ELSEVIER

Energy and Buildings 33 (2001) 151–166

ENERGY AND BUILDINGS

www.elsevier.com/locate/enbuild

Predicting air-conditioning energy consumption of a group of buildings using different heat rejection methods

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Received 19 August 1999; accepted 2 August 2000

Abstract

Water-cooled air-conditioning systems (WACS) are, in general, more energy efficient than air-cooled air-conditioning systems (AACS). The Laws of Hong Kong prohibit the use of fresh water from town mains for comfort air-conditioning, which rules out the use of cooling towers to most air-conditioned buildings. In the absence of lakes or major rivers in Hong Kong, only those buildings that are situated near the harbor can adopt WACS. As a measure to cut down greenhouse gases emissions, the Hong Kong Government is currently exploring the feasibility and viability of widening the use of WACS by the provision of centralized, district-wide water supply systems, which include seawater supply systems for once-through condenser cooling or for making up of water losses at cooling towers, and district cooling systems. Evaluation of the likely energy, economic and environmental benefits of such capital-intensive infrastructure developments requires estimation of the simultaneous cooling demand of a large group of buildings on a district scale, and the energy use for air-conditioning such buildings. This paper describes the method used in these estimations. Comparisons of the results estimated by this method with results obtained by detailed simulation, and with building energy use data obtained from surveys and audits are presented.

Keywords: Commercial buildings; Energy; Hong Kong; Simulation; Water-cooled air-conditioning systems; Cooling load profiles; Electricity consumption profiles; Surveyed consumption data

1. Introduction

Being intensive electricity consumers, buildings worldwide share a substantial responsibility for the consumption of nonrenewable energy resources and the greenhouse gases emissions consequent to electricity generation. For modern cities in the tropical and sub-tropical regions, air-conditioning systems are the dominant electrical loads in buildings. In such cities, improving the efficiency of using electricity for air-conditioning in buildings is, therefore, a key measure for conservation of energy resources and protection of the environment.

Water-cooled air-conditioning systems (WACS) are, in general, more energy efficient than air-cooled air-conditioning systems (AACS). In consideration of the long-term saving in energy cost, many buildings in Hong Kong that are situated near the harbor and have pump house(s) at the seashore available for their use are already using WACS. For buildings that are remote from the harbor, WACS could still be adopted in conjunction with using cooling towers. The water supply needed for replenishing the water losses at cooling towers would be 1–3% of the condenser water flow rate only, which could be coped with by the town mains for potable water supply. Unfortunately, the Laws of Hong Kong [1] prohibit the use of fresh water from the town mains for comfort air-conditioning, as fresh water is regarded as a scarce resource. Consequently, the majority of buildings in Hong Kong are restricted to AACS. Such a restriction is uncommon amongst modern cities worldwide.

In view of the substantial reduction in electricity consumption that can be made possible through facilitating buildings that are currently restricted to using AACS to adopt or convert to WACS, the Hong Kong Government is exploring the feasibility of widening application of WACS in Hong Kong [2]. This would require the development of centralized systems for supplying seawater to buildings for the purpose of heat rejection, or chilled water that can be used directly for air-conditioning. The schemes being investigated include the following:

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PII: S0378-7788(00)00094-3

1. Centralized piped seawater supply for condenser cooling (CPSSCC).
2. Centralized piped seawater supply for cooling towers (CPSSCT).
3. District cooling systems (DCS).

A CPSSCC system will comprise a centralized seawater pumping station and a supply and return piping network for distribution of seawater to the connected buildings for once-through condenser cooling, and for the used seawater to return to the harbor. A CPSSCT system is similar to a CPSSCC system, but the flow rate to be delivered will be much smaller and there is no need for a return pipe, as the majority of the seawater will be lost at the cooling towers, and the relatively small amount of water bled-off from cooling towers for water quality control can be disposed off through the public sewers. Consideration is also being given to allowing buildings to use fresh water from the town mains for making up of cooling tower water losses, but this scheme can be implemented only in those districts that have water supply systems capable of coping with the additional water demand.

A DCS is a centralized plant that supplies chilled water to a group of buildings. When connected to a DCS, a building will no longer require a major chiller plant of its own, but will still require a pumping system for circulation of the chilled water to the airside equipment. A DCS is able to take advantage of the diversity in cooling demands amongst the connected buildings, and can be run more efficiently, particularly during the light load periods (e.g. between late night and early morning in cool winter days).

There is no evidence that CPSSCC systems have been widely used on a large scale in any major cities. CPSSCT systems that are dedicated for air-conditioning purposes would also be rare, since few places would have the restriction on the use of potable water supply for making up of cooling tower water losses. However, district heating and cooling systems have already been widely used for decades in many countries, particularly in North America, Europe and Japan, for providing steam, hot water and/or chilled water to buildings. More recently, DCS plants can also be found in Southeast Asian countries such as Singapore and Malaysia.

Combining a DCS with plants that provide other energy services, such as heating and electricity, can further increase the overall efficiency of providing the energy services. It has been claimed that, through district cogeneration systems, efficiencies can be boosted to 70–80%, whilst conventional power plants have an average efficiency of about 30% only [3]. Encouraging investments in cogeneration plants, however, would require deregulation of electricity supply [4], but this will remain impossible in the near future in Hong Kong, albeit the power companies that have the monopoly to generate and sell electricity could also be the providers of cooling service for buildings.

The centralized systems under consideration for implementation in Hong Kong, especially the CPSSCC and DCS schemes, are capital-intensive infrastructure developments. Detailed studies are therefore required prior t making implementation decisions. The range of studie should embrace comparisons of the energy, economic an environmental benefits of each of the schemes, and th capital investment and the degree of difficulty that will b involved in the implementation. Greater difficulties ar anticipated in the implementation of the CPSSCC an DCS schemes in developed districts, but much less so i new districts, as there will be much less interruption from th engineering work and will not involve replacement o equipment in existing buildings. The marketability an potential of attracting private investments, the scale an stages of implementation etc. will also need to be carefull assessed.

2. Comparison of air-conditioning electricity consumption of existing buildings using AACS and WACS

In order to obtain an indication of the energy saving th would be achievable by converting AACS in buildings t WACS, the electricity consumption data of 23 existin office/commercial buildings and 16 existing hotels in Hon Kong were analyzed and compared. These data were co lected in recent energy surveys and audit studies [5,6]. Th electricity consumption data shown in Table 1 are th landlords' electricity consumption of the surveyed offic commercial buildings, whilst those summarized in Table are the annual air-conditioning energy consumption of t audited hotels.

The landlord's consumption refers to the total electrici consumption of central services systems in a building, whi includes air-conditioning and mechanical ventilation sy tems, lighting installations in public areas, vertical tran portation systems, plumbing and drainage systems, a various other systems connected to the landlord's electric power system. Tenants in a building are supplied wi electricity through feeders that are separate from tho for the landlord's services and their consumption is indi dually metered by the power company, and are in general n available for audits.

The annual electricity consumption data summarized Tables 1 and 2 have been normalized by the gross floor are (GFA's) of the respective buildings, and are referred to energy use intensity (EUI) or air-conditioning energy u intensity (A/C EUI). The "mean" values shown in Table are the area-weighted mean electricity consumption of t landlord's services amongst the surveyed office/commerc buildings.

It can be seen from Tables 1 and 2 that even though t same heat rejection medium is used, the electricity c sumption for air-conditioning can vary largely from o building to another. Such variations could arise from t differences in the building envelope designs, maintain indoor conditions and ventilation rates, hours of operati

Table 1
Characteristics and the landlord's EUI of 23 office/commercial buildings in Hong Kong[a]

Description	No. of buildings			
	Minimum	Maximum	Mean	Total
(A) Buildings with AACS				
(1) Direct air-cooled — 10				
Area per floor in office tower (m^2)	213	2110	1200	
Total GFA in office tower (m^2)	4050	10200	29800	298000
Area per floor in podium (m^2)	0	5530	1830	
Total GFA in podium (m^2)	0	33200	11900	54300
Total GFA of building (m^2)	5270	105000	35200	352000
Landlord's EUI (kW h/m^2)	110	250	206	
(2) Indirect air-cooled — 2				
Area per floor in office tower (m^2)	1180	1710	1530	
Total GFA in office tower (m^2)	50800	145000	98000	196000
Area per floor in podium (m^2)	1300	6890	4740	
Total GFA in podium (m^2)	13000	110000	61600	123000
Total GFA (m^2)	63800	256000	160000	319000
Landlord's EUI (kW h/m^2)	195	315	219	
(3) All buildings with AACS — 12				
Area per floor in office tower (m^2)	213	2110	1310	
Total GFA in office tower (m^2)	4050	145000	41100	494000
Area per floor in podium (m^2)	0	6890	3190	
Total GFA in podium (m^2)	0	110000	20200	178000
Total GFA (m^2)	5270	256000	56000	672000
Landlord's EUI (kW h/m^2)	110	315	212	
(B) Buildings with WACS				
(1) Indirect SW cooled with cooling towers — 17				
Area per floor in office tower (m^2)	469	3450	1860	
Total GFA in office tower (m^2)	7500	122000	59400	416000
Area per floor in podium (m^2)	750	5100	2230	
Total GFA in podium (m^2)	2250	20400	8930	62500
Total GFA (m^2)	9750	138000	68300	478000
Landlord's EUI (kW h/m^2)	134	316	177	
(2) Indirect SW cooled with heat exchangers — 4				
Area per floor in office tower (m^2)	975	2210	1440	
Total GFA in office tower (m^2)	21200	39600	28500	114000
Area per floor in podium (m^2)	1730	2920	2430	
Total GFA in podium (m^2)	3690	14600	9700	38900
Total GFA (m^2)	34900	46500	38200	153000
Landlord's EUI (kW h/m^2)	182	249	211	
(3) All buildings with WACS — 11				
Area per floor in office tower (m^2)	469	3450	1750	
Total GFA in office tower (m^2)	7500	122000	48200	530000
Area per floor in podium (m^2)	750	5100	2300	
Total GFA in podium (m^2)	3690	20400	57400	101000
Total GFA (m^2)	9750	138000	57400	631000
Landlord's EUI (kW h/m^2)	134	316	185	

[a] Energy use intensity (EUI) means the annual electricity consumption per square meter of the floor area in the building; GFA means gross floor area.

intensity of internal loads and occupancy densities in the different types of premises in the buildings, and in the efficiency of the air-conditioning systems. Nonetheless, it can be seen that there is a significant difference in the mean EUI values between buildings that are equipped with AACS and WACS. For office/commercial buildings, the difference in the average landlord EUI is 27 kW h/m^2 (=212–185, Table 1), and for hotels, the difference in the average A/C EUI is 49 kW h/m^2 (=217–168, Table 2).

The differences in electricity consumption are quite substantial and may be regarded as the "average" saving that would be achievable by using WACS in lieu of AACS, for a group of office/commercial and hotel buildings, implemented on an individual building basis. Even greater saving may be expected if a DCS is employed to provide chilled water for a group of buildings. The difference for hotels is larger because their air-conditioning systems are continuously operated, whereas systems are only intermittently operated

Table 2
Characteristics and A/C EUI of 16 hotel buildings in Hong Kong[a]

Description	No. of hotels			
	Minimum	Maximum	Mean	Total
(A) Hotels with **AACS**[b] — 6				
Grade (no. of stars)	3	5	3.8	
Year built	1988	1993	1990	
No. of guest rooms	216	500	372	2232
No. of restaurants	1	6	2.5	15
Total GFA of building (m^2)	12900	32600	21400	129000
Annual energy consumption per m^2 (MJ/m^2)	1570	2950	2100	
EUI ($kW\,h/m^2$)	320	439	384	
A/C EUI ($kW\,h/m^2$)	166	257	217	
(B) Hotels with WACS[b] — 10				
Grade (no. of stars)	4	5	4.7	
Year built	1969	1994	1983	
No. of guest rooms	450	862	591	5909
No. of restaurants	1	8	5.5	55
Total GFA of building (m^2)	28800	66900	44800	448000
Annual energy consumption per m^2 (MJ/m^2)	1538	3371	1980	
EUI ($kW\,h/m^2$)	250	844	412	
A/C EUI ($kW\,h/m^2$)	128	231	168	
(C) All hotels in the sample[b] — 16				
Grade (no. of stars)	3	5	4.4	
Year built	1969	1994	1986	
No. of guest rooms	216	862	509	8141
No. of restaurants	1	8	4.4	70
Total GFA of building (m^2)	12900	66900	36000	577000
Annual energy consumption per m^2 (MJ/m^2)	1070	3370	2030	
EUI ($kW\,h/m^2$)	250	844	406	
A/C EUI ($kW\,h/m^2$)	128	257	177	

[a] A/C means air-conditioning; energy use intensity (EUI) means the annual electricity consumption per square meter of the floor area in the building; GFA means gross floor area.

[b] Envelope design: (A) curtain wall — 1, window wall — 5; (B) curtain wall — 6, window wall — 4; (C) curtain wall — 7, window wall — 9.

in office/commercial buildings. Also, many hotels in the sample use direct seawater-cooled chiller plants, which are more energy efficient than the indirect seawater-cooled plants and plants with seawater cooling towers that are more commonly used in the surveyed office/commercial buildings (Table 1).

These results are prima facie evidence that promoting wider use of WACS would be very effective in reducing electricity use for air-conditioning buildings in Hong Kong.

3. Cooling load prediction methods

Detailed evaluation of the energy, economic and environmental benefits that could be realized by adopting each of the WACS scheme options requires the ability to predict the simultaneous cooling load of a variety of buildings on a "district" scale. Such buildings would comprise a mix of uses, such as offices, retail shops, restaurants and hotel guestrooms. Both the simultaneous design peak cooling load and the simultaneous realistic cooling load of the buildings in a district need to be predicted. The design cooling load prediction would be needed to determine the capacity required of the central cooling water supply system or the district cooling system, which would ensure that the plant capacity so sized would be sufficient to cope with the cooling demand for a sufficiently high confidence level (97.5% in the cooling months is recommended by American Society of Heating, Refrigeration and Air Conditioning Engineer (ASHRAE) [7]). The realistic cooling load predictions would allow the simultaneous demands for electricity and for condenser cooling water or chilled water, at different times in the year, to be estimated. The relative benefits of the WACS scheme options can then be assessed.

Three simulation programs, namely HKDLC [8], HTB2 [9] and BECON [10], were used as prediction tools in this study. HKDLC is a design cooling load calculation program, whereas HTB2 is a detailed building heat transfer simulation program that can predict the realistic cooling loads of a building at different times of the year. BECON is an air-conditioning system simulation program, which can predict the hourly power consumption of air-conditioning equipment on the basis of the cooling loads predicted by HTB2. More detailed descriptions of these programs are given in Appendix A.

Although HKDLC, HTB2 and BECON could be used repeatedly to generate cooling load and air-conditioning electricity consumption predictions for a large number of buildings, their use would require the preparation of rather detailed input data for adequately describing the buildings and the air-conditioning systems. Given the large number of buildings that would be involved in studying the performance of district-wide systems, the time and effort required for preparing the input files and to perform the simulation work are prohibitive. Therefore, a simplified method has been developed for faster determination of the profiles of design and realistic cooling loads, and the air-conditioning electricity consumption in buildings.

3.1. Cooling load profile models

The approach adopted was to establish a design and a realistic cooling load profile model for each major type of premises that can be found in typical air-conditioned buildings. Since offices, retail shops, restaurants and hotel guestrooms are the major types of premises in buildings in a commercial district, models were established for each of these premises, which were based on detailed simulation predictions using HKDLC and HTB2. In order to make the models applicable to premises of different floor areas, the predicted cooling loads were normalized into intensities of cooling loads per square meter of the GFA of the premises. Having established these cooling load profile models, the cooling load of an office/commercial building complex can be estimated from the office, retail shop and restaurant models. Likewise, the guestroom, retail shop and restaurant models will allow the cooling load of a hotel to be estimated. The method is expressed mathematically as follows:

$$Q_{\mathrm{D},k}(t) = \sum_{i=1,2,3,4} q_{\mathrm{D},i}(t) A_{i,k} \tag{1}$$

$$Q_k(t) = \sum_{i=1,2,3,4} q_i(t) A_{i,k} \tag{2}$$

where $Q_{\mathrm{D},k}(t)$ is the design cooling load of building k at time t (a given month and hour in the day) (kW), $q_{\mathrm{D},i}(t)$ the normalized design cooling load of type i premises at time t (kW/m^2), $Q_k(t)$ the cooling load of building k at time t (a particular hour among the 8760 h in a year) (kW), $q_i(t)$ the normalized cooling load of type i premises at time t (kW/m^2), and where $A_{i,k}$ is the area of type i premises in building k (m^2).

As shown in Eqs. (1) and (2), each cooling load profile model ($q_{\mathrm{D},i}(t)$ or $q_i(t)$) comprises a time series of the year-round hourly cooling load intensities of a specific type of premises. This is an essential feature to allow the cooling load variation patterns of different types of premises to be taken into account in the determination of the simultaneous cooling load of a building.

The simultaneous design cooling load ($Q_{\mathrm{D,total}}(t)$) and realistic cooling load ($Q_{\mathrm{total}}(t)$) of a group of buildings at a particular time in the year can be determined as follows:

$$Q_{\mathrm{D,total}}(t) = \sum_k Q_{\mathrm{D},k}(t) \tag{3}$$

$$Q_{\mathrm{total}}(t) = \sum_k Q_k(t) \tag{4}$$

From the hourly results, the simultaneous peak cooling load on a district cooling system can also be determined.

In order that the models would be able to provide good predictions for a large number of buildings, the cooling load intensity data in the models should be representative of the "average" cooling load intensities of the corresponding types of premises in buildings in Hong Kong.

3.2. Office premises

The survey on the 23 office/commercial buildings (summarized in Table 1) did not aim at obtaining comprehensive information about their building construction, which restricted the use of these buildings in detailed cooling load simulation studies. Instead, the design and realistic cooling load profile models for office premises were established based on the office towers of six existing office/commercial buildings, five new building designs and one hypothetical office tower design, of which the required data were available. Characteristics of the 12 buildings and the internal load criteria adopted in the simulation studies are summarized in Table 3. The cooling load profiles were developed from the sum of concurrent cooling loads of the 12 buildings, as predicted by HKDLC and HTB2, and normalized by the total GFA of these buildings.

The patterns of occupancy and lighting loads used in the simulation study are summarized in Table 4, in fractions of their design intensities. Appliance loads in office buildings, however, were assumed to remain at 25 W/m^2 during the occupied hours. The lighting load intensities shown in Table 3 are actual figures used in designing air-conditioning systems for the buildings. The average design lighting load intensity of these 12 office buildings is 20.1 W/m^2.

It was found in a recent energy end-use survey [11] that lighting energy use in offices in Hong Kong amounted to 1906 TJ in 1994. The size of this building segment was 6,895,000 m^2. This reported energy use figure however includes energy use of lighting installations both inside and outside air-conditioned office spaces, such as lighting in staircases, lift lobbies, toilets, etc. The calculated average figure of 20.1 W/m^2 would lead to an annual electricity consumption of 1738 TJ for the same total area of offices as in 1994 over a year-round total of 3484 operating hours of (the total hours of operation in a year used in the simulation). This accounts for 91% of the total energy use for lighting in the office building segment in 1994, which is considered a reasonable figure for lighting installations inside air-conditioned office spaces. Therefore, the average value of the design lighting load intensities of the 12 office buildings

Table 3
Summary of characteristics of office towers[a]

	Building											
	A	B	C	D	E	F	G (model)	H	I	J	K	L
GFA (m^2)	61600	34300	23500	1904	36860	70140	51840	48960	21000	55480	61440	32160
Aspect R	1.6	1.5	1.4	1	4.4	1.1	1	1.1	1.8	1.5	1.6	1.5
Major exp	NE, SW	N	E, W	SE	W	N and S	N, E, S and W	E, W	W	N, S	N, S	N and W
WWR	0.16	0.8	0.49	0.4	0.53	0.7	0.5	0.58	0.18	0.35	0.29	0.42
Wall U ($W/m^2 K$)	1.4	2.8	0.2	1.9	2.2	0.5	0.9	0.7	1.2	0.6	0.7	0.4
Roof U ($W/m^2 K$)	0.7	0.5	0.5	0.7	3.5	1	0.5	0.4	N/A	N/A	0.35	0.58
Glass U ($W/m^2 K$)	2.7	5.3	5.5	3.1	5.3	4.9	5.4	5.3	5.1	5.3	5.3	5.2
Glass SC	0.45	0.5	0.25	0.63	0.53	0.73	0.45	0.2	0.3	0.34	0.22	0.24
OTTV (W/m^2)	11.8	38.8	18.1	15.5	39.1	75.2	34.7	20.7	15.8	19.2	17.8	15.7
Indoor T (°C)	25.5	23	24	23	24	23.5	25.5	24	25.5	25	24	24
Indoor RH (%)	54	55	55	55	55	55	54	55	55	54	55	55
Occup (m^2 per person)	14	9	9	9	9	14.2	9	9.4	9	5.9	8	9
Lighting (W/m^2)	16	25	24	25	18	14	25	21.3	25	21.6	25	25
Appliance (W/m^2)	25	25	25	25	25	25	25	25	25	25	25	25
V. rate (l/s per person)	14.2	13.4	7	8	5.1	12	10	6.7	10	6.3	6.5	10
Inf. Rate (ACH)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
HRM	DSWC	InDSWC	DSWCCT	Aircool	Aircool	InDSWC	Aircool	Aircool	Aircool	InDSWC	DSWC	DSWCCT
COP	4.1	5.1	4.6	2.5	2.4	4	2.8	2.6	2.9	4.1	5.2	4.8
Airside S	fcu	vav	vav	cav	vav	cav + vav	vav	vav	vav	vav	vav	vav

[a] GFA: gross floor area; Occup: occupancy; DSWC: direct seawater cooled; Aspect R: aspect ratio of floor plan; Lighting: lighting load intensity; InDSWC: indirect seawater cooled; Major exp: major exposure; Appliance: appliance load intensity; DSWCCT: DSWC with cooling tower; WWR: window to wall area ratio; V. rate: ventilation rate; Aircool: air cooled; Wall U: average U-value of wall; Inf. rate: infiltration rate; fcu: fan coil unit system; Roof U: average U-value of roof; HRM: heat rejection method; cav: constant air volume system; Glass U: U-value of glass; COP: rated cop of chiller; vav: variable air volume system; Glass SC: shading coefficient of glass; Airside S: air-side system design; cav + vav: dual conduit system; OTTV: overall thermal transfer value; ACH: air change per hour; Indoor T: indoor dry-bulb temperature; Indoor RH: indoor relative humidity.

Table 4
Occupation, lighting load profiles and fresh air supply system operating schedule for office premises

Day in the week	Hour	Occupancy	Lighting (perimeter)	Lighting (interior)	Fresh air supply
Weekdays	1–7	0	0.05	0.05	Off
	7–8	0.05	0.1	0.1	Off
	8–9	0.4	0.5	0.5	On
	9–10	0.95	0.9	1	On
	10–11	0.95	0.9	1	On
	11–12	0.95	0.9	1	On
	12–13	0.95	0.9	1	On
	13–14	0.95	0.8	0.9	On
	14–15	0.95	0.9	1	On
	15–16	0.95	0.9	1	On
	16–17	0.95	0.9	1	On
	17–18	0.5	0.8	0.8	On
	18–19	0.25	0.5	0.5	On
	19–20	0.1	0.3	0.3	Off
	20–21	0.05	0.2	0.2	Off
	21–24	0	0.05	0.05	Off
Saturdays	1–7	0	0.05	0.05	Off
	7–8	0.05	0.1	0.1	Off
	8–9	0.3	0.5	0.5	On
	9–13	0.6	0.75	0.8	On
	13–17	0.1	0.2	0.2	Off
	17–18	0.05	0.1	0.1	Off
	18–24	0	0.05	0.05	Off
Sundays	1–9	0	0.05	0.05	Off
	9–17	0.05	0.1	0.1	Off
	17–24	0	0.05	0.05	Off

may be considered representative of office buildings in Hong Kong.

In the energy end-use survey [11], the energy consumption of equipment in office buildings in Hong Kong in 1994 was found to be 2192 TJ. When converted into electricity consumption per unit area, this amounts to about 88 kW h/m^2. Assuming the annual operating hours to be also 3484 h, the steady rate of electricity consumption of the equipment would be about 25.3 W/m^2. It can be seen that this value compares well with that used in the simulation of cooling load for the 12 buildings.

3.3. Retail shops and restaurants

The cooling loads of retail shops and restaurants are usually dominated by the internal loads from the occupants, lighting and appliances, and by the ventilation loads, whereas the building envelope design will have relatively little influence. Therefore, representative cooling load profiles can be generated as long as the heat gain profiles and ventilation rates used in the simulation studies can reflect the typical conditions arising in retail shops and restaurants.

The cooling load profile models for retail shops and restaurants were each derived on the basis of a model floor, with layout and envelope designs conforming to a retail shop floor and a restaurant in an existing commercial building. The internal load and ventilation criteria adopted and the patterns of variations in occupancy, lighting and appliances loads used in the simulation study are summarized in Table 5. The simulated cooling load profiles were normalized by the GFA of the retail and restaurant model floors, respectively, to yield the cooling load profile models for these premises.

On the basis of the load factors for lighting and equipment loads in retail and restaurant premises, and the annual operating hours, the annual electricity consumption of lighting installations and equipment in retail and restaurant premises have been calculated and summarized in Table 5. The load factors (equivalent full-load hours as a fraction of the total operating hours) were determined on the basis of the assumed operating hours and intensity profiles of lighting and equipment loads (Table 5). The lighting and equipment energy consumption in retail and restaurant building segments given in the energy end-use survey report [11] is summarized in Table 6.

The consumption figures shown in Table 6 are the total values of all retail shops surveyed, which include those in shopping malls and at street sides. However, closer examination of the data revealed that the lighting loads of shops in commercial buildings with central air-conditioning were significantly higher than in other types of buildings. The average lighting load of retail shops in centrally air-conditioned buildings was found to be 297 kW h/m^2, which is close to that on which the model was based (292 kW h/m^2, Table 5). Moreover, the equipment consumption in retail

Table 5
Occupancy, lighting and appliance loads and ventilation rates for retail shops and restaurants

Time (h)	Pattern in the day (fraction of design intensity)							
	Retail				Restaurant			
	Occupancy — 5 m^2 per person	Lighting — 70 W/m^2	Appliances — 30 W/m^2	Ventilation rate — 7 l/s per person	Occupancy — 1.5 m^2 per person	Lighting — 30 W/m^2	Appliances — 30 W/m^2	Ventilation rate — 7 l/s per person
0–6	0	0	0	0	0	0	0.05	0
6–10	0	0	0	0	0.6	0.9	0.75	1
10–11	0.25	0.95	0.75	1	0.6	0.9	0.75	1
11–12	0.25	0.95	0.75	1	0.9	0.9	0.75	1
12–14	0.75	0.95	0.75	1	0.9	0.9	0.75	1
14–18	0.25	0.95	0.75	1	0.05	0.5	0.6	1
18–22	0.75	0.95	0.75	1	0.75	0.95	0.75	1
22–24	0	0	0	0	0.05	0.25	0.1	1
Occupied hours per day	12	12	12	12	18	18	18	18
Load factor		0.95	0.75			0.75	0.5	
Annual electricity consumption (kW h/m^2)		292	99			148	131	

Table 6
Lighting and equipment load in retail shops and restaurants

	Unit	Retail	Restaurant
Total area	m^2	5214008	3092287
Lighting consumption	TJ	4327	1890
	kW h/m^2	231	170
	kW h/m^2	297[a]	144[a]
Equipment consumption	TJ	2581	4110
	kW h/m^2	138	369
	kW h/m^2	100[a]	126[a]

[a] Adjusted values.

areas includes the consumption of other services' systems serving the premises, such as vertical transport systems and plumbing and drainage systems. Discounting the consumption of these systems, which are outside the air-conditioned spaces, the equipment load in retail premises reduced to around 100 kW h/m^2, which is close to that used in establishing the cooling load profile model (99 kW h/m^2, Table 5).

For restaurants, the lighting and equipment load figures include lighting installations and equipment in both the sitting areas and the kitchens. Assuming that the sitting area accounts for 85% of the lighting load, and 35% of the equipment load, the lighting and equipment load becomes 144 and 129 kW h/m^2, respectively. These values are close to those used in establishing the cooling load profiles for restaurants (148 and 131 kW h/m^2, Table 5).

3.4. Hotels

A building model for the guestroom tower of a hotel was devised for predicting the cooling loads in hotel guestroom floors using HKDLC and HTB2. The model was established on the basis of the average number of guestrooms and floor areas of 16 existing hotels, the characteristics of which are summarized in Table 2. The model guestroom tower comprises 500 guestrooms on 25 stories, each with a floor area of 800 m^2 accommodating 20 guestrooms. The building envelope design has been tuned such that its OTTV (34 W/m^2) is within the limit specified in the Code of Practice for OTTV in buildings for hotel tower blocks (35 W/m^2 [12]). Reference has also been made to the survey data on lighting and appliances loads, and year-round occupation rates, in existing hotels [6]. Unfortunately, the data for hotels given in the energy end-use database report [11] were aggregated data of the guestroom and commercial portions in hotel buildings. The total consumption was not broken down into consumption of each of these two types of spaces for comparison with the results from the survey of the 16 hotels [6].

The assumed building characteristics of the hotel tower model, the internal load intensities, and the assumed patterns of occupancy, lighting and appliances loads are as summarized in Table 7. The occupancy, lighting and appliances load intensities in hotel guestrooms are expressed on per-room basis, which are more consistent amongst hotels. Less consistent values would result if the load intensities were expressed on per unit area basis, due to the varied room sizes amongst different hotels.

3.5. Normalized cooling load profiles

Fig. 1(a) shows the hourly cooling loads per square meter of GFA for the four types of premises in a day in July, which were extracted from the hourly cooling load profiles for these premises. Fig. 1(b) shows the monthly mean cooling load profiles of these premises, which were calculated from the hourly cooling load profiles. It can be seen that the cooling load intensity in restaurants is the highest amongst the four types of premises in commercial buildings in Hong Kong. Its diurnal and year-round variations are also the highest, which is given rise to by the dominant cooling load component associated with treatment of the large quantity of outdoor air for ventilation. The significantly different load patterns illustrate the importance of accounting for the cooling load characteristics of different types of premises in the prediction of the simultaneous cooling of a building that comprises a mix of premises.

4. Power consumption profiles

4.1. Approach

For predicting the electricity consumption of buildings for air-conditioning, electricity consumption profile models have been developed on the basis of predictions of HTB2 and BECON for the building and plant models of the office/commercial and hotel buildings. The objective is to allow electricity consumption for air-conditioning a building at a particular time to be predicted according to the concurrent building cooling load as predicted by the cooling load profile models outlined above. Four air-conditioning electricity consumption profile models have been established for air-cooled systems, water-cooled systems with cooling towers, direct seawater-cooled systems and indirect seawater-cooled systems (with heat exchangers between the fresh condenser water and the seawater circuits), respectively.

The rated coefficient of performance (COP) of the chillers assumed in the simulation for the four heat rejection methods are 2.8 for air-cooled systems, 4.7 for water-cooled systems with cooling towers and for indirect seawater-cooled systems, and 5.2 or direct seawater-cooled systems. The built-in chiller models within BECON [13] were used to model the part-load performance of chillers.

It is noted that, as long as an air-conditioning plant remains in operation, the airside equipment and at least one chiller unit and its associated pump(s), and where appropriate, one cooling tower, will continue to operate even if the cooling load on the plant approaches zero. Consequently, a significant amount of electricity will still be consumed under such conditions. The electricity con-

Table 7
Characteristics of the model for guestroom floors in a hotel building

Type	% of guestrooms	Time	Fraction of full occupancy	Fraction of maximum lighting load	Fraction of maximum small power load	Indoor temperatu (°C)
(A) Indoor conditions adopted in design load estimation for energy simulation						
1	72	0–8	1.00	0.17	0.54	24
		8–20	0.00	0.20	0.54	28
		20–24	1.00	0.97	0.99	24
2	20	0–8	1.00	0.17	0.55	24
		8–20	1.00	0.85	0.65	24
		20–24	1.00	0.97	0.99	24
3	8	0–8	0.00	0.17	0.47	28
		8–20	0.00	0.20	0.47	28
		20–24	0.00	0.17	0.47	28
Overall	100	0–8	0.92	0.17	0.54	–
		8–20	0.20	0.33	0.56	–
		20–24	0.92	0.91	0.95	–
(B) Indoor conditions adopted in design load estimation						
		0–8	1.00	0.17	0.54	24
		8–20	0.25	0.33	0.56	24
		20–24	1.00	0.91	0.95	24

(C) Characteristics and indoor design conditions for guestrooms
Gross floor area — 20,000 m^2
No. of stories — 25
No. of guestrooms — 500
Aspect ratio — 2.44
Major exposure — SE/NW
Window to wall area ratio — 0.5 for the major facade
Wall U-value — 1.74 W/m^2 K for the major facade
Roof U-value — 0.4 W/m^2 K
Glass U-value — 5.83 W/m^2 K
Glass shading coefficient — 0.56
OTTV — 33.8 W/m^2
Indoor temperature — 24°C reset to 28°C when unoccupied
Indoor relative humidity — 50%
Occupancy — two persons per room
Lighting load — 600 W per room
Appliance load — 100 W per room
Ventilation rate — 34.1 l/s per room
Infiltration rate — 0.1 ACH

sumption profile, therefore, needs to be decomposed into two components: one representing the consumption that varies with the cooling load on the chiller plant ($w_{\mathrm{var},j}$), and the other representing the minimum rate of electricity that the system will consume under zero load ($w_{\mathrm{min},j}$). The minimum consumption component has been expressed as a fraction of the rated power demand of the chiller plant in the models. The variable consumption models were derived from the difference between the predicted total air-conditioning system consumption (using BECON) and the minimum consumption at each hour of operation, which were then normalized by the corresponding cooling load on the system.

The air-conditioning electricity consumption profile models can be used to predict the electricity consumption for air-conditioning a building comprising a mix of premises types ($W_k(t)$) or a group of building complexes ($W_{\mathrm{total}}(t)$) as show below:

$$W_k(t) = w_{\mathrm{var},j}(t)Q_k(t) + w_{\mathrm{min},j}(t)\mathrm{PCap} \qquad (5$$

$$W_{\mathrm{total}}(t) = \sum_k W_k(t) \qquad (6$$

where $W_k(t)$ is the electricity consumption for air-conditioning building k at time t (kW), $w_{\mathrm{var},j}(t)$ the variable ai conditioning system electricity consumption at time t, fo heat rejection method j per kilowatt of cooling load on th system (kW/kW), $w_{\mathrm{min},j}(t)$ the minimum constant air-con ditioning system electricity consumption at time t, for hea rejection method j per kilowatt of installed plant capacit (kW/kW), and where PCap is the installed cooling capacit of the central air-conditioning plant (kW).

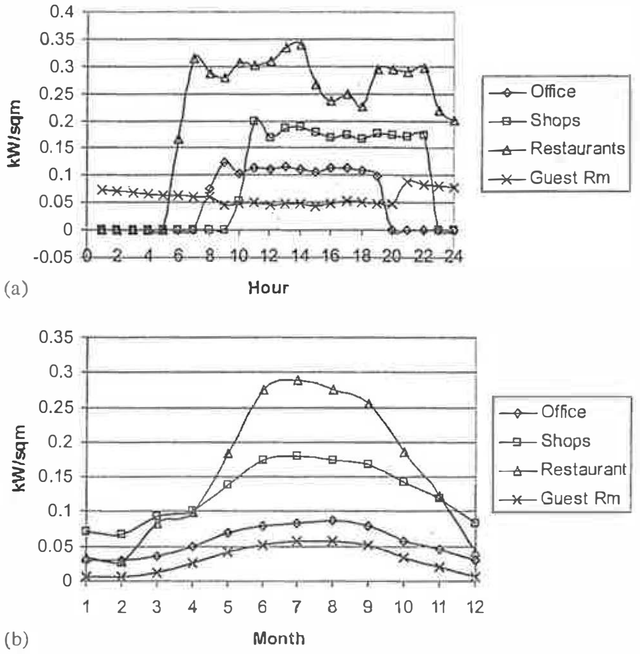

Fig. 1. Cooling load profiles of offices, retail shops, restaurants and hotel guestrooms: (a) hourly values in a day in July; (b) monthly mean values in the year (based on occupied hours for the respective type of premises).

By expressing the air-conditioning electricity consumption profile model as a time series of normalized hourly values throughout the year, the effects of variations in the outdoor air or seawater conditions in the year on the efficiency of the air-conditioning plants can be preserved.

Fig. 2 shows the monthly mean hourly chiller COP for four selected months, as well as the monthly mean COP values over the year, as predicted by the power consumption profile models for the four heat rejection methods. Fig. 2(e) shows that the monthly mean chiller COP would peak in April–May. This reflects the effect of lowering in the cooling medium temperature (air or seawater) during the mild weather months, leading to the improved chiller performance. It would become slightly lower during the hottest months of June–October. However, the monthly mean COP would drop substantially during the cold months, which is a result of the large reduction in cooling load, leading to chillers running under unfavorable part-load conditions.

5. Condenser water flow rate and cooling tower make-up rate profiles

Apart from the cooling load and the air-conditioning electricity consumption, the required water supply flow rates for condenser cooling and for cooling tower make-up for a group of buildings are essential variables that need to be evaluated for estimating the required output and power consumption of the centralized pumping systems of the CPSSCC and the CPSSCT schemes. The cooling water demand from a group of buildings ($V_{\text{total}}(t)$) was estimated based on the following equation:

$$V_{\text{total}}(t) = C_0\left(C\sum_k Q_k(t) + \sum_k V_{k,\min}\right) \tag{7}$$

where C is the conversion factor for determining the condenser water flow rate from the cooling load (=0.0529 l/s kW), $V_{k,\min}$ the minimum water flow rate demand from the kth building (l/s), $C_0 = 1.0$ for CPSSCC scheme, $C_0 = 0.017$ for CPSSCT using fresh water, and $C_0 = 0.03$ for the CPSSCT scheme using seawater.

The total condenser water flow rate in a water-cooled air-conditioning plant was estimated on the basis of a C value of 0.0529 l/s kW of cooling output of the chillers, in conjunction with the hourly cooling load of the building ($Q_k(t)$), as predicted by the cooling load profile model. This condenser flow rate corresponds to a chiller with a COP of 4.5 and a temperature difference of 5.5°C across the chiller condenser. The condenser water flow rate so estimated would also be taken as the water demand of a building when its plant is connected to a CPSSCC system (therefore, $C_0 = 1.0$).

For a chiller plant comprising multiple chillers, the condenser water flow rate will vary in steps according to the number of chillers that are put into operation at a particular time. Assuming there are four chillers in each building, the condenser water flow rate will vary as shown by the dotted line in Fig. 3.

For simplicity in calculations, the condenser water flow rate was assumed to be directly proportional to the cooling load ($=CQ_k(t)$, as shown by Line 1 in Fig. 3). However, this obviously would lead to under-estimation of the water flow rate, except at those conditions where the running chillers are fully loaded. To correct for this underestimation, Line 1 is shifted upward by a constant flow rate ($V_{k,\min}$, Eq. (7)) that equals half of the condenser flow rate for the chiller that would remain operating in the smallest cooling load range. Thus, the flow rate predicted by Eq. (7) would be related to the cooling load in the manner as shown by Line 2 in Fig. 3. This implies that the assumption that there are equal chances of over- and under-estimation has been made.

Water losses at cooling towers that need to be replenished by water supply from a CPSSCT system include losses due to evaporation, drift and blow down. The required make-up flow rate is usually determined on the basis of an evaporation loss and a drift loss equivalent to 1.0 and 0.2% of the condenser water flow rate, respectively [14]. The blow down rate, however, is dependent on the tolerable concentration of impurities in the system water, quantified as a ratio to the impurity concentration in the supply water by the parameter "number of concentration" [14].

The Carrier Handbook [15] recommends that the blow down rate should be 50–200% of the evaporation rate. As the evaporation rate is about 1% of the condenser water flow rate and the drift rate is about 0.2%, the make-up rate would be in the range of 1.7–3.2% of the condenser water flow rate. The

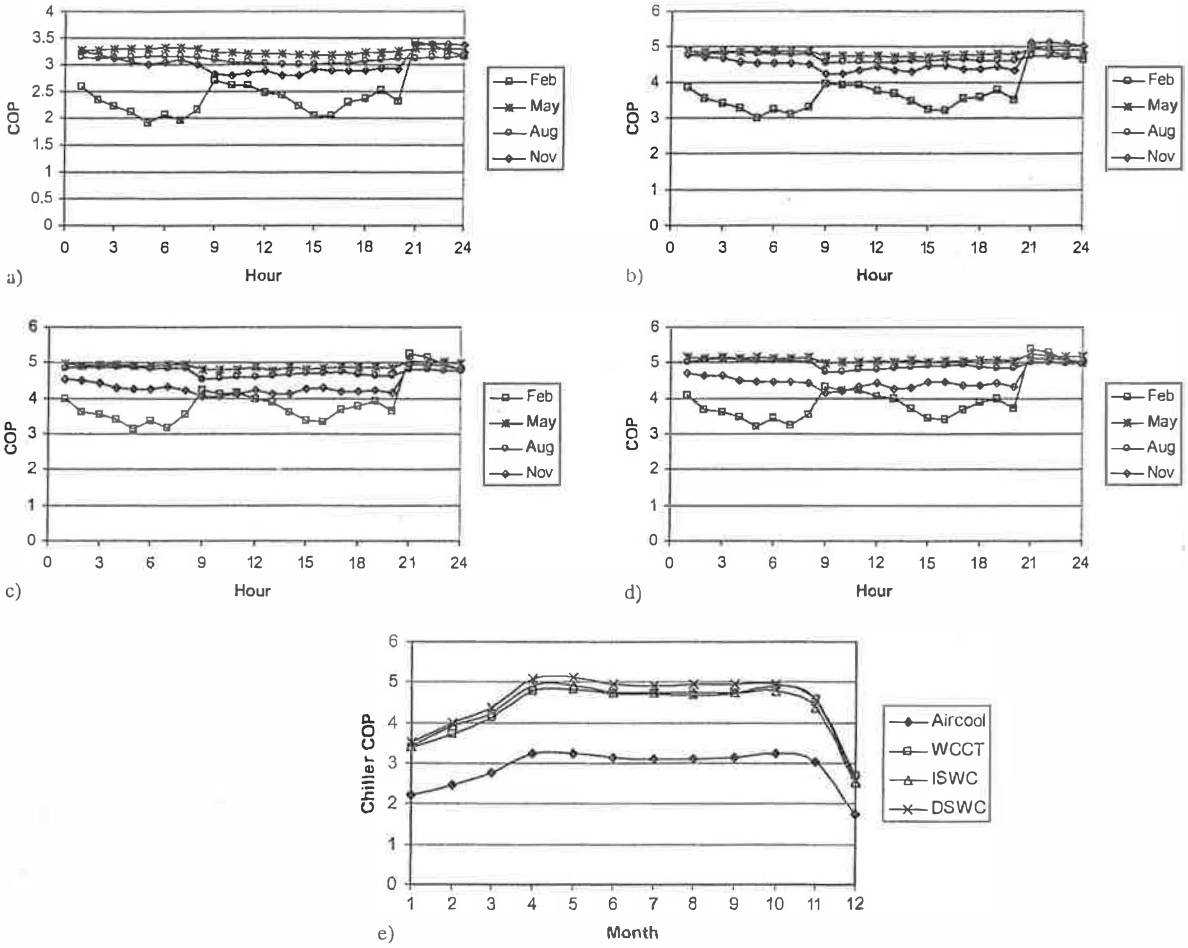

Fig. 2. COP of chillers in the electricity consumption profile model: (a) monthly mean hourly COP of air-cooled chillers in selected months in the year; (monthly mean hourly COP of water-cooled chillers with cooling towers in selected months in the year; (c) monthly mean hourly COP of indirect seawat cooled chillers in selected months in the year; (d) monthly mean hourly COP of direct seawater-cooled chillers in selected months in the year; (e) month mean COP of air-cooled chillers, water-cooled chillers with cooling towers and direct and indirect seawater-cooled chillers.

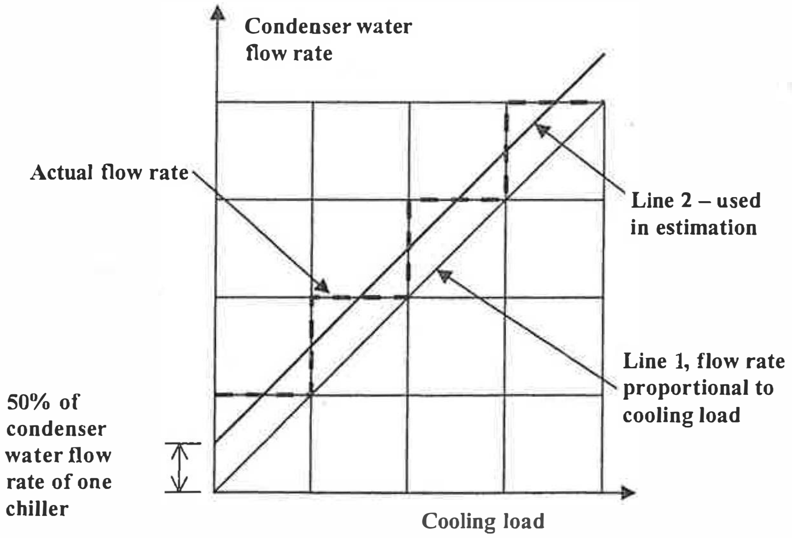

Fig. 3. Condenser water flow rate in a chiller plant.

lower end is recommended for cases where there is no severe water problem, e.g. fresh water. This corresponds to a number of concentration of about 2.5 and a flow rate of 0.86×10^{-3} l/s kW of the cooling capacity. However, no explicit guideline on the blow down rate required for systems using seawater is given.

On the basis of plant operation records of an existing building [16], where seawater cooling towers are used, the annual seawater consumption in that building was found to be about 2.8% of the circulation rate. Based on a number of concentration of 1.5, the required blow down rate will be 1.8% and the total cooling tower water make-up rate will be approximately 3% of the condenser flow rate, which is close to the empirical figure of 2.8%. The figure of 3% is equivalent to a flow rate of 1.587×10^{-3} l/s kW of the cooling capacity.

Therefore, the values of C_0 in Eq. (7) corresponding to a CPSSCC scheme and CPSSCT schemes using fresh water and seawater were set as 1.0, 0.017 and 0.03, respectively.

Note that the above method will be applicable only to the determination of the supply flow rate for once-through cooling of chiller condensers (CPSSCC) or for making up of cooling tower losses (CPSSCT). For the prediction of the chilled water flow rate demand on a DCS, a different method will have to be used, as the relation between the chilled water flow rate demand and the cooling load is nonlinear, and is dependent on the characteristics of the cooling coils in the air-handling units. It will be predicted by using a cooling coil model in conjunction with the cooling load predicted by the above-described simplified model for individual connected buildings. The prediction method has been incorporated into a special version of BECON that can simulate the performance of a DCS, the details of which will be described in a separate paper [17].

6. Trial runs and verification of predictions

Having established the cooling load, electricity consumption and water demand profile models, the procedures involved in predicting the simultaneous cooling load, electricity consumption and water demand of a building comprising a mix of premises and for a group of buildings would become relatively straightforward. The procedures have also been computerized into a spreadsheet program, with the profile models incorporated into the program as its database. The input required would involve only the GFA of various premises in the buildings to be modeled.

Table 8
Comparison of predictions by the simple model and by detailed simulation: office-only building

Heat rejection method	A/C EUI of the office-only building (kW h/m^2)		
	Simple model	Detailed simulation	% Deviation
Air-cooled	104	104	−0.1
Water-cooled cooling towers	95	91	3.5
Indirect seawater-cooled	92	89	2.8
Direct seawater-cooled	86	85	1.6

The A/C EUI of the model office-only building (Building G in Table 3) has been predicted both by detailed simulation using HTB2 and BECON and by using the simplified model. Four cases were studied with the heat rejection method used in the air-conditioning system varied in each case. It can be seen from the results summarized in Table 8 that the A/C EUI values predicted by the simplified model are in good agreement with the predictions of the detailed models.

The simplified models have also been applied to predict the air-conditioning electricity consumption of the surveyed/audited existing office/commercial buildings and hotel buildings summarized in Tables 1 and 2, based on the total GFA's of various types of premises in these buildings. Table 9 shows a comparison of the predicted A/C EUI values for these buildings with estimates based on the surveyed landlord's total consumption of the existing office/commercial buildings. It also includes the metered electricity consumption data of an existing office/commercial building, where detailed sub-meter readings were available [16]. That build-

Table 9
Comparison of air-conditioning electricity consumption (office/commercial buildings)

	No. of buildings	Mean landlord's EUI (kW h/m^2)	Predicted A/C EUI[a] (kW h/m^2)	A/C to landlord EUI[b] (kW h/m^2)	Estimated A/C EUI[c] (kW h/m^2)	% Deviation[d]
(A) Buildings with AACS						
Direct air-cooled	10	206	159	0.77	159	0.0
(B) Buildings with WACS						
Seawater cooled with cooling towers	7	177	143	0.81	133	7.6
Indirect seawater cooled with heat exchangers	4	211	160	0.76	158	0.9
(C) Metered data for a office/commercial building [16]	1	173	130	0.75	126[d]	3.0

[a] Predictions of the simplified model.

[b] Ratio of predicted A/C EUI to surveyed landlord total EUI.

[c] Assumed to be 77% of mean landlord's EUI for air-cooled systems, and 75% for water-cooled systems.

[d] Audit result.

Table 10
Comparison of air-conditioning electricity consumption (hotel buildings)

	No. of buildings	A/C EUI		
		Surveyed ($kW h/m^2$)	Model ($kW h/m^2$)	% Deviation
Hotels with AACS	6	217	217	−0.09
Hotels with WACS	10	168	179	6.67

ing is air-conditioned by direct seawater-cooled chillers with cooling towers. The EUI for air-conditioning in that building, including the consumption of waterside and airside equipment, was found to be 126 $kW h/m^2$ [16]. The predicted A/C EUI values and the data obtained from the audit studies for the existing hotels are shown in Table 10 for comparison.

It can be seen from the comparisons summarized in Tables 9 and 10 that the model predictions compare well with the measured data for the audited office/commercial building and with the mean values of the surveyed hotel buildings. Since only the landlords' total EUI values were available for the other office/commercial buildings, the predictions were compared with A/C EUI values estimated from the landlords' total EUI values. The deviations are within a few percent of the estimated values, although such comparisons would be subject to large uncertainties. Nevertheless, it can be seen that the simplified model can provide estimates that are reasonably close to the mean values of existing buildings.

Fig. 4 compares the profiles of monthly electricity use for air-conditioning as predicted by the simplified model and obtained from metered readings in the audited office/commercial building described in [16]. It can be seen from this figure that the predicted monthly electricity consumption is close to the metered readings.

Fig. 5 shows the percentage deviation between the model predictions and the audit/survey results for 21 of the 23 existing office/commercial buildings, on individual building basis (the two with indirect air-cooled plants were excluded). Buildings 1–10 have direct air-cooled chiller plants, 11–17 have seawater-cooled plants with cooling towers and 18–21 have indirect seawater-cooled plants. This comparison shows that the model may not provide accurate predictions when compared to an individual building, but the predictions are close to the mean values amongst the surveyed/audited buildings.

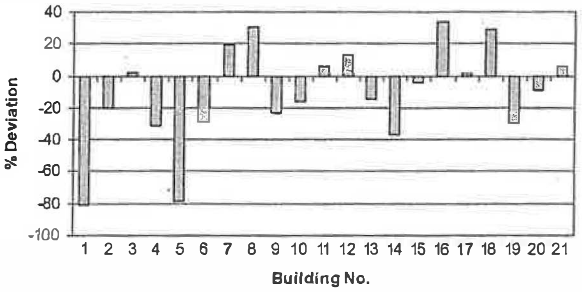

Fig. 5. Percentage deviations between A/C EUI values predicted by the simplified model and estimates from survey/audit data — A/C EUI assumed to be 77% of landlord's EUI for the air-cooled system, and 75% for water-cooled systems.

7. Conclusions

Analysis of the energy consumption data of 23 existing office/commercial buildings and 16 existing hotel buildings, which included buildings that use AACS and WACS, showed that a significant difference existed in the average annual electricity consumption between buildings using the two types of air-conditioning system heat rejection methods. Hence, facilitating buildings that would otherwise be restricted to using AACS to adopt or convert to WACS would potentially lead to significantly reduced electricity use for air-conditioning buildings in Hong Kong. However it would require the development of centralized systems fo supplying water to such buildings, for condenser cooling (CPSSCC) or for making up of cooling tower losses (CPSSCT). District cooling systems (DCS's) would als

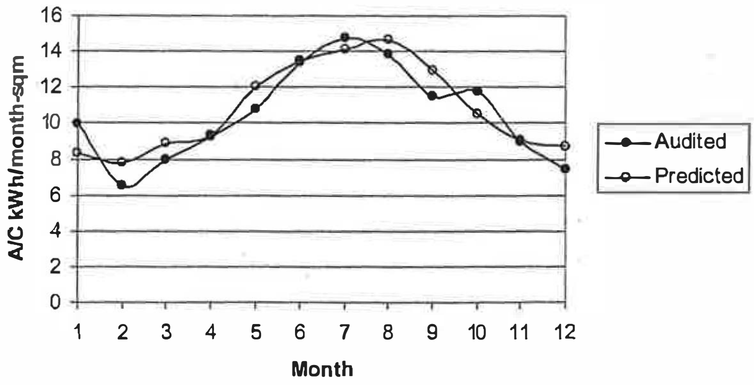

Fig. 4. Comparison of monthly power consumption profiles predicted by the simplified model and obtained from metered data in an office/commerci building.

be feasible and may yield the greatest saving, but would involve the highest capital investment.

Evaluation of the energy, cost and environmental benefits of such schemes requires an efficient method for determining the simultaneous cooling load, water demand and air-conditioning electricity consumption of a large number of buildings using different heat rejection methods. A simplified method has been developed to allow these estimations to be accomplished speedily. The method is based on cooling load profile models for different types of premises and power consumption profile models for different heat rejection methods. The cooling load patterns of different types of premises are taken into account in this method, which is an essential feature for predicting the cooling load of buildings comprising a mix of premises for different uses. These profile models were established from detailed simulation studies. Reference was made as far as possible to data of existing buildings obtained from building energy surveys and audits to ensure the input parameters used in the simulation calculations would match with actual situations. The model can also account for the effect of variations in the outdoor weather conditions and seawater temperatures on the efficiency of air-conditioning plants.

Predictions obtained using this simplified model have been compared with detailed computer simulation results and electricity consumption data obtained from surveys and audits in existing buildings. Although large deviations may exist for individual buildings, the predictions were found to agree reasonably well with mean values of groups of buildings.

The method presented in this paper has set the foundation for other stages of studies on the feasibility and viability of wider application of WACS in Hong Kong. The method has been used to generate cooling loads of buildings in districts of different building mixes, which are essential to the estimation of energy consumption of centralized piped seawater supply systems for condenser cooling or making up of cooling tower losses, and of district cooling systems. Other studies on greenhouse gas emissions, delay of the need for new power plants, environmental impacts of water discharge into the harbor, identification of potential sites for implementation, and cost studies, etc. were based on these energy use predictions.

The methodologies presented for estimating the cooling loads of buildings, the electricity consumption for air-conditioning individual buildings and the cooling water demand for condenser cooling or making up of water losses at cooling towers may also be applied to other cities in feasibility studies on the adoption of centralized cooling systems for groups of buildings. The cooling load profiles and energy consumption profiles, however, would need to be generated based on typical characteristics of buildings and weather conditions in the specific city concerned. Although the use of cooling towers may already be a common practice in certain cities, such methodologies may still be useful if consideration needs to be given to the implementation of DCS to replace chiller plants in buildings in the interest of achieving higher overall efficiency of air-conditioning buildings.

Acknowledgements

The work presented in this paper formed part of a consultancy study commissioned by the Hong Kong SAR Government, which was undertaken by a group of consultants including the lead consultant Scott Wilson (HK) Ltd. and the Hong Kong Polytechnic University. The authors thank the Electrical and Mechanical Services Department of the Hong Kong SAR Government for their permission to publish this work.

Appendix A.

HKDLC [8] is a design cooling load prediction program developed by the Department of Building Services Engineering of The Hong Kong Polytechnic University. It was developed according to the CLTD/SHGF/CLF method of the American Society of Heating, Refrigeration and Air Conditioning Engineer (ASHRAE) [7], with appropriate modifications to suit local weather conditions of Hong Kong.

HTB2 [9] is a detailed dynamic building heat transfer simulation program developed by the Welsh School of Architecture of the University of Wales, Cardiff College. It can predict the heating and cooling load that will arise in a building when subjected to changing weather conditions and intensities of internal heat gains. More detailed descriptions about HTB2 can be found in [18,19]. A special version of HTB2 was used in this study, which has been incorporated with additional features, such as expanded maximum zone number that can be handled, and output of data files that can be directly read by BECON. The weather data used in the simulation are actual hourly weather data of Hong Kong in 1989, which has been identified as the representative year [20].

BECON [10] is an air-conditioning system simulation program developed by the Department of Building Services Engineering of the Hong Kong Polytechnic University. It can predict the hourly plant electricity consumption for providing cooling over the year, on the basis of the hourly cooling load predicted by HTB2. BECON is capable of modeling plants using different heat rejection methods, including air-cooled systems, water-cooled systems with cooling towers, and direct and indirect seawater-cooled systems.

A model that can predict the temperature of seawater available from the Hong Kong harbor has also been incorporated into BECON for modeling seawater-cooled systems. This model was developed on the basis of the year-round seawater temperature records at North Point in 1994, which were obtained from the Hong Kong Observatory [21,22]. BECON also includes cooling tower and heat exchanger models for modeling water-cooled systems with cooling towers and indirect seawater-cooled systems. More detailed descriptions on BECON can be found from [22–24].

The chiller models inside BECON were developed from performance data obtained from chiller manufacturers. The models can take into account the effects of variations in the cooling load on the chiller, and in the temperature of the cooling medium entering the chiller. More detailed descriptions of the chiller models can be found in [13].

Also included in [24] are descriptions about the results of a comparison between the predictions of HTB2 and BECON with measured cooling load and power consumption in an existing commercial building. Comparison of predictions of the chiller models with measured data in existing plants is included in [13]. In those comparison studies, HTB2, BECON and the chiller models were shown to be capable of providing predictions that matched with the measured data within acceptable accuracy.

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