Carbon Emissions of Chiller Systems in Hong Kong Hotels under Climate Change

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ABSTRACT

Building energy simulation is a common technique to forecast future energy use and develop strategies for meeting carbon reduction targets. The purpose of this study is to analyze the trend of electricity use and carbon emissions of chiller systems—the most energy intensive type of system—using building energy simulation for hotels in subtropical zones under climate change. Based on a typical meteorological year weather file for subtropical Hong Kong, weather data were forecasted for climate change scenarios in 2020, 2050 and 2080. The building simulation program EnergyPlus was used to model a reference hotel with two typical chiller system designs. Simulation results show that a system capacity extension by up to 5% could be considered to satisfy the increasing cooling demand for a 15-year operating span. Various strategies have been discussed for chiller systems to reduce carbon emissions by the demand side. A rigorous carbon intensity target by power companies should be in place to reduce the increasing carbon emissions by hotels in subtropical zones.

Keywords: Hotel energy simulation; Carbon emissions; Chiller system; Climate change

INTRODUCTION

Hotels, among other commercial buildings, constitute a significant part of energy use because of their intensive engineering systems, round-the-clock operation and increasing stock with speedy economic growth. According to a study on the energy performance of hotels

(Chan, 2005), the normalized performance indicator of hotels in subtropical Hong Kong could vary from 228-719 kWh/m^2 per annum, with an average range of 313-361 kWh/m^2 per annum. This at least doubles the normalized performance indicator of 138 kWh/m^2 for a typical office building with baseline energy performance in Hong Kong (Yik et al., 2001). It is worth prioritizing an analysis of energy implications and carbon emissions of hotels.

Given that building energy use is one of the reasons for climate change, there are many worldwide studies on their interaction to formulate strategies that address climate change by controlling carbon emissions. Based on two carbon emissions scenarios, Lam et al. (2010) predicted that the electricity consumption of air-conditioned commercial buildings in Hong Kong could increase by 5.7% from 2009-2038, 12.8% from 2039-2068 and 18.4% from 2069-2100 in relation to the average value from 1979-2008. According to Wan et al. (2011), climate change could increase the annual cooling energy by 11.4-24.2% and decrease the annual heating energy by 13.8-26.6% for office buildings located in five major climatic regions in China. Kharseh and Altorkmany (2012) investigated how the thermal characteristics of a building envelope influenced the cooling and heating demands and the performance of ground source heat pumps under different climate change scenarios. Teng et al. (2012) used the analytic network process (ANP) method to develop a list of carbon reduction criteria with weightings for hotels in Taiwan. In the ANP method, a decision problem is formulated with a network of a goal, decision criteria and alternatives. A system of pairwise comparisons is used to measure the weights of the components and then rank the alternatives (Saaty, 1996).

Building energy simulation software and weather generation models are prerequisites for the analysis of building energy use under climate change. Some studies have demonstrated the techniques for developing a typical meteorological year (TMY) weather data file for building energy simulation in response to climate change (Chan et al., 2006; Belcher et al., 2005; Guan, 2009; Wong et al., 2012; Gugliermetti et al., 2004; Hong and Jiang, 1995; Huang, 2006). A TMY for a specific location is a collection of 8,760 hourly weather observations containing real weather sequences in a period of, say, 20-30 years that represent the long-term climatic mean conditions for that location. All these techniques form a basis for developing weather data files under various climate change scenarios. Based on some surveys (Chan, 2005), over

50% of the total electricity use in hotels in a subtropical city is taken by the air conditioning systems. Improving the design and operation of air conditioning systems is the key to reducing their energy consumption under climate change. Yet most aforementioned studies have not addressed in great detail the implications of climate change on the design and operation of air conditioning systems.

The energy consumption of air conditioning systems varies with weather conditions and the energy performance of system components. In a central air conditioning plant serving a hotel, a chiller system is commonly installed to provide cooling energy and it contains multiple sets of chillers, pumps and heat rejection devices like condenser fans and cooling towers. The operation of chiller systems can take up the highest proportion of total electricity consumption in commercial buildings (Yang et al. 2012). Chiller systems dictate the seasonal variations of building electricity use and the peak demand for electricity generation due to their varying operating characteristics in response to the changing weather conditions.

Chillers operate under a refrigerant vapor compression cycle to produce chilled water. There are pumps circulating chilled water to air handling units which contain heat exchange coils to supply cool and dehumidified air to maintain thermal comfort conditions in indoor areas. The energy performance of chillers depends mainly on whether the heat rejection system is by air-cooled or water-cooled means. The energy performance of air-cooled chillers is low compared with that of water-cooled chillers. This is because the heat absorbed by air-cooled chillers is rejected to outdoor air and they work at a high condensing temperature 10-20°C above the dry bulb temperature of outdoor air. That causes high compressor work in the vapor compression process, hence the large electric power consumption. Water-cooled chillers, on the other hand, make use of cooling towers to reject heat by evaporation of fresh water via outdoor air. The condensing temperature can be maintained at 4-8°C above the wet bulb temperature of outdoor air. Yet the operation of cooling towers consumes considerable water and leads to a potential threat of spreading Legionnaires' disease resulting from improper water treatment.

Where water shortage and conservation are concerned, air-cooled chiller systems are an unavoidable design option for an air conditioning plant. In cities where the supply of electricity and water is stable, water-cooled chiller systems are preferable over air-cooled ones to enhance energy efficiency. Since 2006, the local Hong Kong government has encouraged the wider use of fresh water in cooling towers for energy efficient air conditioning systems for non-domestic buildings (EMSD, 2006).

The energy performance of chiller systems is one of the factors to be considered in sustainable or green buildings as stated in some building environmental assessment programs like Leadership in Energy and Environmental Design (LEED) (U.S. Green Building Council, 2012), ASHRAE Standard 90.1—Energy standard for buildings except low-rise residential buildings (ASHRAE, 2010), BREEAM—Buildings environmental assessment methods by Building Research Establishment Ltd. (BRE) (BRE, 2012) and BEAM Plus—Building environmental assessment methods—used in Hong Kong (BEAM Society Ltd., 2012). The energy performance of chillers is usually expressed as the coefficient of performance (COP)—the cooling capacity output in kW divided by the electric power input to the compressor in kW. For compliance with the assessment programs, the COP of chillers should be above the minimum levels, say, 2.7 for air-cooled chillers and 5.7 for water-cooled chillers. These values are identified to be slightly above the average COP of current chiller products. Complying with these minimum levels may call for the use of modern highly efficient products as existing chillers operating for more than five years may fail to meet the minimum COP requirements. For other components of a chiller system like pumps, the maximum allowable power per unit of chilled water flow rate may be specified to limit the pumping energy use.

There are many research studies on enhancing the energy performance of chiller systems. Some of them promote the wider use of variable speed drives in all system components (e.g. Hartman, 2001). Chillers with variable speed control can achieve optimum efficiency even under part-load conditions. The COP of variable speed water-cooled chillers is claimed to be higher (up to 11.4) at part load operation than at full load operation (around 6.1) (York, 2012). Some are developing advanced controls for optimizing the components' operation (e.g. Yu and Chan, 2009). With variable speed drives for the system pumps and cooling tower fans, their rotating speed could be regulated in response to the building cooling load to achieve minimum power consumption. Alternatively, variable speed drives complement adjustments to temperature settings used for the conventional control of chilled water and condenser water to achieve system optimization (Crowther and

Furlong, 2004). Although sophisticated variable speed technologies have been available in recent decades, components of existing chiller systems are controlled mainly at constant speed. That is because system operators may perceive variable speed control as complicated and unreliable and as a replacement of manual operation and maintenance. The utilization rate of variable speed chillers is still low at present because of their much higher initial cost compared with constant speed chillers. Furthermore, if detailed simulation of building cooling demand is absent, chiller systems will often be designed with redundant capacity which greatly affects their operating performance. A study of three existing chiller plants serving hotels showed that early running of chillers with frequent part load operation was commonly observed and there was a 9-23% increase in the annual system energy consumption. (Yu and Chan, 2005).

PURPOSE OF THIS STUDY

It is hypothesized that there is a rising trend of carbon emissions by the building sector due to the increasing stock of buildings. In fact, there is a lack of studies emphasizing the energy and carbon implications of chiller systems operating round-the-clock for hotels requiring year-round cooling. The purpose of this study is to analyze quantitatively how climatic variables interact with the design and operation of the chiller systems commonly used to provide cooling energy for hotels in subtropical zones. The impacts of climate change scenarios on the design and operation of the system will be discussed. The potential impacts of electricity consumption and carbon emissions by the system will be analyzed. Some essential considerations will be highlighted on the sustainable design and operation of chiller systems under climate change. It is hoped that these results will be useful for hotel managers to identify the energy and carbon implications of their hotels and to implement measures for the sustainable design and operation of chiller systems under climate change in order to alleviate carbon emissions, considering that the application of chiller systems is unavoidable to maintain thermal comfort conditions in hotels in subtropical regions. This study is part of research work on identifying carbon implications by chiller systems in commercial buildings and a similar study on office buildings is given elsewhere (Yu et al., 2012).

METHOD

It is hypothesized that climatic variables will vary with global warming in future decades and the electricity consumption of chiller systems in hotels interacts with climate change scenarios. To test this hypothesis, a weather generator program launched by the Intergovernmental Panel on Climate Change (IPCC) was used to predict hourly weather data under climate change scenarios. A sophisticated building energy simulation program was used to model a reference hotel in Hong Kong with typical chiller systems and then to predict electricity consumption based on the forecasted weather data. The research goal is to identify quantitatively the energy and carbon implications of the hotel under climate change.

Description of "Present-day" Weather

Table 1 shows some key variables and their ranges in the TMY weather file for Hong Kong (22°19′ N latitude and 114°11′ E longitude) compiled by Chan et al. (2006). The dry bulb temperature and global horizontal radiation are the major variables affecting the ventilation gain and solar heat gain in the calculation of building cooling demand. The TMY file forms the "present-day" file representing typical weather data over a 25-year period from 1979-2003. The median year—1990—was considered the reference year of the 25-year period. It was compiled in the EPW format suitable for use in EnergyPlus (2012), a sophisticated building simulation program. The file consists of composite sets of hourly weather data from multiple years in the monitoring period. Each month comprising the TMY was selected to represent prevailing weather conditions of the same month over the entire period. Based on the TMY weather file, the maximum hourly dry bulb temperature and the coincident wet bulb temperature were identified to be 32.8°C and 28.1°C, respectively. These were used as the annual cooling design conditions for air conditioning systems to meet all cooling demands under all operating conditions.

Generation of Weather Files for Climate Change Scenarios in 2020, 2050 and 2080

The Intergovernmental Panel on Climate Change (IPCC) (2012) is the leading international body for the assessment of climate change. It launches assessment reports from time to time to let people know

Table 1.
Key climatic variables and their ranges in the TMY weather file of Hong Kong

		Dry bulb temperature (°C)			Global horizontal radiation (MJ/m^2)			Wind speed (m/s)		
Year	Month selected	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.
1982	Sep	32.8	27.5	23.6	933	167	0	9.5	3.7	0
1984	Oct	31	25.3	20.6	864	169	0	7	3.1	0
1986	Apr	30.1	22.6	14.8	919	140	0	9	3.4	0
1988	Feb	23.3	16.3	10.2	856	112	0	8	3.6	0.5
1989	Nov	27.8	21.5	12.4	797	144	0	8	2.9	0.5
1990	Jun	32.5	27.9	23.1	936	161	0	11	3.3	0.5
1993	Dec	24.8	17.1	9.2	725	127	0	8	2.9	0
1995	Jan	22.5	16.1	9.3	717	106	0	7	2.8	0.5
1997	May	31.3	26.1	21.4	969	153	0	8	2.6	0.4
2000	Jul	32.8	28.8	25	972	205	0	9.5	3	0.4
2002	Aug	32.7	28.4	24.6	953	180	0	9	2.8	0.4
2003	Mar	26.4	19	11.7	881	121	0	8.5	2.9	0.1

more about climate change scenarios and their impacts. The weather generator program CCWorldWeatherGen (2012) was developed based on the Hadley Centre Coupled Model, version 3 (HadCM3) under the third assessment report of the IPCC. It is a free downloadable program that was used to generate climate change scenarios for Hong Kong in three future periods (2010-2039, 2040-2069 and 2070-2099) represented by three benchmark years of 2020, 2050 and 2080. The TMY weather file (in the EPW format) for Hong Kong (2012) was the input file for the program. The HadCM3 model drew on a morphing procedure to project future climate weather data based on data in the present-day weather file. The algorithm of morphing future hourly data (x) involves shifting and stretching the present-day data (x_0), as illustrated by Eq. (1), where Δxm represents the shift component and αm represents the stretch component for °C in the month m. is the monthly mean of x_0 for month m.

$$x = x_0 + x_m + \alpha_m (x_0 - \{x_0\}_m) \qquad (1)$$

To illustrate how each hourly data x was predicted in climate change scenarios, the hourly dry bulb temperature of 28°C at 12 a_m, the September 1 in the TMY was taken as an example. Here x_0 is 28°C. The monthly mean of the dry bulb temperature in September $\{x_0\}_9$ was calculated to be 27.54°C. According to the weather generator program, Δx_9 and α_9 were set to be 0.72°C and -0.0526, respectively, in 2020. Based on equation (1), the dry bulb temperature predicted for 12 a_m, September 1 in 2020 was evaluated to be 28 + 0.72-0.0526(28-27.54) = 28.7°C. The whole set of hourly dry bulb temperatures throughout the year was predicted in this way.

Hourly data "x" to be morphed for each benchmark year include the dry bulb temperature, dew point temperature, global horizontal radiation, direct normal radiation, diffuse horizontal radiation, atmospheric pressure and wind speed (see Glossary for their meanings). They are weather variables influencing the building cooling load calculation and operating performance of an air conditioning system. Detailed equations for morphing each variable are given in Belcher et al. (2005).

Figure 1 shows the projected changes of key climatic variables (dry bulb temperature, global horizontal radiation, moisture content and wind speed) under three climate change scenarios (2020, 2050 and 2080) in relation to the baseline (TMY). Due to global warming, the dry bulb temperature rises by various degrees from the corresponding baseline value in the TMY. The monthly mean dry bulb temperature in 2020 could increase, on average, by 0.75°C per decade, in relation to the baseline, while the temperature rise in 2050 and 2080 appears to be gentler at about 0.4°C per decade. The drop is probably related to more stringent targets on carbon emissions in the future. Compared with summer months, the temperature rise in the longer term tends to be high in winter months. The moisture content changes with the dry bulb temperature, given that all the hourly data of relative humidity in the three future years follow the TMY. In all the three benchmark years, the monthly mean global horizontal radiation tends to decrease in summer months but increase in winter months in relation to the baseline. The summer decrease is probably due to a situation where the percentage of cloud cover and the concentration of suspended particulates could increase. The increase in winter months, on the contrary, could be associated with more days with a brighter sky and fewer suspended particulates. A minor drop in wind speed from the baseline is observed across different months in 2020. However, in 2050 and 2080, the change of wind speed could fluctuate greatly, especially in July—October during which typhoons tend to prevail.

Simulation of the Hotel and its Air Conditioning System

EnergyPlus (2012) was employed to model a reference hotel in Hong Kong. It is one of the popular building energy simulation programs during the last decade (Crawley et al., 2001; Fumo et al., 2010). It is also one of the authorized software packages used for demonstrating compliance with ASHRAE Standard 90.1 and LEED. It contains many innovative simulation features like user-configurable system modules and building components integrated with a heat and mass balance-based zone simulation. This facilitates the simulation tasks with simulation results of better quality. The energy use of various system design options can be analyzed expeditiously by using the "autosize" feature in various system templates.

Unlike office buildings of considerably typical design, hotels are generally in different envelope forms and capacities in terms of the number of guestrooms. There is no typical building configuration for the energy analysis of hotels in Hong Kong. This analysis drew on the envelope design of a large-scale hotel used for comprehensive building energy analysis in the U.S., but certain changes had been made to fol-

Figure 1.
Change of monthly mean weather data in 2020, 2050 and 2080 from the baseline

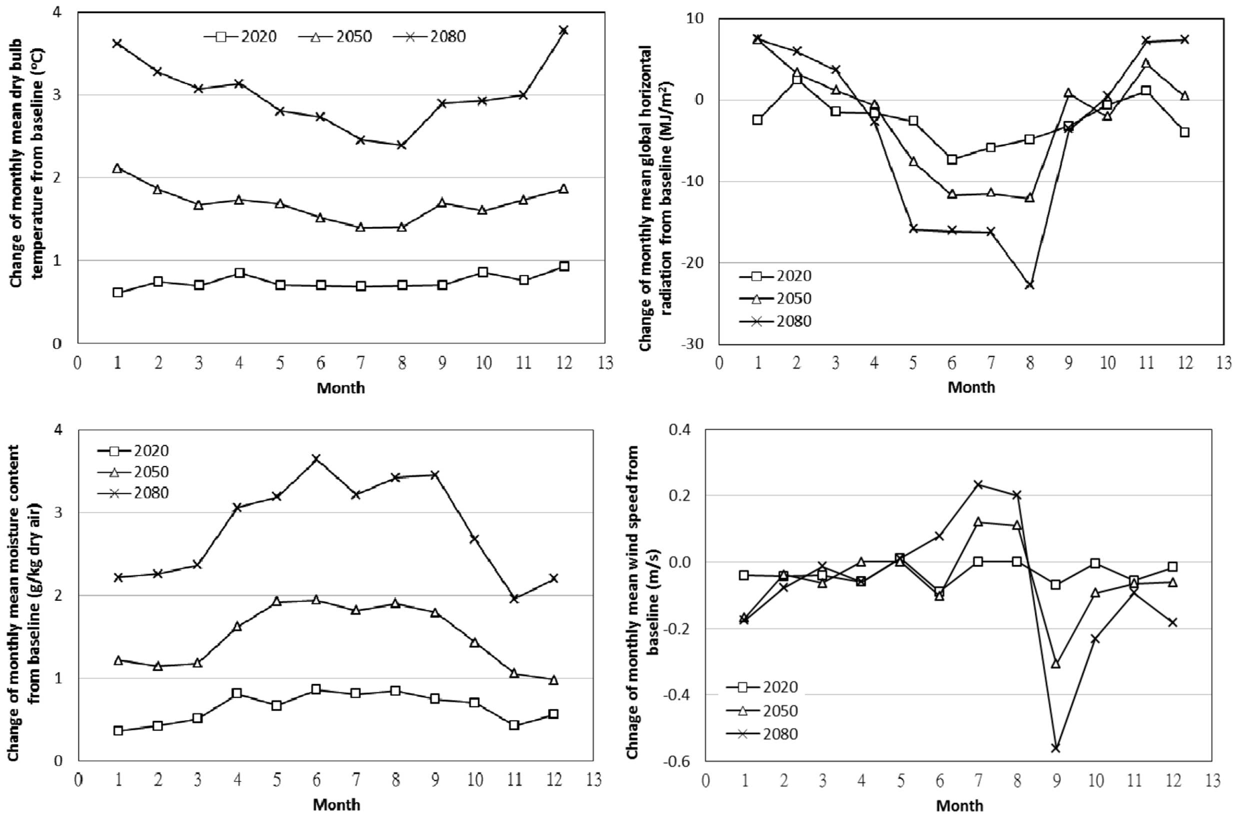


Table 2
General specifications about the reference hotel

General									
Total gross floor area (GFA) (m^2)	17,476								
Average floor area per floor (m^2)	1,100								
Number of floors	16								
Average floor to floor height (m)	3.1								
Total floor area of functional areas (m^2)									
A. Banquet rooms	331.66								
B. Basement back of house	1,978.83								
C. Catering areas with kitchens	623.82								
D. Corridors and lobbies	4,835.51								
E. Laundry rooms	78.04								
F. M & E plant rooms	164.24								
G. Storage rooms	94.76								
H. Retail shops	144.74								
I. Guestrooms (number = 356)	9,223.82								
Construction details									
Window to wall ratio	0.29								
U-value of external wall ($W/m^{2o}C$) (U-value is the heat transmission coefficient in conduction heat gain analysis)	0.51 – 0.70								
U-value of window ($W/m^{2o}C$)	3.24								
U-value of roof ($W/m^{2o}C$)	0.35								
Shading coefficient of glass	0.39								
Functional areas	A	B	C	D	E	F	G	H	I
Zone design criteria									
Temperature (°C)	24	26	24	24	26	28	26	24	24
Relative humidity (%)	50	60	50	50	60	60	60	50	50
Ventilation rate (L/s/person)	10	8	10	10	8	8	8	8	15
Occupancy (m^2/person)	1	4	1.5	15	4	-	4	2.5	15
Equipment power density (W/m^2)	20	5	10	0	10	0	5	30	23
Lighting power density (W/m^2)	23	13	23	15	13	13	13	20	17
Air-conditioning system operating schedules									
Weekdays, Saturdays and Sundays	0600-2400	0100-2400	0600-2400	0100-2400	0100-2400	0100-2400	0100-2400	0700-2100	0100-2400

low the practice for Hong Kong hotels. The hotel model was modified from one of the built-in examples provided in EnergyPlus. Table 2 summarizes the general specifications of the hotel. The design criteria and operating schedules of various functional areas follow specifications given in a local performance-based building energy code (EMSD, 2007).

Table 3 shows basic information on two typical designs of air conditioning system serving the reference hotel. Chiller performance in the two designs complies with the minimum COP requirements stated in the local performance based building energy code (EMSD, 2007). In design option 1, the waterside system involves four sets of air-cooled centrifugal chillers with a nominal COP of 2.7 at full load to meet the peak building cooling load of 3765 kW. Chiller sequencing is implemented under which an additional chiller in the system will be turned on only when the load carried by each operating chiller exceeds its nominal capacity while the changing building cooling loads are met. The chilled water distribution circuit was designed with a primary loop having constant speed pumps coupled to the chillers and a secondary loop having variable speed pumps. The waterside system in design option 2 comprises two water-cooled centrifugal chillers with a nominal COP of 5.7 at full load. Cooling towers with two speed fans meet the heat rejection capacity of the chillers. Chiller sequencing and the 2-loop chilled water distribution arrangement are also applied to design option 2. A fan-coil unit (FCU) system—consisting of cooling coils and fans to deliver cool and dehumidified indoor air—provides for all functional areas requiring air conditioning under the two design options. The systems in each design option were formed by choosing proper system templates complete with the "autosize" feature and some built-in and default data. The capacity of system components was specified with the sizing factor of one. EnergyPlus computed the design capacity of each system component and then performed simulation of hourly operating variables and electricity consumption.

RESULTS AND DISCUSSION

Impact of Climate Change on the Design and Operation of the Chiller Systems

The weather files for climate change scenarios in 2020, 2050 and 2080 were generated by the program CCWorldWeatherGen. To determine the capacity of each unit of air conditioning equipment, the annual cooling design temperatures (dry bulb and coincident wet bulb) are: 32.8°C and 28.1°C for the TMY; 33.5°C and 28.7°C for 2020; 34.6°C and 29.7°C for 2050; 35.6°C and 30.6°C for 2080. The maximum dry bulb temperature could rise, on average, by 0.35°C per decade. This rise would call for greater equipment capacity to match the peak cooling demand.

Table 3
General information on the air conditioning system

	Design option 1	Design option 2
Waterside system		
Chiller type	Air-cooled centrifugal	Water-cooled centrifugal
Number of chiller and pump sets	4	2
Nominal COP at full load	2.7	5.7
Design chilled water supply/return temperature (^oC)	7/12.5	7/12.5
Design condenser water entering/leaving temperature (^oC)	-	29.4/34.4
Cooling tower type	-	2-speed fan
Chilled water loop	Constant primary-variable secondary	Constant primary-variable secondary
Airside system		
Type	FCU	FCU
Minimum airflow fraction	0.2	0.2
Fan motor efficiency	0.9	0.9

Table 4 shows how the equipment capacity with design options 1 and 2 will vary in 2020, 2050 and 2080 in relation to the TMY. In response to the higher cooling design temperatures under the climate change scenarios, the capacity of each piece of equipment needs to be extended by various degrees to meet the increasing peak cooling demand. Considering a 15-year operating life for air conditioning systems, the capacity should be extended by 3.0-3.3% for the chiller system and 0.02-1.78% for the airside equipment. This may suggest the use of a very moderate safety factor of up to 1.05 (increased capacity of 5%) instead of other arbitrary safety factors, say, from 1.1 to 1.2 to avoid oversizing of equipment while meeting the peak cooling demand.

Predicted Electricity Consumption and Carbon Emissions by the Chiller Systems

EnergyPlus performed the hour-by-hour simulation of the system cooling loads and hence the power of each system component, given each set of hourly weather data. Figure 2 shows the simulated monthly total electricity consumption of the chiller system with design options 1 and 2 under the baseline case. Data of the monthly mean dry bulb temperature are also included in Figure 4. A correlation was observed between the electricity consumption and the dry bulb temperature, because their variation follows a similar profile. This is consistent with findings of an existing chiller system by Chan et al. (2003). To reduce the electricity consumption of the chiller system, it is important to make the system components operate at their highest possible efficiency under the boundary ambient conditions.

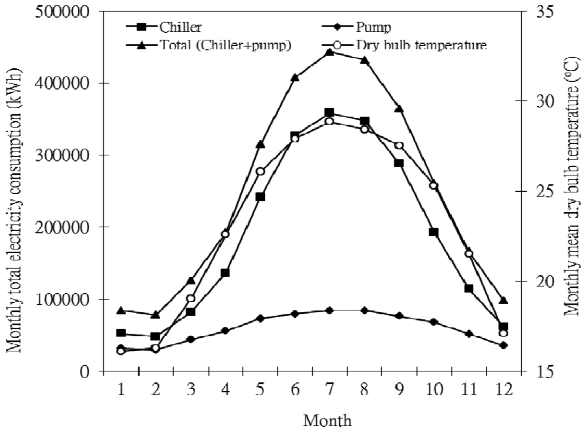
With regard to water-cooled chiller systems, the wet bulb outdoor temperatures dictate the boundary conditions, while the physical boundary to reduce compressor power for air-cooled chiller systems is the dry bulb outdoor temperature. As addressed by some studies, the existing head pressure control for both systems fails to draw on the lower limit of the temperature boundaries to minimize the trade-off between the powers of chiller system components (Joudi and Namik, 2003; Manske et al., 2001; Yang et al., 2012). The compressor power is kept high with a high condensing temperature for all operating conditions under head pressure control. Floating condensing temperature control is an alternative approach to reduce the compressor power of chillers operating at part load when the outdoor temperature drops from a design level. Electricity savings by this control could be around

Table 4
Equipment capacity with design options 1 and 2

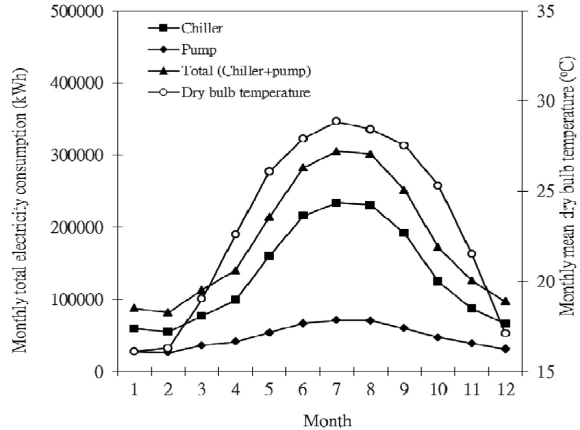
					Percentage change from the TMY (%)		
Year	TMY	2020	2050	2080	2020	2050	2080
System capacity (kW)	3765	3918	4180	4426	4.06	11.03	17.56
Waterside system (Option 1: Air-cooled chiller system)							
Chiller capacity (kW)	941	979	1045	1107	4.06	11.03	17.56
Primary/secondary chilled water pump flow (m^3/s)	0.13	0.14	0.15	0.16	4.06	11.03	17.56
Primary/secondary chilled water pump rated power (kW)	34.36	35.75	38.15	40.39	4.06	11.03	17.56
Waterside system (Option 2: Water-cooled chiller system)							
Chiller capacity (kW)	1883	1959	2090	2213	4.06	11.03	17.56
Primary/secondary chilled water pump flow (m^3/s)	0.13	0.14	0.15	0.16	4.06	11.03	17.56
Primary/secondary chilled water pump rated power (kW)	34.36	35.75	38.15	40.39	4.06	11.03	17.56
Condenser water pump flow (m^3/s)	0.19	0.20	0.21	0.23	4.06	11.03	17.56
Condenser water pump rated power (kW)	49.32	51.32	54.76	57.98	4.06	11.03	17.56
Airside system (FCUs for options 1 and 2)							
Functional areas							
A. Total capacity (kW)	120.80	122.73	125.76	128.35	1.60	4.11	6.25
A. Total flow (m^3/s)	3.51	3.53	3.56	3.59	0.57	1.42	2.28
A. Total rated power (kW)	0.38	0.38	0.38	0.39	0.60	1.58	2.45
B. Total capacity (kW)	265.05	268.66	274.44	279.40	1.36	3.54	5.41
B. Total flow (m^3/s)	8.82	8.82	8.82	8.83	0.00	0.00	0.11
B. Total rated power (kW)	0.94	0.94	0.95	0.95	0.04	0.10	0.15
C. Total capacity (kW)	196.15	199.52	205.06	209.87	1.72	4.55	7.00
C. Total flow (m^3/s)	6.57	6.62	6.71	6.78	0.76	2.13	3.20
C. Total rated power (kW)	0.70	0.71	0.72	0.73	0.79	2.07	3.21
D. Total capacity (kW)	867.75	881.61	903.76	923.23	1.60	4.15	6.39
D. Total flow (m^3/s)	28.43	28.62	28.92	29.19	0.67	1.72	2.67
D. Total rated power (kW)	3.05	3.07	3.10	3.13	0.68	1.74	2.71
E. Total capacity (kW)	14.42	14.75	15.28	15.74	2.29	5.93	9.17
E. Total flow (m^3/s)	0.51	0.52	0.53	0.54	1.96	3.92	5.88
E. Total rated power (kW)	0.05	0.06	0.06	0.06	1.30	3.24	4.94
F. Total capacity (kW)	12.26	12.48	12.98	13.41	1.84	5.88	9.38
F. Total flow (m^3/s)	0.57	0.58	0.60	0.61	1.75	5.26	7.02
F. Total rated power (kW)	0.06	0.06	0.06	0.07	1.07	4.08	6.56
G. Total capacity (kW)	15.45	15.73	16.19	16.59	1.81	4.76	7.37
G. Total flow (m^3/s)	0.53	0.53	0.54	0.54	0.00	1.89	1.89
G. Total rated power (kW)	0.06	0.06	0.06	0.06	0.72	1.80	2.75
H. Total capacity (kW)	41.43	42.24	43.56	44.75	1.95	5.15	8.01
H. Total flow (m^3/s)	1.40	1.41	1.43	1.44	0.71	2.14	2.86
H. Total rated power (kW)	0.15	0.15	0.15	0.15	0.81	2.07	3.21
I. Total capacity (kW)	1906.16	1943.88	2006.17	2062.47	1.98	5.25	8.20
I. Total flow (m^3/s)	81.84	82.44	83.41	84.27	0.73	1.92	2.97
I. Total rated power (kW)	8.77	8.83	8.94	9.03	0.74	1.90	2.95

Note: The meaning of areas A to I is given in Table 2.

Figure 2.
Monthly total electricity consumption of system components in the TMY



(a) Option 1: Air-cooled chiller system



(b) Option 2: Water-cooled chiller system

20% (Yu and Chan, 2010). Yet, floating condensing temperature control is not fully implemented in current chiller products. One reason is that a more sophisticated control algorithm is required to monitor the varying outdoor temperatures and correspondingly regulate the rotating speed of condenser fans for air-cooled chillers and cooling tower fans for water-cooled chillers. Traditional head pressure control for the two types of chiller, in fact, is done simply by maintaining a high temperature set point for all operating conditions. This hinders the optimum trade-off between the compressor power and fan power for power minimization.

The air-cooled chiller system led to a 36.7% increase in the annual electricity consumption in relation to the water-cooled system in the TMY, due to the lower COP of the chillers. When an air-cooled chiller system is an unavoidable choice for water conservation, it is important to design and operate air-cooled chillers at their highest COP as far as possible. Designing chillers with different capacities can increase capacity steps to enhance their high load operation at different cooling demands. About 9% of chiller electricity consumption could be reduced by this tactic if four equally sized chillers are replaced by two large and two small chillers (Yu and Chan, 2006). The analysis of such potential electricity savings calls for detailed simulation of a building cooling load profile which is not often considered a compulsory task in the detailed system design stage.

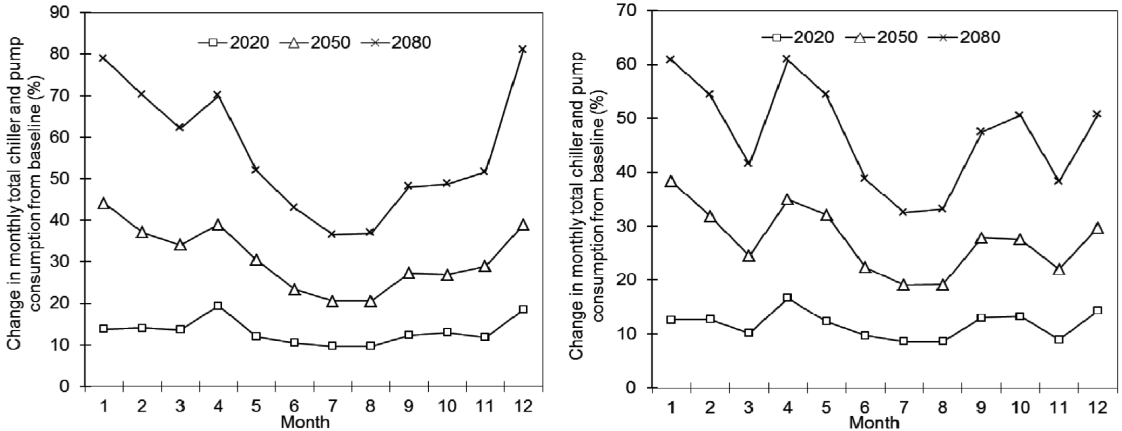
The outdoor air entering the condensers can be cooled by evaporative means to increase the COP of air-cooled chillers at part load operation, considering a likely considerable drop in the outdoor temperature from dry bulb to wet bulb in a hot and dry climate. With regard to air-cooled chillers operating under head pressure control, an electricity saving of around 5% could be achieved when mist is used to cool outdoor air for heat rejection. The electricity savings could be further increased to about 20% when mist pre-cooling of outdoor air is applied to air-cooled chillers operating under floating condensing temperature control (Yu and Chan, 2010). According to some pilot studies (Yu and Chan 2010; Yang et al. 2012), it is technically feasible to install mist systems for existing air-cooled chiller systems as they involve only several sets of compact high pressure pumps and a piping network to spray water mist near the air-cooled condensers. The switching of mist systems can be linked directly to the chillers operating. The water consumption for mist generation accounts for around 10% of water consumption for cooling towers in water-cooled chiller systems. More quantitative analysis and experimental tests will be undertaken to promote mist pre-cooling for air-cooled condensers as a standard measure to improve the COP of air-cooled chiller systems.

The energy effectiveness of a water-cooled chiller system can be improved by reducing its pumping power. Load based speed control should be considered for the chilled water pumps and condenser water pumps running at variable speed. Such control is also crucial for cooling tower fans to optimize the trade-off between the compressor power, pump power and fan power. About 10% electricity savings could be achieved from the control (Yu and Chan, 2012). Yet it may be infeasible to retrofit variable speed drives and implement load based speed control for existing chiller systems with constant speed control. One challenge is the use of fixed differential pressure control across the flow control valves to maintain the required flow rate of chilled water across the fan coil units. An insufficient flow of chilled water will occur in the fan coil units if the pressure setting of the control valves does not match the pump's pressure head available at the reduced flow rate. Another challenge is the minimum flow rate of chilled water and condenser water required to pass through the chillers. Chiller operators tend to be concerned about the operational instability and decline of efficiency when chillers operate at flow rates below the design conditions.

Figure 3 shows how climate change scenarios imposed changes in the monthly electricity consumption of the chiller systems from the baseline. Regarding a functional life of 15 years, the annual electricity consumption could increase by 9.9-10.6% for the air-cooled chiller system and 8.2-8.8% for the water-cooled chiller system. These percentage increases could partly account for the rising total electricity use in the hotel sector estimated by Chan (2005). The difference in the percentage range between the two systems suggests the importance of selecting highly efficient equipment which can maintain their performance to temper the increasing electricity consumption under climate change. Advanced controls should be fully implemented for air-cooled chillers to boost their COP, given that their application is unavoidable when water conservation is concerned.

Figure 4 gives the annual electricity consumption and carbon emissions of the chiller systems under the base year of 1990 and the climate change scenarios. From 2020 to 2080, the annual electricity consumption of the chiller system rises at an increasing rate. One way to temper the increasing electricity consumption is to adopt aforementioned technolo-

Figure 3.
Percentage change in monthly total electricity consumption of the systems in 2020, 2050 and 2080 from the baseline (TMY)



(a) Air-cooled chiller system

(b) Water-cooled chiller system

gies to boost the operating performance of chiller systems. Yet energy efficiency improvements (done on the demand side) may result in a moderate effect on reducing carbon emissions under climate change, considering that they cannot bring down greatly electricity consumption due to the increasing stock of hotels. If the carbon emission intensity in terms of kg CO_2/kWh remains constant, the trend of carbon emissions will follow the increasing electricity consumption. In fact, proactive carbon emissions control by the supply side—local power companies—is in place in response to the local government's intention to follow the Kyoto Protocol's target to reduce greenhouse gas emissions by at least 5% below 1990 levels from 2008-2012 (Lam, 2007). The decreasing trend in the annual carbon emissions by the chiller system in the reference hotel is due to the use of an indicative CO_2 emissions intensity target provided by a local power company—0.84 kg CO_2/kWh for the TMY; 0.7 kg CO_2/kWh for 2020; 0.2 kg CO_2/kWh for 2050; 0.07 kg CO_2 / kWh for 2080. Such a target is based on the reduction of carbon intensity in electricity generation by 75% in 2050 from the current level of 0.84 kg CO_2/kWh (CLP Holdings Ltd. 2012). Achieving this target will call for improved energy efficiency in power generation and extending

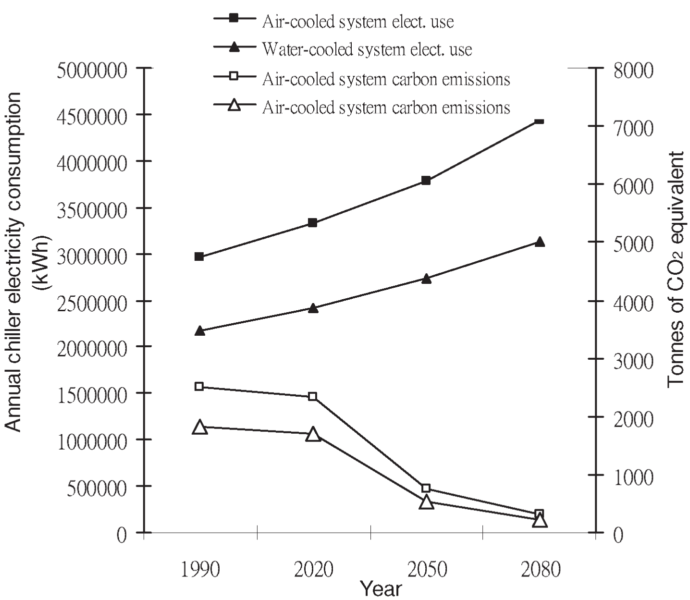


Figure 4. Annual electricity consumption and carbon emissions of the chiller systems in 1990 (base year), 2020, 2050 and 2080

non-carbon emitting power generation technologies including nuclear, large hydro and more than 5% of other renewable energy by 2020, etc.

CONCLUSIONS

The purpose of this study was to analyze how climate change influences electricity consumption and carbon emissions using building energy simulation for a chiller system in a reference hotel in Hong Kong. Two simulation programs were used to generate climate change scenarios and predict building energy consumption. Based on a typical meteorological year weather file for Hong Kong, hourly weather data for three climate change scenarios (2010-2039, 2040-2069 and 2070-2099) were forecasted by using the program CCWorldWeatherGen. The building simulation program EnergyPlus was used to simulate a reference hotel with a typical air-cooled or water-cooled chiller system.

Simulation results show that under climate change, a maximum of 5% extension of system capacity could be considered to meet the increasing cooling demand within a 15-year operating span. The annual electricity consumption could increase by 9.9-10.6% for the air-cooled chiller system and 8.2-8.8% for the water-cooled chiller system when it operates over a 15-year period under the climate change scenarios.

Implementing energy efficient and low carbon technologies in hotels (the demand side) should be considered to temper the increasing electricity consumption and, in turn, carbon emissions under the warmer future climate. Yet power companies (the supply side) need to take a dominant role in controlling their carbon emissions intensity in terms of kg CO_2/kWh in order to meet carbon reduction targets.

Based on some past studies, some feasible energy efficient technologies are highlighted below for designing and operating chiller systems with improved performance.

- Design a system with different chiller capacities to increase its capacity steps to match various system loads (indicative electricity saving of around 9%)
- Use floating condensing temperature control in lieu of head pressure control to improve part load performance, drawing on the benefits of enhanced heat rejection with moderate outdoor temperatures (indicative electricity saving of around 20%)

- Apply load based speed control to chilled water pumps, condenser water pumps and cooling tower fans to reduce pump and fan power under part load conditions (indicative electricity saving of about 10%)
- Use mist precooling of outdoor air to improve the heat rejection effectiveness of air-cooled chillers operating in a hot and dry climate (indicative saving of about 5% under head pressure control and 20% under floating condensing temperature control)

The significance of this study is to let building energy managers know more about how the operation of energy intensive chiller systems in hotels influences the electricity demand trend and carbon emissions under climate change. The indicative electricity savings were identified to be in the range of 5-20% when improving the energy performance of chiller systems based on the aforementioned energy efficient technologies. A building energy manager could benefit from energy and cost savings by implementing the aforementioned energy efficient technologies. With support from the top management, staff of the engineering division can perform financial analysis to ascertain which energy management opportunity is economically viable under the budgetary constraints. It is anticipated that the building sector would perceive a positive image on efforts paid to alleviate carbon emissions resulting from proactive implementation of energy efficient technologies in engineering systems in hotels.

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Glossary

1. Air-handling unit—a device used to cool and dehumidify air by cooling coils and as a part of an air conditioning system.
2. Chiller—a machine which produces chilled water via a vapor compression cycle to absorb heat from indoor areas. It basically consists of an evaporator to absorb heat, a compressor for refrigerant compression work, an expansion valve to control refrigerant

flow and a condenser to reject the heat absorbed.

3. Coefficient of performance (COP) —defined as the cooling energy output in kW over the compressor electric input in kW.
4. Cooling tower—a device to transfer heat absorbed from a water condenser to the outdoor by evaporation of water. It contains a fan to deliver the amount of outdoor air required for the evaporative process.
5. Fan coil unit—a device consisting of a cooling coil and a fan to deliver conditioned air to indoor areas.
6. Typical meteorological year (TMY) —a collection of representative hourly weather data from multiple years over a long period of time which presents the long-term averages of the data.
7. Weather variables:
   - Atmospheric pressure—the force exerted onto a surface of unit area by air above that surface (unit: Pa).
   - Dew point temperature—the temperature below which water vapor in moist air will condense into liquid water (unit: °C).
   - Diffuse horizontal radiation—the solar radiation component that strikes a point on a unit area of a horizontal surface from the sky (unit: W/m^2)
   - Direct normal radiation—the amount of solar radiation on a unit area of a surface from the direction of the sun (unit: W/m^2)
   - Dry bulb temperature—the temperature of air measured by a thermometer freely exposed to the air but shielded from radiation and moisture (unit: °C)
   - Global horizontal radiation—the sum of direct radiation normal to a surface and diffuse horizontal radiation on that surface (unit: W/m^2).
   - Moisture content—the amount of water vapor contained in moist air (unit: g/kg dry air)
   - Wind speed—the travelling distance of outdoor air per unit time (unit: m/s)

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