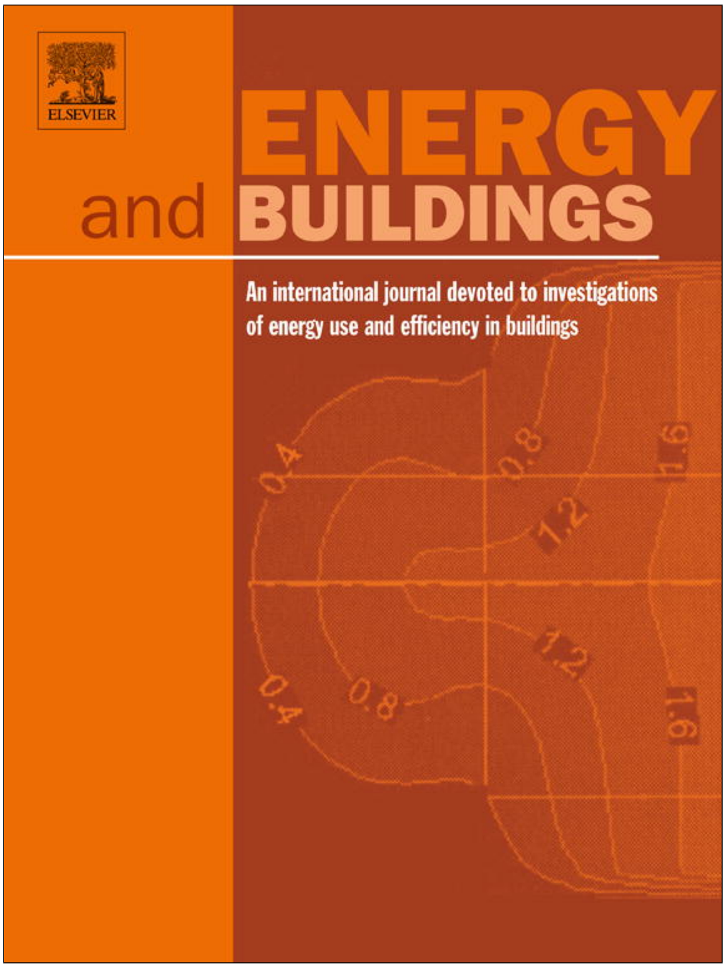
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Energy consumption of air conditioners at different temperature set points[☆]

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ABSTRACT

Energy saving in air conditioners is a primary concern in building projects, since air conditioners consume a large proportion of the energy in building service equipment. Research on energy saving in air conditioners focuses mostly on the chiller system and the associated control strategies. For air conditioners in buildings, the thermal control strategy to adjust the temperature set point is very easy to implement and very effective to save energy. In this paper an energy consumption calculation model of a data center in South Africa is presented to estimate the energy consumption of air conditioners at different temperature set points. In order to illustrate the accuracy of this model, measured energy consumption from a data center is compared with the calculated energy consumption from this model, and the coefficient of variation of the root mean square error between the estimated data and measured test data is 11.5%.

1. Introduction

In recent years, energy consumption in data centers has been increasing. The reduction of energy consumption in data centers is an interesting problem. The U.S. Environmental Protection Agency reports that the energy consumed by service equipment such as air conditioners (ACs) and the lighting system is almost the same as that consumed by information technology (IT) equipment [1]. Therefore, the energy saving in ACs is very important in reducing the energy consumption of data centers.

For saving energy in ACs, existing research focuses on developing new energy-efficient equipment, applying complex control strategies, using solar energy as a new energy source, etc. Delfani et al. [2] studies the energy saving in a packaged unit AC by adding an indirect evaporative cooling system. Henning [3] summarizes some issues for using solar energy as assisted energy in ACs. Ma and Wang [4] illustrates energy-efficient control strategies for controlling the variable speed pumps in a central AC. The results show that the energy consumption of pumps can be lowered by using these control strategies. A feedback controller for ACs is designed, and the experiment shows that the energy efficiency of an AC can be improved by this controller [5]. To reduce the energy consumption of an AC in an office building, Zhao et al. [6] presents a temperature and humidity independent control strategy. The experimental results show that the strategy can provide a better coefficient of performance of the AC and a comfortable indoor environment even in very hot and humid weather. Ahmed et al. [7] presents a thermostat setting scheme to maintain the indoor temperature and humidity and to reduce the energy consumption of the AC compressor. For multi-unit ACs, a fuzzy logic control strategy is used to control the operational number of compressors and fans to enhance energy efficiency [8]. For the ACs, the thermal control strategy-adjustment of the temperature set point is employed in Ref. [9], who concludes that the air temperature set point of a computer room can be raised to 28 °C without causing any discomfort. Using computer simulation, the impact of changing the temperature set point is tested in a single-family home, located in Miami, FL, USA [10]. Wan et al. [11] predicts the energy consumption of ACs in office buildings in Hong Kong by regression analysis at different temperature set points. Wang et al. [12] studies the energy saving of ACs in a room by experiment when the temperature set point is increased to 23 °C. Wang et al. [13] presents a model to estimate the energy consumption of ACs in a room by cooling load analysis; however, the latent load caused by the change in indoor moisture is not discussed.

Whether using a variety of control strategies, renewable energy, or adding new equipment, the cost is much higher than that of temperature set point adjustment. A data center is a facility used to house computer systems and associated components, such as telecommunications and storage systems. The people will enter the data center occasionally while the computer and other equipment need to be maintained. According to the conclusion of Ref. [9], the indoor temperature set point of the computer room can be raised

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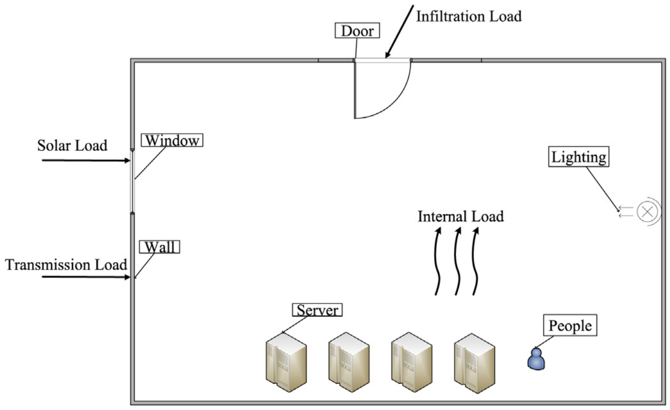

Fig. 1. The components of cooling load.

to 28 °C without causing any adverse effect on computers. Due to these reasons, increasing the temperature set point of ACs in the data center by one degree is a simple but effective method. The energy consumption of ACs in data centers can be lowered by this method; however the exact amount of saving is usually unknown.

This paper presents a mathematical model for the energy consumption calculation for this temperature set point adjustment.

2. System description

The data center to be considered in this paper has several storeys and each storey has the same height, single glazing glass windows and concrete walls as all the others. According to South African National Standard SANS 10400-A [14], single glazing glass is a common requirement for windows. Solar radiation can be transmitted into the data center directly through the windows. The data center has no special shading device for solar radiation absorption. There are no chimneys or any other natural ventilation devices in the data center. It can be assumed that all the rooms in the data center have the same temperature and humidity. The thermal storage of all walls and furniture is ignored. The ACs are used to ensures that the indoor temperature remains equal to the temperature set point. The data center is operated 24 h every day. Hence, the ACs in the data center are running continuously. The components of the cooling load for the ACs are shown in Fig. 1. According to Fig. 1, the cooling load for the ACs generally consists of four parts, that is, the transmission load, infiltration load, solar load and internal load. As shown in Fig. 1, the transmission load is the heat gain due to a temperature difference across the building elements such as walls, frames of windows, etc. The infiltration load is the heat gain due to the flow of outdoor air into a conditioned space through doors, windows, etc. The solar load is the heat gain because of the directly transmitted solar radiation. The quantity of radiation directly entering the building is determined by the solar transmittance of windows. Internal load is the sensible heat gain due to the release of heat into a space (light, equipment, people, etc.). In the data center, the heat is generated by lighting, computer systems and associated components.

3. Calculation model

3.1. Cooling load calculation

To maintain the required indoor temperature, the AC will remove the heat generated by the outdoor climates, lighting and facilities in the data center. The calculation models of the different parts of the cooling load can be given as follows:

3.1.1. Transmission load

The transmission load can be calculated as [15]

$$Q_t = US(T_o - T_i), \tag{1}$$

where Q_t is the transmission load in W, T_o is the outdoor temperature in K, T_i is the indoor temperature in K, U is the heat transfer constant in W/m^2 K, and S is the transmission area in m^2.

3.1.2. Infiltration load

Infiltration is also known as air leakage into a building. It includes sensitive heat and latent heat. The sensitive load is estimated as [15]

$$Q_{sl} = q_v c_p \rho (T_o - T_i), \tag{2}$$

where c_p is the specific heat of air in J/K, ρ is the air density in kg/m^3, and q_v is the volumetric air flow rate in m^3/s and satisfies [16]

$$q_v = A_L(I_0 + HI_1|T_o - T_i|), \tag{3}$$

A_L is the building effective infiltration area in m^2, I_0 and I_1 are the coefficients determined by different wind speed and outdoor temperature, and H is the building average stack height in m. The latent load caused by the difference between the indoor and outdoor humidity is given by [17]

$$Q_{lat} = hq_v \rho (W_o - W_i), \tag{4}$$

where h is the enthalpy difference between the indoor and outdoor air in J, W_o is the outdoor specific humidity and W_i is the indoor specific humidity. Depending on the flow rate and the humidity conditions of the outdoor air, indoor specific humidity can instantly and prominently respond to air movement across enclosure boundaries. The response of indoor specific humidity to air movement across infiltration can be expressed as [18]:

$$W_i = W_o + (W_{ro} - W_o) \exp\left(-\frac{q_v}{V} t\right), \tag{5}$$

where W_{ro} is the initial room specific humidity and V is the volume of room in m^3. Eqs. (5) and (4) can be rewritten as

$$Q_{lat} = hq_v \rho \left((W_o - W_{ro}) \exp\left(-\frac{q_v}{V} t\right)\right). \tag{6}$$

3.1.3. Solar load

The solar load can be given by the directly transmitted radiation as [15]

$$Q_s(t) = A_w S(t) E, \tag{7}$$

where $S(t)$ is the solar heat gain coefficient function, t is the time, E is the irradiance of the direct solar beam in W/m^2, and A_w is the window area of the data center in m^2.

3.1.4. Internal load

The primary source of heat from lighting is light-emitting elements, or lamps. Generally, the sensible heat gain from electric lighting can be calculated as [15]

$$Q_{light}(t) = G_{light} F(t), \tag{8}$$

where G_{light} is the total light wattage in W, $F(t)$ is the lighting use factor. It is a function of operational status against time, and $F(t)$ equals 1 if the lighting system is on at time t and 0 otherwise.

The heat generated by computers is dominated by winding resistance (copper loss) which is hardly affected by the indoor and outdoor temperatures, therefore this heat can be assumed as constant. Note that this constant heat is also proportional to the number of facilities in the floor area A, thus this load can be assumed as c_0A [15]. From the above calculation, the internal load is given by

$$Q_{int}(t) = G_{light}F(t) + c_0A. \tag{9}$$

3.2. Energy consumption calculation

The energy consumption of ACs in this model is calculated by cooling load analysis. The latent load caused by the changes in indoor moisture is included in the model. From the above analysis, the total cooling load can be calculated as

$$\begin{aligned} Q_{cool}(t) &= Q_t + Q_{sl} + Q_{lat} + Q_s + Q_{int} = US(T_o - T_i) + q_v c_p \rho (T_o - T_i) \\ &+ hq_v\rho\left((W_o - W_{ro})\exp\left(-\frac{q_v}{V}t\right)\right) + A_W S(t)E + G_{light}F(t) + c_0A. \end{aligned} \tag{10}$$

Since the height of each storey is assumed to be constant, S, A_W and A_L are proportional to the floor circumference L, where $L = 4\sqrt{A}$. Equations (3) and (10) can be rewritten as

$$q_v = a_0 4\sqrt{A}(I_0 + a_1 HI_1 |T_o - T_i|), \tag{11}$$

$$\begin{aligned} Q_{cool}(t) &= Ua_2 4\sqrt{A}(T_o - T_i) + q_v c_p \rho (T_o - T_i) \\ &+ hq_v\rho\left((W_o - W_{ro})\exp\left(-\frac{q_v}{AH}t\right)\right) + a_3 4\sqrt{A}S(t)E \\ &+ G_{light}F(t) + c_0A. \end{aligned} \tag{12}$$

Formula (12) can be simplified as

$$\begin{aligned} Q_{cool}(t) = 4\sqrt{A}(&b_0\Delta T + b_1|\Delta T|\Delta T \\ &+ b_2\Delta W\exp\left(-\frac{4b_3}{\sqrt{A}} - \frac{4b_4|\Delta T|}{\sqrt{A}}\right) \\ &+ b_5|\Delta T|\Delta W\exp\left(-\frac{4b_3}{\sqrt{A}} - \frac{4b_4|\Delta T|}{\sqrt{A}}\right) + b_6S(t)) \\ &+ b_7A + G_{light}F(t), \end{aligned} \tag{13}$$

where $\Delta T = T_0 - T_i$, $\Delta W = W_o - W_{ro}$, $b_0 = Ua_2 + C_p a_0 I_0 \rho$, $b_1 = a_0 a_1 HI_1 C_p \rho$, $b_2 = ha_0 I_0 \rho$, $b_3 = \frac{a_0 I_0}{H}$, $b_4 = a_0 a_1 I_1$, $b_5 = ha_0 a_1 I_0 HI_1 \rho$, $b_6 = a_3E$, and $b_7 = c_0$. The unknown coefficients $b_0, b_1, \ldots, b_7$ can be simulated by existing measured data.

Assume that T_s is the AC temperature set point, $T_i(t_0) = T_s - \Delta$ and $W_i(t_0) = W_s$, where t_0 is the initial time instant, Δ is the AC operating constant such that the AC will switch on when $T_i = T_s + \Delta$ and switch off when $T_i = T_s - \Delta$. Then the main parts of the cooling load Q_{cool} will increase the indoor temperature T_i. The humidity of the data center will be increased by air movement. After δt_1 time duration, the indoor humidity is increased to $W_i(\delta t_1)$, the indoor temperature is increased to $T_s + \Delta$. Then the AC will start to remove the accumulated heat and water vapour. The temperature and humidity will be reduced to $T_s - \Delta$ and W_s again after the AC has been running for a time period of δt_2. This whole duty cycle will be repeated. Assume that the duty cycle starts from time $t_0 = 0$, then the heat balance equation can be written as

$$\begin{aligned} &\int_0^{\delta t_1 + \delta t_2} Q_{cool}(t)dt \approx \frac{(Q_{cool}(0) + Q_{cool}(\delta t_1))\delta t_1}{2} \\ &+ \frac{(Q_{cool}(\delta t_1) + Q_{cool}(\delta t_1 + \delta t_2))\delta t_2}{2} \\ &= COP_{cool}P_{cool}(\delta t_1)\delta t_2 \approx COP_{cool}\int_{\delta t_1}^{\delta t_1 + \delta t_2} P_{cool}(t)dt, \end{aligned} \tag{14}$$

where COP_{cool} is the coefficient of performance of the AC cooling capacity, $P_{cool}(t)$ is the power consumption of cooling at time t. The indoor temperature at time $t = 0$, δt_1 and $\delta t_1 + \delta t_2$ can be calculated as

$$\begin{aligned} T_i(0) &= T_s - \Delta, \\ T_i(\delta t_1) &= T_s + \Delta, \\ T_i(\delta t_1 + \delta t_2) &= T_s - \Delta. \end{aligned} \tag{15}$$

The energy consumed by the AC during a duty cycle is $P_{cool}(\delta t_1)\delta t_2$. Therefore, formula (14) can be rewritten as

$$\begin{aligned} E = P_{cool}(\delta t_1)\delta t_2 &= \frac{(Q_{cool}(0) + Q_{cool}(\delta t_1))\delta t_1}{2COP_{cool}} \\ &+ \frac{(Q_{cool}(\delta t_1) + Q_{cool}(\delta t_1 + \delta t_2))\delta t_2}{2COP_{cool}} \end{aligned} \tag{16}$$

Assume that the time period $[t_0, t_N]$ consists of N duty cycles: $[t_0, t_1]$, $[t_1, t_2]$, ..., $[t_{N-1}, t_N]$. Note that the time duration of one duty cycle may not be the same as that of another duty cycle. The corresponding temperature T_o and humidity W_o in (13) at the kth duty cycle are denoted by $\overline{T}_o^k$ and $\overline{W}_o^k$ which are mean temperature and humidity in the k-th duty cycle, respectively. The $S(t)$ and $F(t)$ can be simplified in the same way.

According to (15), formula (16) can be rewritten as

$$E = \frac{(Q_{cool}(0) + Q_{cool}(\delta t_1))(\delta t_1 + \delta t_2)}{2COP_{cool}}. \tag{17}$$

Since the time period $[t_0, t_N]$ consists of N duty cycles, then $\frac{\delta t_1 + \delta t_2}{COP_{cool}}$ can be simplified as

$$\frac{\delta t_1 + \delta t_2}{COP_{cool}} = \frac{t_k - t_{k-1}}{COP_{cool}}. \tag{18}$$

The COP_{cool} at the k-th duty cycle are denoted as $COP_{cool}^k (k = 1, \ldots, N)$ which can be expanded as

$$COP_{cool} = \alpha_1 \overline{T}_o^k + \alpha_2 T_s, \tag{19}$$

where α_1, α_2 are coefficients. During the fixed time period $[t_0,t_N]$, the total electric energy consumed at the set point 22 °C, denoted by E_{22}, is

$$\begin{aligned} E_{22} = \sum_{k=1}^{N} \frac{t_k - t_{k-1}}{2COP_{cool}} [&4\sqrt{A}(b_0\Delta T_1 + b_1|\Delta T_1|\Delta T_1 \\ &+ b_2\Delta W\exp\left(-\frac{4b_3}{\sqrt{A}} - \frac{4b_4|\Delta T_1|}{\sqrt{A}}\right) \\ &+ b_5|\Delta T_1|\Delta W\exp\left(-\frac{4b_3}{\sqrt{A}} - \frac{4b_4|\Delta T_1|}{\sqrt{A}}\right) \\ &+ b_6\overline{S(t)}) + b_7A + G_{light}\overline{F(t)} + 4\sqrt{A}(b_0\Delta T_2 \\ &+ b_1|\Delta T_2|\Delta T_2 + b_2\Delta W\exp\left(-\frac{4b_3}{\sqrt{A}} - \frac{4b_4|\Delta T_2|}{\sqrt{A}}\right) \\ &+ b_5|\Delta T_2|\Delta W\exp\left(-\frac{4b_3}{\sqrt{A}} - \frac{4b_4|\Delta T_2|}{\sqrt{A}}\right) + b_6\overline{S(t)}) \\ &+ b_7A + G_{light}\overline{F(t)}], , \end{aligned} \tag{20}$$

where $\Delta T_1 = T_0 - 22 - \Delta$, $\Delta T_2 = T_0 - 22 + \Delta$, $\Delta W = W_o - W_s$, $\overline{S(t)}$ is the average of $S(t)$ in the duty cycle, and $\overline{F(t)}$ is the average of $F(t)$. The total electric energy consumed at the set point 23 °C, denoted by E_{23}, can be calculated by replacing ΔT_1 and ΔT_2 by $T_0 - 23 - \Delta$ and $T_0 - 23 + \Delta$, respectively.

Now the energy consumption calculation model is developed. The unknown parameters in (20) can be identified by measured

Table 1
Brief information of measured data.

Month (measured days), Durban, South Africa, 2009	Energy consumption (MWh)	Average ambient temperature (°C)	Average specific humidity (kg/kg)	Set point (°C)
May (30)	2.11	19.45	0.010219	22
June (30)	2.04	18.29	0.0082235	22
July (22)	1.45	16.46	0.0070424	22
February(28)	1.71	24.18	0.014689	23
March (31)	1.87	23.52	0.013654	23
April (30)	1.74	21.54	0.011931	23
September (29)	1.41	18.94	0.010564	23
October (31)	1.48	20.31	0.012384	23

data of a specific data center. After the parameters have been identified, the energy consumption of the AC at the temperature set point 23 °C can be calculated. The energy saving is calculated as

$$E_{saving} = E_{22} - E_{23}. \tag{21}$$

4. Case study

Consider a data center located in South Africa. The floor area of the data center is 750.3 m^2. The total light wattage G_{light} is 4.038 kW. The relative humidity set point is 50%. The specific humidity is different when the relative humidity is the same while the indoor temperature is different. Therefore, when the relative humidity set point is 50%, the specific humidity is 0.0086613 kg/kg for 22 °C and is 0.0081481 kg/kg for 23 °C. For simplicity, a fixed time period $[t_0, t_N]$ is chosen to be 1 h, and let $N = 1$. The value of $S(t)$ will change with time. The hourly energy consumption of the AC is measured at the different temperature set points. Brief information about the measured data is shown in Table 1. From the data in Table 1, it is observed that the energy consumption of the AC decreased when the ambient temperature and specific humidity decreased. This is because the AC consumes less energy to cool and dehumidify the inlet air when the outdoor temperature is low. Although the temperature difference between June and September is little, the energy consumption in June is almost 1.4 times as much as in September. The reason is that the temperature set point determined in February is 22 °C; the AC will consume a lot of energy to maintain the indoor temperature at a lower temperature set point.

The hourly energy consumption and hourly weather conditions are measured at every hour of every day during the measured month. But some measured data are missing. Therefore, there are 5544 records in the measured data; each record includes hourly energy consumption, ambient temperature and specific humidity. 70% of the measured data are considered as training data to identify the unknown coefficients of the formula (20). The rest of the measured data are considered as test data to test the accuracy of the formula (20). To measure the error between the calculation results and measured data, the coefficient of variation of the root mean square error (CVRMSE) is used, which is defined as follows

$$CVRMSE = \frac{\sqrt{\sum_{i=1}^{M}(x_i - x_i')^2/M}}{\bar{x}} \times 100, \tag{22}$$

where x_i is the ith measured datum, $x_i{}'$ is the estimated value of x_i, M is the number of the measured data and $\bar{x}$ is the average of the measured data. The acceptable range of CVRMSE is between 0% and 15%.

Table 2
Summary of training results.

Data type	Number of data	CVRMSE
Training data	3880	9.7%
Test data	1664	11.5%

Table 3
The coefficients of formula (20)

The coefficients	Value	The coefficients	Value
α_1	0.4762	b_3	−0.0105
α_2	5.6813	b_4	−19.8399
b_0	0.6238	b_5	−14.6580
b_1	0.2894	b_6	0.3194
b_2	0.3325	b_7	−16.4603

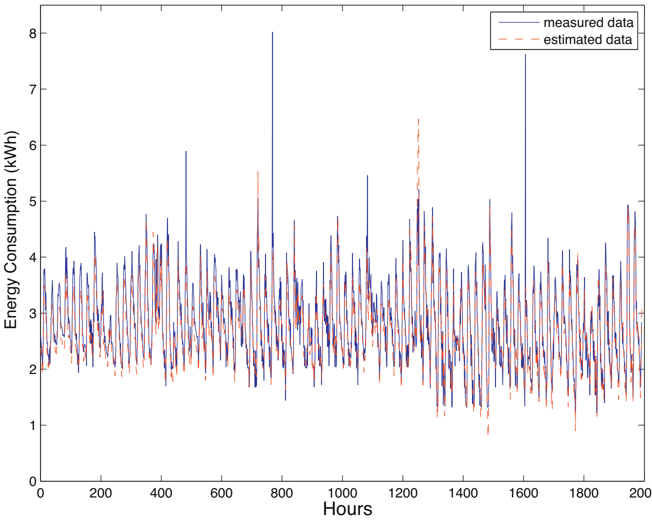

Fig. 2. Comparison between measured data and estimated data with $T_s = 22$ °C, $\Delta = 1.11$ °C.

The ideal value of CVRMSE is 0%. A summary of the training results is shown in Table 2. It shows that the number of training data is 3880, and the CVRMSE between the training results and training data is 9.7%. The number of test data is 1664, and the CVRMSE between the estimated data and test data is 11.5%. The coefficients of formula (20) are identified and shown in Table 3. The comparison between the measured data and estimated data in different temperature set points is shown in Figs. 2 and 3. This comparison shows that the difference between the measured and estimated data is small. The comparison between measured data and estimated results in different months is shown in Table 4. The outdoor weather conditions

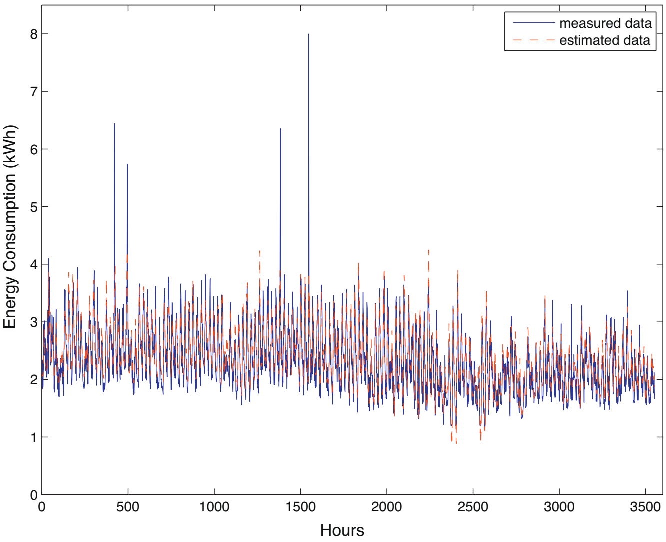

Fig. 3. Comparison between measured data and estimated data with $T_s = 23$ °C, $\Delta = 1.11$ °C.

Table 4
Comparison of actual data and calculated results.

Month	Actual data (MWh)	Calculated results (MWh)	CVRMSE (%)	Set point (°C)
May	2.11	1.96	9.15	22
June	2.04	1.94	11.09	22
July	1.45	1.41	11.03	22
February	1.71	1.738	10.59	23
March	1.87	1.923	8.9	23
April	1.74	1.784	10.57	23
September	1.41	1.488	10.29	23
October	1.48	1.579	9.82	23

Table 5
The outdoor climate in other months.

Month	Average ambient temperature (°C)	Average specific humidity (kg/kg)
January	23.7	0.014961
August	18.0	0.0087912
November	20.5	0.011959
December	22.4	0.01433

in other months are given in Table 5. From Table 5, the energy consumption in each month at different temperature set points can be estimated. The estimated energy consumption of the data center in each month at a temperature set point of 22 °C and $\Delta = 1.11$ °C is shown in Fig. 4. As shown in Fig. 4, the maximal energy consumption of 2.4250 MWh occurs in January, and the minimal energy consumption of 1.9 MWh is in July. The estimated energy consumption of the data center in each month at a temperature set point of 23 °C and $\Delta = 1.11$ °C is shown in Fig. 5. At this setting the AC will switch on when the indoor temperature reaches 24.11 °C. As shown in Fig. 5, the maximal energy consumption of 1.925 MWh occurs in January, and the minimal energy consumption of 1.477 MWh in July. The energy saving of the AC in each month is shown in Fig. 6. As shown in Fig. 6, the total energy saving for the year is 5.492 MWh. The estimated daily average energy consumption in each month at a temperature set point of 22 °C is indicated in Fig. 7. The maximal daily average energy consumption of 78.86 kWh occurs in February, and the minimal energy consumption of 61.3 kWh in July. According to Table 1, the ambient temperature in July is lower than in other months. Therefore, the energy consumption in July is the lowest. The estimated daily average energy consumption in each month at

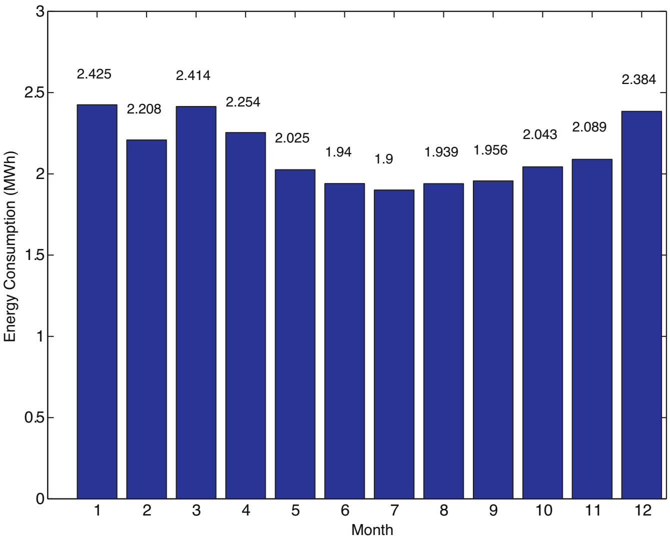

Fig. 4. Energy consumption in each month with $T_s = 22$ °C, $\Delta = 1.11$ °C.

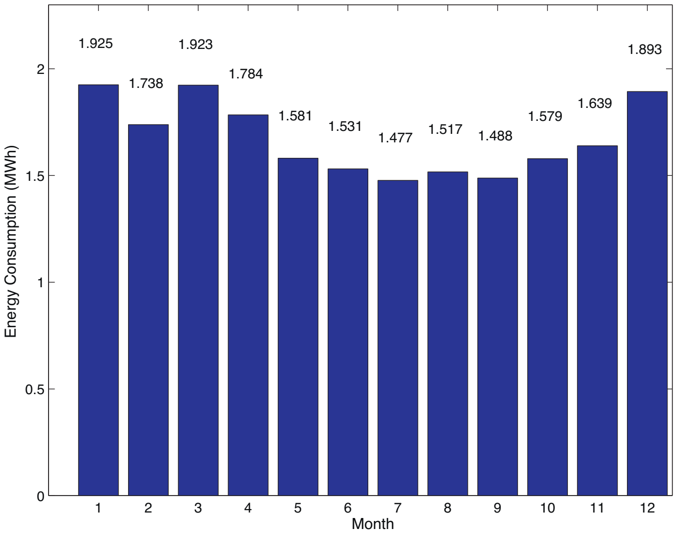

Fig. 5. Energy consumption in each month with $T_s = 23$ °C, $\Delta = 1.11$ °C.

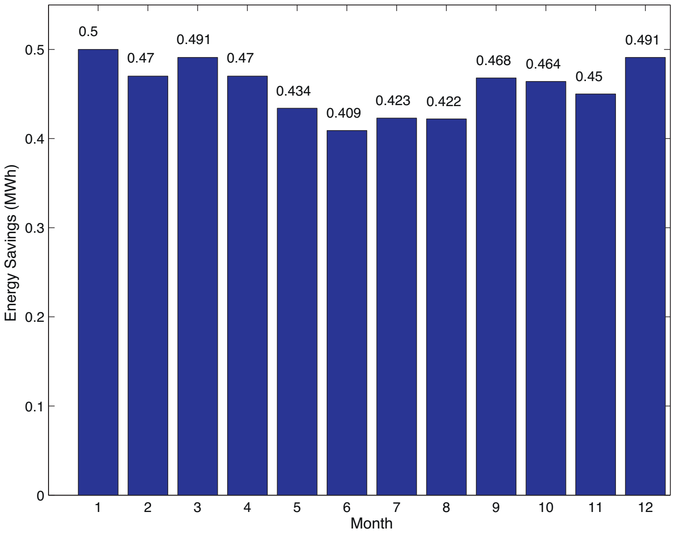

Fig. 6. Energy saving in each month.

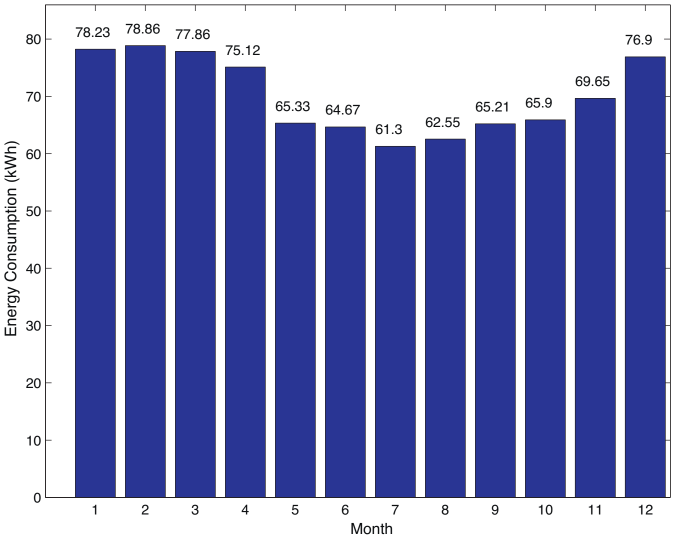

Fig. 7. Daily average energy consumption in each month with $T_s = 22$ °C, $\Delta = 1.11$ °C.

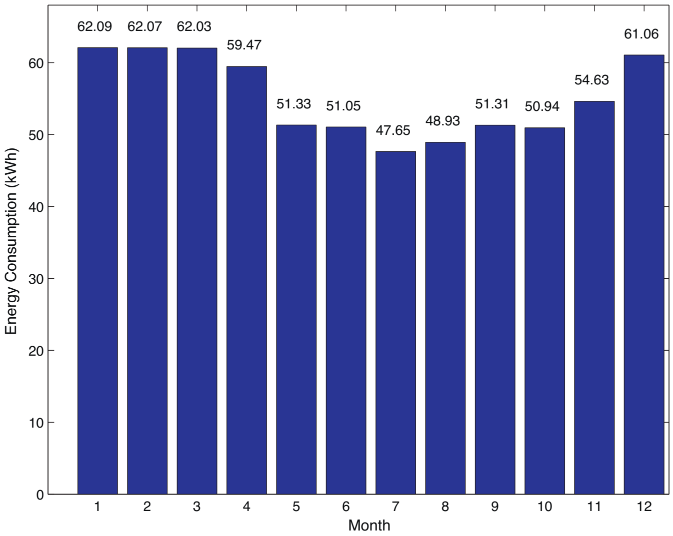

Fig. 8. Daily average energy consumption in each month with $T_s = 23\,^\circ\mathrm{C}$, $\Delta = 1.11\,^\circ\mathrm{C}$.

Table 6
Daily average energy savings in different months.

Month	Daily average energy savings (MWh)	Average ambient temperature (°C)
January	0.016145	23.7
February	0.01679	24.18
March	0.015829	23.52
April	0.015657	21.54
May	0.01524	19.45
June	0.013618	18.29
July	0.013652	16.46
August	0.013619	18.0
September	0.013902	18.94
October	0.014963	20.31
November	0.015012	20.5
December	0.015836	22.4

a temperature set point of 23 °C and $\Delta = 1.11\,^\circ\mathrm{C}$ is shown in Fig. 8. As shown in Fig. 8, the maximal daily average energy consumption of 62.07 kWh occurs in February, and the minimal energy consumption of 47.65 kWh in July. The ambient temperature in February is higher than in other months. Therefore, the energy consumption during February is the highest. The estimated daily average energy saving in different months is given in Table 6. It can be seen that more energy can be saved when the ambient temperature is high.

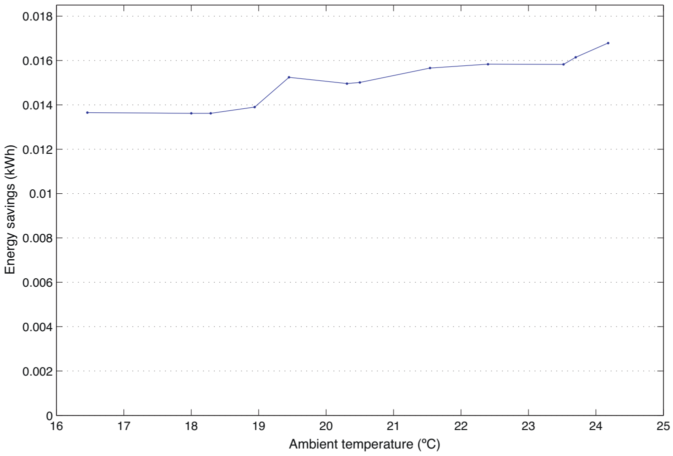

Fig. 9. Energy saving vs. temperature.

Table 7
Energy consumption per unit area at the different temperature set points.

Month	Energy consumption per unit area at 24 °C (kWh/m^2)	Energy consumption per unit area at 25 °C (kWh/m^2)	Energy consumption per unit area at 26 °C (kWh/m^2)
January	2.328	2.116	1.923
February	2.104	1.898	1.722
March	2.334	2.120	1.930
April	2.183	2.009	1.849
May	1.949	1.793	1.654
June	1.887	1.747	.625
July	1.869	1.781	1.705
August	1.863	1.723	1.601
September	1.834	1.705	1.594
October	1.930	1.783	1.667
November	2.003	1.847	1.715
December	2.314	2.127	1.974

The relation of the ambient temperature and the monthly energy saving is shown in Fig. 9. As shown in Fig. 9, the adjustment of AC temperature set points is more effective when the ambient temperature is higher. The estimated energy consumption at the different set points is shown in Table 7. It can be seen that less energy will be consumed when the temperature set point is higher.

5. Conclusion

This paper formulates an energy consumption calculation model to estimate the energy consumption of AC in a data center. In order to illustrate the accuracy of this model, measured energy consumption from a data center in South Africa is compared with the calculated energy consumption from this model. The measured data are divided into two parts, that is, the training data and the test data. The coefficient of variation of the root mean square error (CVRMSE) between the training results and training data is 9.7%, while the CVRMSE between the estimated data and test data is 11.5%. The model established in this paper involves only infiltration of air in latent load calculation, and the thermal storage of the building envelope such as walls or window frames is ignored. A more complete model including the load caused by evaporation, surface condensation, etc., will be considered in future work.

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