3, 15-16]; therefore, we can determine the impacts of climate change on the building energy consumption under the conditions of rapid urbanization. In this study, we selected commercial, office and residential buildings in a large city, Tianjin, in northern China and simulated their energy consumption with a simulation tool (TRNSYS). The purpose of this study was to determine the impacts of climate change or urbanization on the heating or cooling energy consumption of different buildings.

2. Material and Methods

2.1. Selection of Building

Three types of buildings (i.e. residential, commercial and office buildings) were selected. A summary of the key design parameters of these buildings is shown in Table 1. The residential buildings generally use coal for winter heating, whereas commercial and office buildings use natural gas for both cooling and heating (year-round use with air-conditioning). In the present study, a nine-story residential building with a total area of 2,790 m^2 and a 2.8 m floor-to-floor height was selected. The selected commercial building is a five-story building with a 5 m floor-to-floor height and a total gross floor area of 17,024 m^2. The selected office building has a 4.2 m floor-to-floor height and a total gross floor area of 36,818 m^2. It is necessary to note that only energy consumption for heating rather than cooling in residential building was analyzed because central heating systems are not applied to the cooling of residential building. The opening time is 8 a.m. to 9 p.m. for both commercial building air-conditioning and heating systems, and 7 a.m. to 4 p.m. for the office building.

Table 1. *Design data for the selected commercial and residential buildings.*

Building type	Building envelope HTC (w/m^2°C)			Indoor design condition Summer/winter			Internal load density			Window-to-wall ratio			
	Wall	Roof	Floor	T (°C)	RH (%)	ACR (1/h)	Occupancy (m^2/person)	Lightin (W/m^2)	Equipmen (W/m^2)	East	South	West	North
Commercial	0.53	0.48	2.04	25/18	60/30	1.5	3-4	13	13	0.48	0.46	0.30	0.29
Office	0.57	0.48	2.04	26/20	60/30	1	8	11	20	0.48	0.46	0.30	0.29
Residential	0.55	0.46	0.49	18	30	0.5	12	1.3	2.5	0.18	0.48	0.18	0.25

Note: HTC, heat transfer coefficient; T, Temperature; RH, Relative humidity; ACR, Air change rate

2.2. Simulation of Building Energy Consumption

Energy simulation was made by the TRNSYS 17. The TRNSYS software is a transient system simulation program with a modular structure that was designed to solve complex energy system problems because it can break a complex problem down into a series of smaller components [14]. TRNSYS has been commercially available since 1975 and is extensively used for simulating solar energy applications, conventional buildings and even biological processes. Building energy simulation using TRNSYS is becoming an accepted and widely used analysis technique [3, 15-16].

To carry out the simulation of energy consumption, two types of dominant initial inputs were needed. First, the building parameters related to the energy consumption should be inputted for the TRNSYS simulation project. Detailed information can be seen in Table 1. In addition to building input data, weather data file was also built into the software as an input file. To obtain the hour-by-hour energy consumption over the 30 years (1981-2010), data for multiple climatic variables in the form of 8,760 hourly records per variable (dry bulb temperature, DBT; wet bulb temperature, WBT; global solar radiation, GSR; wind speed, WS; and wind direction, WD) for each year from 1971 to 2010 were required for the energy simulation rather than typical meteorological year (TMY) data. The WS and WD were directly collected from observed data. The dry-bulb temperature and relative humidity recorded four times per day were used to generate the hourly data through cubic spline interpolation and permitted calculation of the wet-bulb temperature. The hourly solar radiation was first generated from daily total solar radiation by using the Collores-Perein and Rabl model and then adjusted for rainy, foggy and sunny weather conditions. Comparisons of the generated hourly dry-bulb temperature, relative humidity and solar radiation with the observed hourly data from the five most recent years (2006-2010) were conducted to verify the reliability of the generated data.

To guarantee reliability of the simulated data, the energy consumption of buildings was monitored during the heating period in 2010-2011. It is found that the measured and simulated energy consumption showed a very similar hourly pattern and very small differences (data not shown). Bland-Altman analyses revealed good agreement between the measured and simulated energy consumptions because the differences between the measured and simulated data is in a small range and only few points are outside the 95% limits of the agreement (data not shown). This indicates the energy consumption simulation could efficiently reflect the real energy consumption. Using simulated hourly heating or cooling energy consumption per unit area, we obtained the daily, monthly or yearly energy consumption. The building heating (15 November ~15 March of the next year) and cooling (1 June ~30 August) energy consumption were analyzed and compared for each type of building.

2.3. Collection of City Urbanization Data

The urbanization, to a large extent, is characterized by the large increase of building area and population. In the present study, we collected the yearly building areas of the three types of buildings during 1990 to 2010 from the Tianjin Statistical Yearbook 1991-2012. The energy consumption per unit area was then multiplied by the yearly total area of each type of building to obtain the total energy consumption of each type of building in the city scale. It is necessary to note that the unit area energy consumption is generally considered to be dominantly affected by climate change. Therefore, the energy consumption per unit was used to represent climate-driven energy consumption, whereas the total energy consumption was affected by climate change and variations in building area, single or combination. In addition, to show the total energy consumption and unit area energy consumption in a figure, the unit area energy was multiplied by 107 for the commercial and office buildings and by 108 for the residential building.

2.4. Statistical Analysis

Simple linear regression was used to determine the relationships between building energy consumption and climate change or building area. Multiple stepwise linear regressions were used to identify the dominant variables affecting the building energy consumption. All statistical analyses were performed using SPSS 11.0 for Windows, and all significance levels were set at $P < 0.05$.

3. Results

3.1. Climate Change Impact on Energy Consumption

Table 2 showed that the energy consumption for commercial building heating was dominantly affected by dry bulb temperature (DBT) (R2 = 0.90). In addition, solar radiation (SR) and minimum temperature (MIT) also had a very small impact (Table 2). In contrast to heating, wet bulb temperature (WBT) first entered into the regression model, accounting for approximately 94% of the variations in cooling energy consumption for the commercial building (Table 2).

DBT was also the dominant affecting factor for the office building heating, and solar radiation (SR) and minimum temperature (MIT) also had a large contribution (Table 2). DBT, SR and wet bulb temperature (WBT) jointly affected 89% of the variations in cooling energy consumption for the office building. The heating energy consumption for the residential building was dominantly affected by the DBT (R2 = 0.997, Table 2).

Table 2. *Stepwise multiple linear regression analysis for annual building energy consumption per unit against the climatic parameters (n=30).*

			Model 1	Model 2	Model 3
Commercial building	heating		-0.500×DBT	-0.490×DBT	-0.435×DBT
				-0.000847×SR	-0.000945×SR
					-0.0374×MIT
		Constant	3.108	3.974	3.575
		R2	0.897***	0.914***	0.927***
	cooling		0.472×WBT	0.482×WBT	
				0.0003011×SR	
		Constant	-5.993	-6.693	
		R2	0.942***	0.965***	
Office building	heating		-0.768×DBT	-0.731×DBT	-0.609×DBT
				-0.00336×SR	-0.00357×SR
					-0.0819×MIT
		Constant	4.498	7.932	7.059
		R2	0.730***	0.854***	0.878***
	cooling		0.07925×DBT	0.07601×DBT	0.04630×DBT
				0.0002145×SR	0.0002570×SR
					0.05703×WBT
		Constant	-0.583	-0.844	0.207
		R2	0.614***	0.783***	0.891***
Residential building	heating		-0.672×DBT	-0.675×DBT	
				0.0002992×SR	
		Constant	9.452	9.150	
		R2	0.997***	0.998***	

Note: *** P< 0.001

3.2. Yearly Variations in Total Energy Consumption

Commercial building

The total building area of commercial buildings had no apparent yearly variation trend during the period of 1990-2002, followed by a linear increase thereafter (Figure 1a). The total energy consumption for commercial building heating had a large fluctuation until 2007, with a significant increase over the most recent four years (Figure 1a). The R2 of regression analysis indicated the yearly variations of commercial building energy consumption was dominantly related to climate change (R2 = 0.65) (Table 3), and building area also had significant effect (R2 = 0.39). In particular, the large increase over 2007-2010 has a close relationship with the area of commercial buildings.

The total cooling energy consumption showed a significant and fluctuant increase (Figure 1b). The variations in cooling energy consumption were mainly affected by building area (R2 = 0.73, Table 3). Climate change had no significant impact.

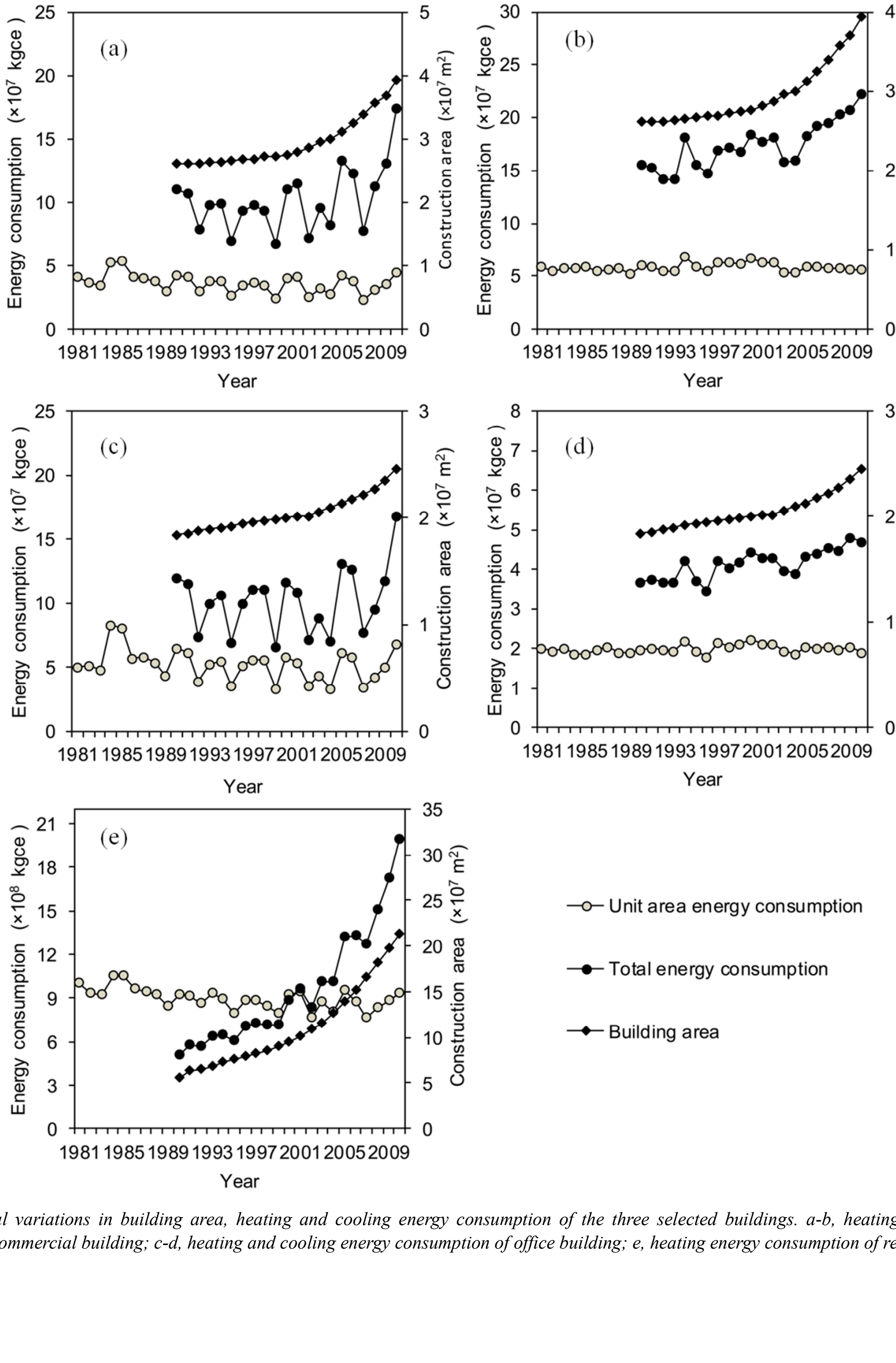

Figure 1. *Annual variations in building area, heating and cooling energy consumption of the three selected buildings. a-b, heating and cooling energy consumption of commercial building; c-d, heating and cooling energy consumption of office building; e, heating energy consumption of residential building.*

Table 3. *Regression analysis between total energy consumption and building area of building or unit area energy consumption for different buildings. The coefficients of determination and significance levels are given.*

		TEC vs CA	TEC vs UAEC
Office building	Heating	0.154ns	0.86**
	Cooling	0.652**	0.225*
Commercial building	Heating	0.389**	0.653**
	Cooling	0.733**	0.055ns
Residential building	Heating	0.854**	0.007ns

Note: TEC, Total energy consumption; CA, Building area; UAEC, Unit area energy consumption; *, $P < 0.05$; **, $P < 0.01$; ns, no significance

Office building

The total building area of office buildings showed a weak increase from 1990 to 2005, with a fast increase after 2005 (Figure 1c). The total energy consumption had an apparent large fluctuation but no apparent trend, except for a higher value in 2010. The unit area energy consumption had a strong relationship with total energy consumption (Table 3, R2 = 0.86), indicating that the total heating energy consumption was dominantly affected by climate change. Building area had no significant effect on the total heating energy consumption (R2 = 0.15, $p > 0.05$, Table 3).

The total cooling energy consumption of office buildings showed a significant increase (Figure 1d). Building area could account for approximately 65.2% of the total cooling energy consumption (Table 3), and the unit area cooling energy consumption also significantly related to the total cooling energy consumption (Table 3, R2 = 0.23, $p < 0.05$). These indicate that the total energy consumption was impacted by the combination of both building area and climate change.

Residential building

The building area of residential buildings showed a very significant increase over 1990-2010 ($p < 0.001$). Affected by the increase in building area (Table 3), the total heating energy consumption of the residential building increased significantly (Figure 1e, $p < 0.001$). The unit area energy consumption had no relationship with total heating energy consumption (R2 = 0.007, $p > 0.05$), indicating that climate change has no effect on the total heating energy consumption for the residential buildings.

4. Discussion

The impacts of climate change and urban expansion on energy consumption for different buildings of a large city in northern China were investigated. The unit area energy consumption was considered to be dominantly impacted by climate change, whereas the energy consumption per unit area multiplied by the total building area was expressed as the total energy consumption for each building type at the city scale.

The heating energy consumption per unit area for the three types of buildings is dominantly affected by DBT, which can explain 73% to 99% of the variations in the heating energy consumption. By contrast, the cooling energy consumption is dominantly related to the combination of temperature, humidity or solar radiation. These results may indicate that heating degree-days calculated by temperature can be used to reflect the heating energy consumption, but it is not ample to calculate cooling energy consumption by only considering the temperature effect. This information may be useful as a basis for energy-saving or adjusting operations of heating or air conditioning systems when taking into account the climate impacts.

At the conditions of constant building area of buildings, the energy consumption for heating or cooling is dominantly affected by the climatic factors. However, at the city scale, the building energy consumption is not only related to climate but also, to a large extent, the variations in building area of buildings. For the total heating energy consumption of commercial or office buildings at the city scale, climate change is the dominant impacting factor, whereas climate change has no impact on the heating energy consumption of residential building. The lack of relationship of heating energy consumption with climate change may be due to the rapid increase in residential buildings, which obscures the climate change impacts. The cooling energy consumption of commercial and office buildings at the city scale is dominantly impacted by building area, with no or small impacts by climate change. These indicate that, compared with the cooling energy consumption of office or commercial buildings for the whole city, the heating energy consumptions are more sensitive to climate change. The very possible climatic warming in the future and its impacts on building heating energy consumption should be fully considered to promote energy efficiency in the two aspects of operation and design of heating systems. Meanwhile, for the heating energy consumption of residential buildings the total building area and increasing rate should be controlled to save energy consumption at the city scale.

5. Conclusion

In this study, the impacts of climate change and urban expansion on heating/cooling energy consumption of commercial, office and residential buildings in a large city in Northern China were studied. The unit area heating energy consumption is mainly related to temperature, whereas the cooling energy consumption is affected by a combination of temperature, solar radiation and humidity. At the city scale, climate change and urban expansion have different impacts on the building energy consumption for the selected buildings. Although the total energy consumption at the city scale is less affected by climate change, especially for the cities with rapid expansion, efficient measures for saving building energy consumption should be made according to the dominant impacts of climate change or urban expansion. The improvement of energy efficiency according to the beneficial climate conditions under the conditions of rapid urban expansion is one of the most efficient measures for energy saving. In particular, with the rapid increase of urban expansion and building area, the climate warming impact on building heating energy consumption should be fully considered to reduce building energy consumption.

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References

[1] Yao, R., Li, B. and Steemers, K. 2014. Energy policy and standard for built environment in China. *Renewable Energy* 30 (13): 1973-1988. DOI: 10.1016/j.renene.2005.01.013.

[2] Cai, W. G., Wu, Y., Zhong, Y. and Ren, H. 2009. China building energy consumption: situation, challenges and corresponding measures. *Energy Policy* 37 (6): 2054-2059. DOI: 10.1016/j.enpol.2008.11.037 · Source: RePEc.

[3] Wan, K. K. W., Li, D. H. W. and Lam J. C. 2011. Assessment of climate change impact on building energy use and mitigation measures in subtropical climates. *Energy* 36 (3): 1404-1414. DOI: 10.1016/j.energy.2011.01.033.

[4] Li, B. Z. and Yao, R. M. 2009. Urbanization and its impact on building energy consumption and efficiency in China. *Renewable Energy* 34 (9): 1994-1998. DOI: 10.1016/j.renene.2009.02.015.

[5] Lowe, R. 2007. Addressing the challenges of climate change for the built environment. *Building Research Information* 35 (4): 343-350. DOI: 10.1080/09613210701345873·Source: OAI.

[6] Dolinar, M., Vidrih, B., Kaifež-Bogataj, L. and Medved, S. 2010. Predicted changes in energy demands for heating and cooling due to climate change. *Physics and Chemistry of Earth* 35 (1-2): 100-106. DOI: 10.1016/j.pce.2010.03.003.

[7] Yau, Y. H. and Hasbi, S. 2013. A review of climate change impacts on commercial buildings and their technical services in the tropics. *Renewable and Sustainable Energy Reviews* 18 (2): 430-411. DOI: 10.1016/j.rser.2012.10.035.

[8] Yildiz, I. and Sosaoglu B. 2007. Spatial distributions of heating, cooling, and industrial degree-days in Turkey. *Theoretical Applied Climatology* 90 (3-4): 249-261. DOI: 10.1007/s00704-006-0281.

[9] Jiang, F. Q., Li, X. M., Wei, B. G., Hu, R. and Li, Z. 2012. Observed trends of heating and cooling degree-days in Xinjiang Province, China. *Theoretical Applied Climatology* 97 (3-4): 349-360. DOI: 10.1007/s00704-008-0078-5.

[10] Verbai, Z. and Kalmár F. 2014. Heating degree day in Hungary. *Environmental Engineering Management Journal* 13 (11): 2887-2892.

[11] Csáky, I. and Kalmár. 2015. Analysis of degree day and cooling energy demand in educational buildings. *Environmental Engineering Management Journal* 13 (11): 2765-2770.

[12] Xiong, M. M., Li, M. C., Ren, Y., Xu, S. and Yang, Y. J. 2013. Characteristics of electrical load and its relationship to meteorological factors in Tianjin. *Meteorological Science Technology* 41 (3): 577-582. DOI: 10.19517/j.1671-6345.2013.03.027.

[13] Papakostas, K., Mavromatis, T. and Kyriakis, N. 2010. Impact of the ambient temperature rise on the energy consumption for heating and cooling in residential buildings of Greece. *Renewable Energy* 35 (7): 1376-1379. DOI: 10.1016/j.renene.2009.11.012.

[14] Li, M. C., Cao, J. F., Guo, J., Niu, J. D. and Xiong, M. M. 2016. Response of energy consumption for building heating to climatic change and variability in Tianjin City, China. *Meteorological Applications* 23: 123-131. DOI: 10.1002/met.1537.

[15] Lam, J. C., Wan, K. K. W., Lam, T. N. T. and Wong S. L. 2010. An analysis of future building energy use in subtropical Hong Kong. *Energy* 5 (3): 1482-1490. DOI: 10.1016/j.energy.2009.12.005.

[16] Li, M. C., Guo, J., Tian, Z., Shi, J. and Xiong, M. M. 2014. Future climate change and building energy demand in Tianjin, China. *Building Services Engineering Research Technology* 35 (4): 362-375. DOI: 10.1177/0143624413498245.