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Disclaimer

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Introduction to the public audience (lay report)

This report is a public deliverable belongs to Work-Package 1 (To develop the CDC dew point cooling system design framework and database) of this project. To develop the design framework of such a CDC cooling system, the information of the typical data centres currently established in Europe and China are collected. Based on this, (1) the data centres are classified in terms of the data processing capacity, space scale, and function, thus providing a standard data-centres list. (2) The energy saving potential in various types of CDCs are theoretically investigate by using IT load to determine the cooling demand and introducing cold air supply management. (3) The feasibility of applying super dew point cooling system in CDCs is explored.

Bringing together all the space layout and load condition information, a rich-content report that contains full range of information related to data centres is generated. The outcomes of this task formed a foundation for the follow-on works in this programme. They will be used in the following task 1.2 and task 1.3 as the technical foundation of CDC dew point cooling systems analysis and CDC cooling design database. The valuable outcomes will also provide insights regarding the selection of technologies to improve the energy performance of CDCs in work-package 2 to work-package 7.

1. Introduction

The upsurge in information technology (IT) has brought fabulous changes in people's lives. As an important part of the IT industry, Computing Data Centres (CDCs) have been rapidly growing over the past 40 years [1, 2]. Fig 1 illustrates the market scale of the Global CDC market in the past 8 years. In Europe, there are 1014 collocation CDCs that spread across its 27 member states [3], which consume more than 100TWh of electricity each year. In China, capacity of the CDCs has reached 28.5 GW in 2013 [4, 5], with 549.6TWh of annual electrical consumption.

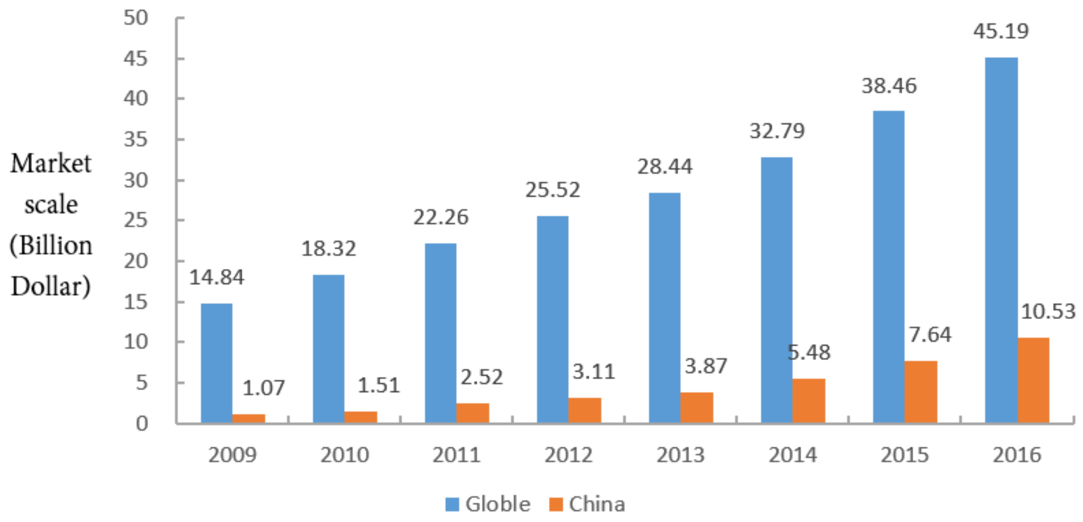


Fig 1. 2009-2016 Global CDC market scale [39]

A data centre, comprising a large number of Information and Communication Technology (ICT) equipment (e.g. servers, data storage, network devices, redundant or backup power supplies, redundant data communications connections, environmental controls and various security devices) and associated components [6], is essential support for the Information and Communication Technology (ICT). With the rapid development of the information technology-based economy, CDCs have become more and more prevalent in both the public and private sectors. They are widely used for web-hosting, intranet, telecommunications, financial transaction processing, research units, central depository information bases of governmental organizations and other fields. In the last few years, CDCs have gained widespread attention from both the academia and industry.

The ICT equipment in CDCs are energy intensive and they need to run continuously without resting during every hour of the 365 days of a year. It was showed that the energy usage of data centres is in the range of 120–940 W/m^2 [7]. And it is keeping increasing significantly, which has reached up to 100 times higher than the energy demand of commercial office accommodations [8]. DCs consumed 61 billion kWh of electricity in the USA in 2006, which is 1.5% of the total energy consumption of the USA in that year [9]. In 2013, the U.S. DCs consumed 91 billion kWh electricity. Moreover, the number is expected to increase to 140 billion kWh annually by 2020 [10]. The huge energy consumptions mean the significant potential of energy saving, so energy conservation measures should be taken in data centres, especially in the situation of global energy shortage, increasing oil prices and energy-related environmental pollutions.

Space cooling (i.e., air conditioning) is a fundamental need of CDCs which, aiming at removing a tremendous amount of heat dissipated from the IT equipment and keeping an adequate space temperature, consumes around 30% to 40% of energy delivered into the centre spaces [5, 11, 12,13].

The objectives of this task are:

To investigate the details of CDCs and classified them into several types so that the energy saving methods for each type of CDCs could be studied.

To theoretically investigate the energy saving potential in various types of CDCs by using IT load to determine the cooling demand and introducing cold air supply management.

To explore the feasibility of applying the super dew point cooling system in CDCs. Analyse the energy saving potential of the super dew point cooling by comparing the $PUE_{mechanical}$ of DCs using traditional cooling systems and super dew point cooling system, and calculating the annual electricity consumption for the two kinds of air conditioning systems.

The results will provide insights regarding the selection of technologies to improve the energy performance of CDCs.

2. Literature survey

2.1. Background

In simple terms, data centres are where internet lives or the storage of digital information available around the world. These storage centres are expanding rapidly and becoming power hungry. In general, electrical utility costs of a data centre is around 15 percent [14] of the total cost of the data centre which includes servers (CPU, memory, storage), network (links, optic fibre cables and equipment) and infrastructure (cooling and power distribution). The data centres are quite diverse from an infrastructure point of view which subsequently affects the electrical power drawn and the cooling system required. Fig. 1 shows different housing or infrastructure for data centres, it ranges from commercial city buildings to purpose-built mega storages.

(a) (b) (c)

Fig.1. A few examples of data centres with different infrastructures [15,16] (a)Data Centre of China Life Insurance. (b)Racks of telecommunications equipment. (c) Cabinet aisle in a CDC

CDCs are categorised into several market segments with respect to the energy share. in China the number reached 56.5 billion kWh in 2011 [40].

Table shows different market segments of CDCs in the United Sates for the year 2011. Small and medium server rooms are the largest number of CDCs (4.9 million) with 49 percent of the total energy share. Enterprise/corporate data centres are the second largest (3.7 million) with a 27 percent of the total electricity share. Among the remaining segments are the multi-tenant data centres, hyper-scale cloud computing and high-performance computing. The total energy/electricity consumed by these CDCs in the USA reached 76.4 billion kWh in 2011 [17], in China the number reached 56.5 billion kWh in 2011 [40].

Table 1 Estimated electricity consumption of data centres in the United States with respect to market segment of year 2011 [17]

Segment	Number of servers (million)	Electricity share	Electricity use （billion kWh/y）
Small and medium server room	4.9	49%	37.5
Corporate CDCs	3.7	27%	20.5
Multi-tenant CDCs	2.7	19%	14.1
Hyper-scale cloud computing	0.9	4%	3.3
High-performance computing	0.1	1%	1
Total	12.2	100%	76.4

2.2. Energy performance metrics and benchmarks for CDCs

It is essential to understand what energy profile an ideal data centre may possess. This will enable to seek and develop a better energy management approach for future data centres. In an ideal scenario, energy consumed by a data centre should match the energy needed to execute an incoming request. For example, the application logic gate receives a data request, it is processed by commanding the CPU, accessing the memory, disk and network. The amount of energy needed to perform such incoming requested can be evaluated to manage energy input. However, there are several energy overheads such as idling of computer (CPU, RAM, Disk), keeping the coolant system running and in power distribution mechanisms. These overheads must be minimised to improve the energy efficiency of data centres [24].

Fig. 2 compares energy consumed by an ideal data centre to the current (the vast majority) data centre, reduced energy consumed by Idle resources and reduced energy consumed by the infrastructure. The comparison shows that, clearly, there are more potential inefficiencies in the data centre and it requires to evaluate magnitude of losses in both of the scenarios highlighted above.

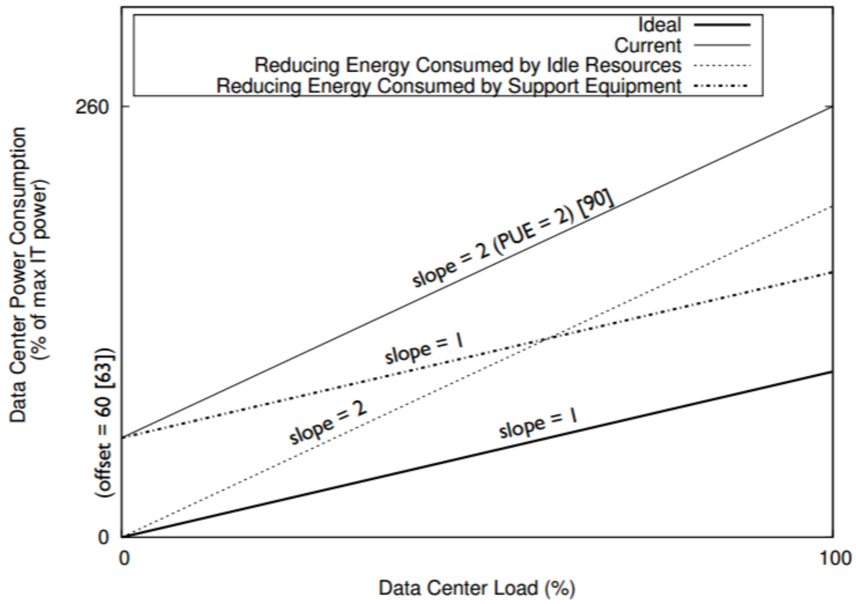


Fig 2. An estimated measure of the energy consumed by a data centre with the work load [25]

Energy efficiency metrics and benchmarks are used to evaluate the performance of CDCs and to identify the potential opportunities to reduce energy consumption in DCs. The most widely used efficiency metric are the Power Usage Effectiveness (PUE) and the Data Centre Infrastructure Efficiency (DCIE) which is the reciprocal of PUE [18]. PUE has become the widely-accepted industry de facto standard [19], which is defined as the ratio of the total facility power in the data center over the power of the ITE on the raised floor, the lower the better, as is shown in equation (1).

$$PUE = \frac{Total\ facility\ power\ use}{IT\ Equipment\ power\ use} \quad (1)$$

The PUE metric is used to reflect the power needed to run the IT under desired conditions. However, it does not consider the useful work done by the data center nor its performance [20].

Total facility power consists of power used by IT equipment and any overhead power consumed by anything that is not considered a computing or data communication device (i.e. cooling, lighting, etc.). An ideal PUE is 1.0 for the hypothetical situation of zero overhead power, the actual PUE is larger than 1.0 for any CDC existing on the earth. The CDCs in the US has an average PUE of 2.0 [21], most CDCs in China has a PUE in the range of 2.0～3.0 [40]. and the state-of-the-art data center energy efficiency is estimated to be roughly 1.2 [22].

Data center overall PUE could be divided into mechanical PUE and electrical PUE to enable a detailed view and assessment of the efficiency of each infrastructure separately. This method will also highlight the systems that appear to consume excessive power and hence energy efficiency measures can be implemented to reduce the power consumption. PUE in equation (1) could be written as:

$$PUE = \frac{P_{mechanical} + P_{electrical}}{P_{IT}} \quad (2)$$

The mechanical power consumption includes all the components of the data centre cooling system, as is calculated in equation (3). Depending on the type of the air conditioning technology, the components will vary from one data centre to another. The mechanical system constitutes the main systems that are used to provide HVAC to the servers and plant rooms that serve the data centre (i.e., raised floor area, UPS rooms, switchgear rooms, etc.). Dedicated mechanical plant includes chillers, chilled water pumps, cooling tower fans, dry or adiabatic cooler fans, makeup water pumps, ventilation fans and CRAC units (including compressor, internal and external fans, humidifier, and preheater). For legacy data centres, these various mechanical systems will typically result in a PUE mechanical of 0.4 and can be as high as 2 [23].

$$PUE_{mechanical} = \frac{Annul\ average\ P_{mechanical}}{Annul\ average\ P_{IT}} \quad (3)$$

The electrical power consumption includes all the power losses starting from the utility through the UPS, PDUs, and RPPs to the IT equipment, as can be calculated from Equation (4) below. The electric system constitutes the main systems that eventually power the servers via the UPS systems. This includes the power to the servers via the static transfer switches (STSs) and power distribution units (PDUs), UPS power (typical efficiency 0.85 to 0.96) and cable distribution losses (typical losses 1% to 1.5%). These various power distribution systems result in a typical electric PUE electrical range from 1.08 to more than 1.5 [23].

$$PUE_{electrical} = \frac{Annul\ average\ P_{electrical}}{Annul\ average\ P_{IT}} \quad (4)$$

The block diagram in Fig. 3 depicts the energy flow and the various energy quantities that are shown in Equations (1) to (4).

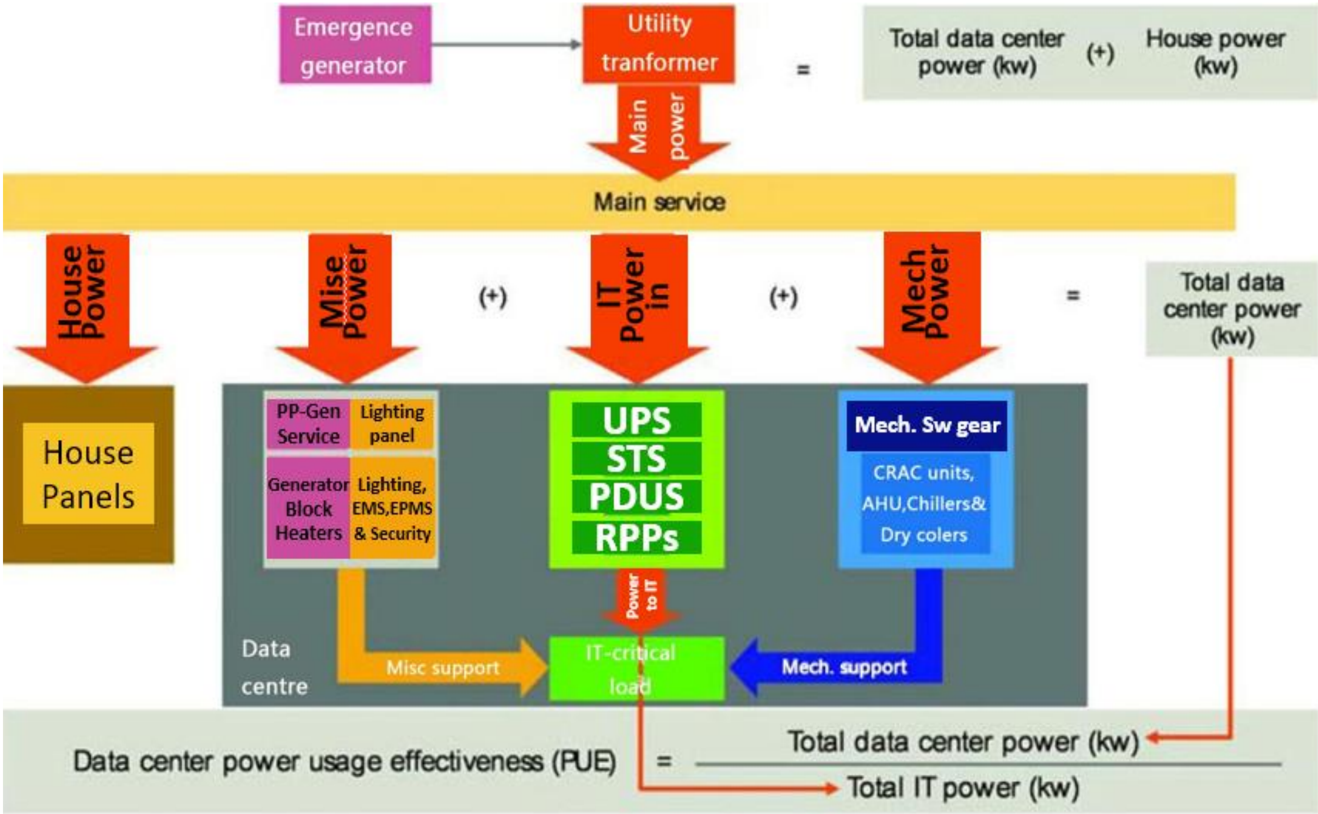


Fig. 3 Block diagram of data centre electrical and mechanical infrastructure [23]

2.3. Classification of Computing Data Centres

It is necessary to classify CDCs in terms of different property, so that each type of data centre could be studied and analyzed. There are diverse ways to classify date centres in terms of data availability, functions and sizes of the data centres.

CDCs could be classified based on functions. There are corporate CDCs, CDCs inclined to provide turnkey solutions to clients, web hosting DCs which may also provide computer infrastructure, and CDCs that use technology to web 2.0. Some CDCs may fall into more than one category and some may vary in the same category. Some of the distinctions among the CDCs include data storage technology in use, the internal and external bandwidth used, the level of server virtualization as well as the number of serves which influences the size of the data centre [26].

Corporate CDCs have closed structures design to optimise functions within the company's IT services and applications. Some of the sectors that have such CDCs are in the oil and gas, IT companies or biotechnology, who's IT capabilities have some patented ideas and trade secrets. Some need high performance computing clusters that will do scientific analysis as part of their day to day activities. Others are open structured and mainly for customer service. [3]

Networks and virtualization is another aspect that is used to differentiate the CDCs. From a network stand point, the advent of fiber optics and the need for fast communication has seen the integration of the fiber technology with the LAN based Ethernet. Also in attempt to make more use of hardware resources, the trend in development of data canters pushed for the use of virtual servers. In a typical CDC, you would expect a mixed network set up with a combination of both physical and virtual servers. [3]

Turnkey CDCs capture the provision of facilities for companies that are looking for already established premises to use. As opposed to going through the exercise of getting property, designing and procuring hardware, this kind of CDCs provide compartmentalized units that suit various needs for probable clients. That means a client will present the desired needs and specifications of systems and will get a "plug-in-ready" set up that will host several companies under the same property. The advantage of such CDCs is the economies of scale make them have advanced features including power, cooling, sustainability features that also include redundant components making the reliability incredibly high. One example is the SAP data centre in Germany. This infrastructure can provide availability to their application and back up information for their clients. Achieving high energy efficiencies is possible in this scale. [3]

Web 2.0 technology data centres have specific inclination in terms of needing physical environments mostly with L3 services at the centre while L2 is used at the periphery. Most of them have local data storage systems, they have their own bandwidth and users access many apps and services from several sources. They are mostly optimised for use in social media platforms as well gaming platforms. [3]

The hosting CDCs vary in size depending on the client base. Some have several CDCs in different corners of the world. The hosting companies offer clients with different services according to their agreement. It is therefore a centre suited to serve external bandwidth. Virtualization demand and needs have led to the expansion in this industry which has made them adjust their network topology to enable migration of the material from clients internally within designations and space provided. [3]

Data availability is a term used by computer storage manufacturers and storage service providers (SSPs) to describe products and services that ensure that data continues to be available at a required level of performance in situations ranging from normal through "disastrous" [27]. A think tank and professional-services organization based in Santa Fe, New Mexico, has defined its own four levels [27]. The levels describe the availability of data from the hardware at a location. The higher the tier, the greater the availability. The annual allowance for unavailability of service of the 4 tier levels is shown in table 2.

Table 2 The annual allowance for unavailability of service of the 4 tier levels [27]

Tier Level	Maximum annual downtime	Guaranteed availability
1	28.8 h	99.67%
2	22.6 h	99.67%
3	1.6 h	99.98%
4	0.4 h	100.00%

This is useful for measuring data centre performance, Investment, and ROI (return on investment). Tier 4 data centre is considered as most robust and less prone to failures. Tier 4 is designed to host mission critical servers and computer systems, with fully redundant subsystems (cooling, power, network links, storage etc.) and compartmentalized security zones controlled by biometric access controls methods. Naturally, the simplest is a Tier 1 data centre used by small business or shops [27].

However, tier level is nothing but a standardized methodology used to define uptime of data centre, which is useful for measuring data centre performance, Investment, and return on investment (ROI). To have the understanding necessary for this project we shall classify them based on their energy consumption.

Munther and Robert [23] collected data from 44 data centres to analyzed the efficiency metrics. In the charts below, the efficiency metrics were plotted versus the climate zone for the audited data centres. Climate zones are based on ASHRAE climate zone designations where 1 is the hottest while 7 is the coldest. The moisture level is indicated by A, B, or C where A stands for moist, B stands for dry or desert while C stands for marine conditions.

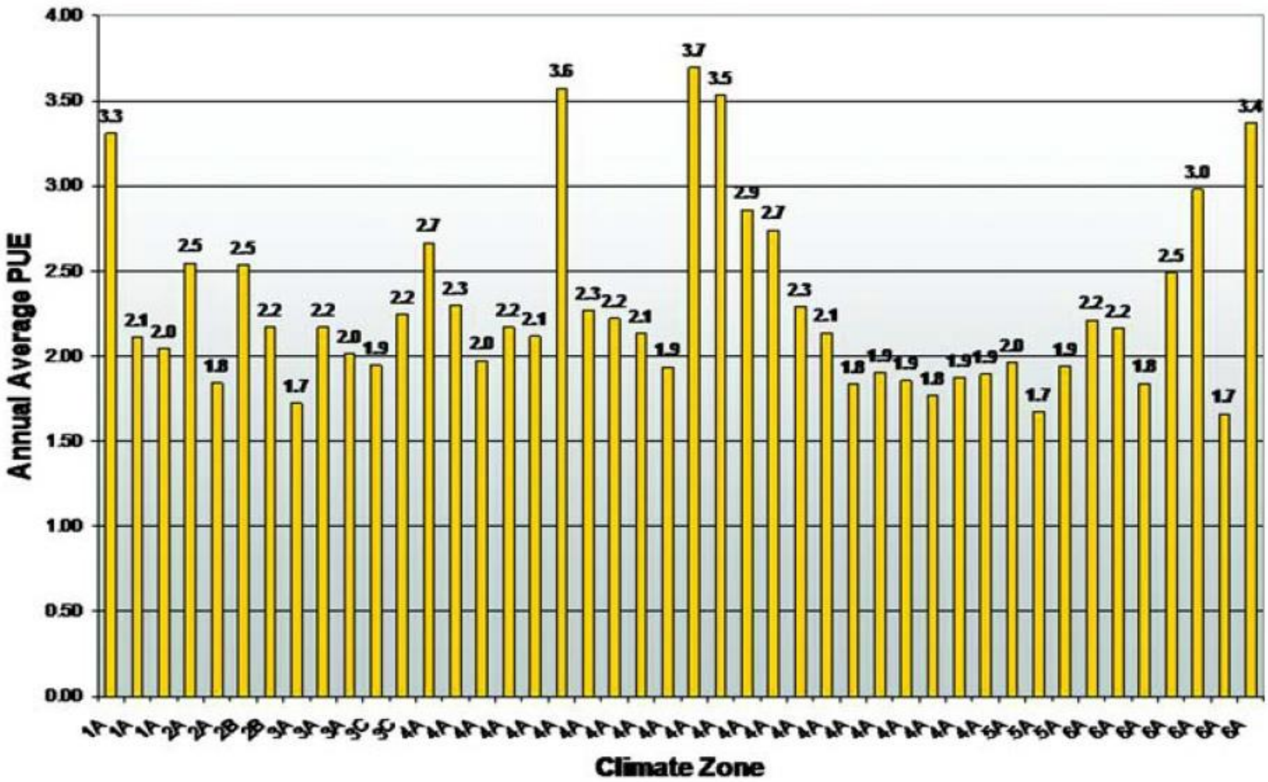


Fig. 4 Annual average PUE of 44 data centres in different climate zones [23]

It can be seen from Fig. 4 that the PUE of 44 CDCs in different climate zones is ranging from around 1.67 to 3.57 with an average of 2.34.

Table 3 Average PUE for CDCs of different size [23]

Data Centre Size	Average PUE	Classification
RFA < 10,000 ft^2	2.8	Small Data Centers
10,000 ft^2< RFA < 30,000 ft^2	2.2	Medium Data Centers
RFA > 30,000 ft^2	2.1	Large Data Centers

The database indicated that small data centres (Raised Floor Area (RFA) <10,000 ft^2) or corporate data centres have higher average PUE than the larger ones. Table 3 depicts this fact. Small data centres were observed to have partially populated IT equipment racks and floors, oversized and aging cooling systems, higher levels of air mixing (recirculation and bypass air) in the raised floor areas, no implementation of free cooling, low UPS load factor, and no direct cooperation between the IT and the facilities departments. However, enterprise CDCs were observed to implement more energy saving techniques such as “free cooling” via water side economizer as well as higher level of cooperation between IT and facilities. Many of those large CDCs were also observed to participate in various professional IT and facilities organizations' seminars to stay informed about new advances in their field as well as industry best practices [23].

The above information suggests that it is reasonable to classify CDCs by size. Raised Floor Area is one way to describe the size of CDCs, but RFA is not accurate to describe how much energy a CDC consumes. IT equipment power consumption is more suitable to indicate how much electricity energy a CDC consumes, how much heat will be generated by IT equipment, and how much waste heat can be collected to make use of. CDCs can be generally classified into 4 types in terms of IT equipment load, i.e., super, large, medium and small sized types, as is listed in Table 4.

Table 4 Classification of DCs in terms of IT equipment load

IT equipment load of CDCs	Classification
P >25,000 kw	Super
7,500 kw < P < 25,000 kw	Large
2,500 kw < P < 7,500 kw	Medium
P < 2,500 kw	Small

3. Methodology

3.1. IT load and air management in CDCs

To ensure the normal operation of IT equipment, the supplied cooling is usually more than required in CDCs, which causes great waste in energy. To improve the energy efficiency, a lot of efforts have been made. There are generally three ways to supply the cooling air into data centres by managing cooling air supply at different level: (1) Managing cooling air supply at room level; (2) Managing cooling air supply at row level; (3) Managing cooling air supply at rack level. [28]

Managing cooling air supply at room level.

Supplying cooling air at room level usually adopts a structure of hot aisle/cold aisle with raised floor, and the configuration and air flow are shown in Fig.5(a). Although supplying air through raised floor has been proved as a feasible way for energy saving [29], it still has a lot of drawbacks, such as cold air bypass and the mixing of hot and cold air. Aisle containment is an effective method for improving the air management. By using the flexible strip curtain of rigid enclosure, the cold aisle and hot aisle are separated to avoid air leakage from the enclosure. Ham et al compared energy consumption of the data centre with and without aisle containment, and results showed that nearly 14% energy was saved by air containment [30] Shrivastava et al compared energy saving performance of two containment strategies including cold aisle containment (CAC) and vertical exhaust duct (VED) [31] The energy consumption was decreased by 24% and 35% with the utilization of CAC and VED system respectively.

Managing cooling air supply at row level (In-Row cooling).

The power density of servers in data centres keeps rising in these years. A survey shows that the percentage of the server rack, which power density is larger than 10kW/rack, has increased to 22% [32]. Accordingly, in-row cooling system started to be used due to a better cooling performance. The configuration and air flow of in-row cooling system are shown in Fig.1(b). Instead of distributing the cooling air evenly into the room, the design of in-row cooling system takes server row as the orientation, which places the cooling unit between the server racks to adjust cooling capacity based on the temperature of servers. Priyadumkol et al compared the performance of room level cooling and in-row cooling, and the results revealed that in-row cooling is more effective to deliver cold air to the top of the server rack, as it can eliminate the hot spot at the top of server rack [33]. Wu investigated six structures, including cold air containment and in-Row cooling, and results showed that in-Row cooling is able to remove overheated servers as well as to provide a lower maximum server inlet temperature compared with aisle containment system [34]. However, no results about energy saving were provided.

Managing cooling air supply at rack level.

For server racks, not only the average power density but also the peak power density has increased significantly. To meet the cooling demand of the racks with extremely high-power density, rack level cooling can be introduced in data centre due to its ability to provide cooling capacity more accurately. The common configuration and air flow is shown in Fig.5(c). Snorkels, which direct cooling air form the under-floor plenum to the cabinet, have been used. According to Onyiorah et al [35]. snorkels can significantly reduce the temperature of the top of cabinets and eliminate over-cooling of the cabinets in the meantime.

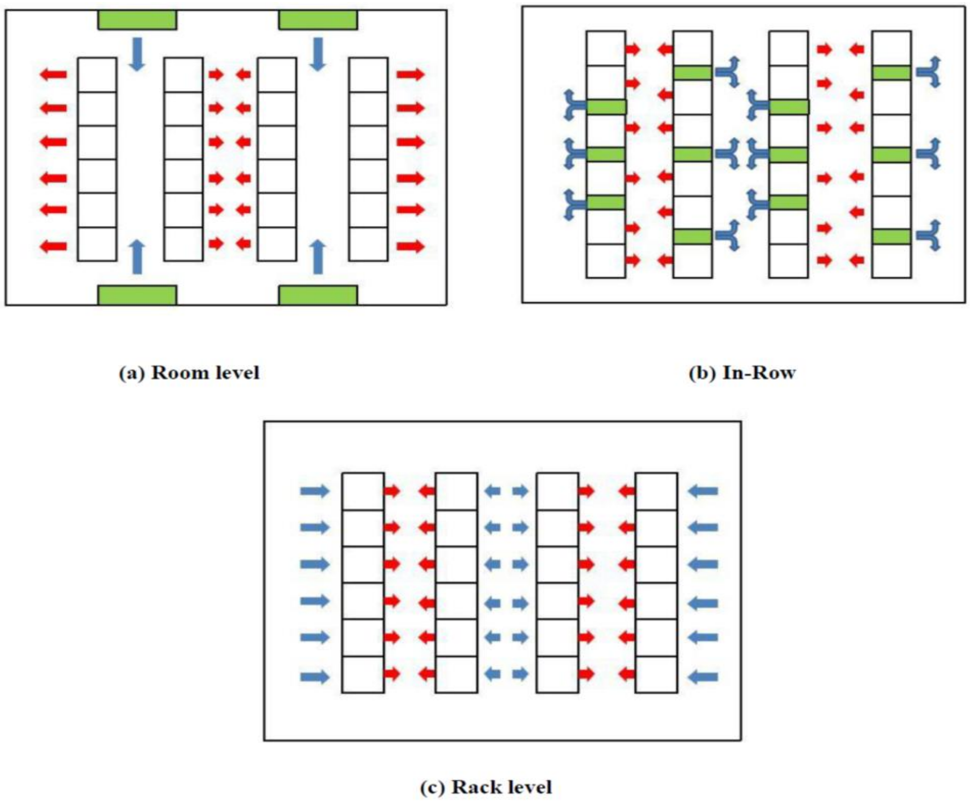


Fig.5 The configuration and air flow for systems supplying cooling air at different levels

To investigate the load profile of CDCs, a model for CDCs should be applied to form a computing program to simulate the IT equipment load. To simplify the model and the computational program, some assumptions was made: Each server consists of 20 processors, the processor is randomly in either idle status or in running status. The power consumptions of a processor in running and idle statuses are 25W and 12.5W respectively, and a server consists of 20 processors. By knowing the status of processors, the power consumption of a server can be determined. The server is considered a basic unit for the energy performance analysis. Servers are contained in racks, racks are arranged in row, and rows are arranged in CDC room.

The processor accounts for most of the power consumption of a server, however, there are some other components such as hard disk and network component, which also consume power. [36] It is assumed that the power consumption of hard disk and network component are 80W and 20W, respectively. Therefore, the cooling demand of server can be corrected as:

$$P_{server} = P_{disk} + P_{net} + \sum_{n=1}^{20} P_{prosessor} \tag{5}$$

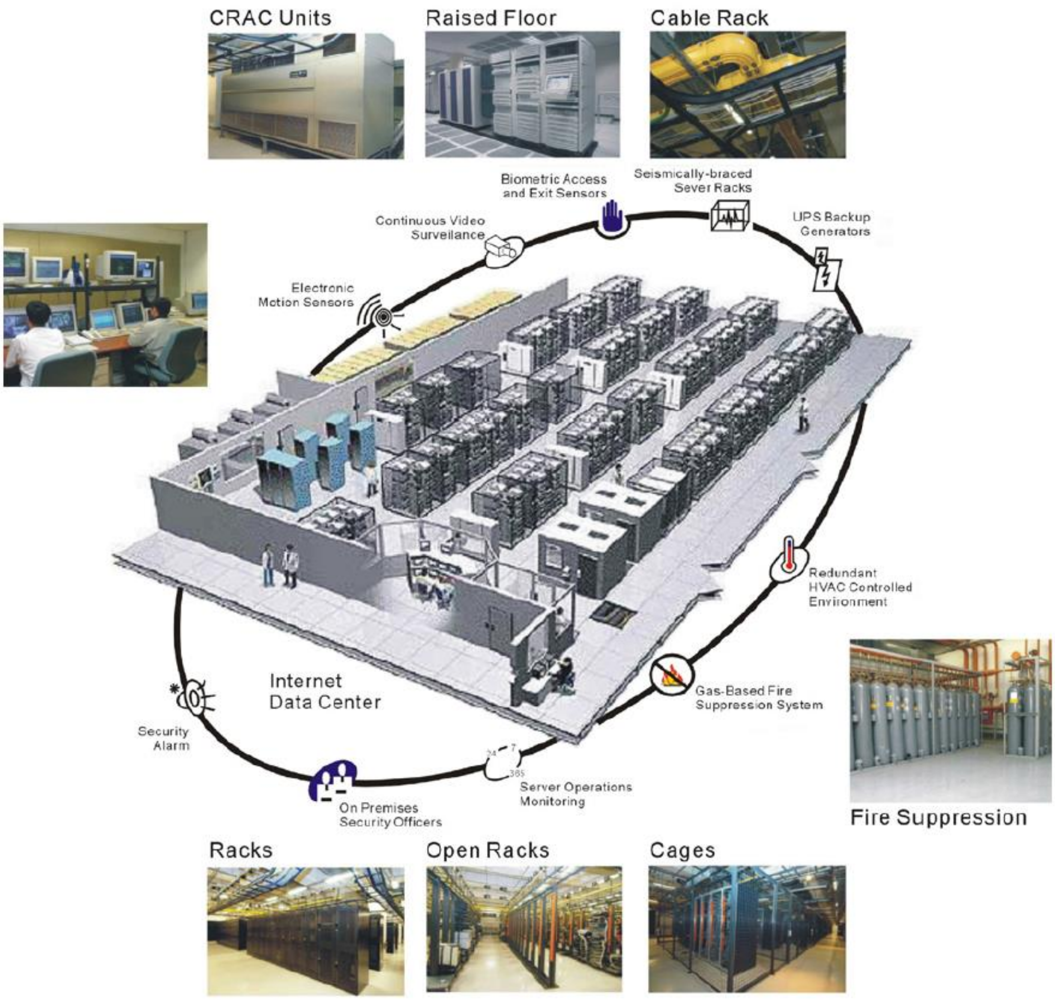


Fig. 6 A typical CDC floor plan showing IT equipment arrangements [23]

Fig. 6 shows the IT server arrangements in a typical CDC floor plan. In this report, the IT equipment arrangements in 4 types of CDC is listed in Table 5.

Table 5 Assumption of IT equipment arrangements in 4 types of CDCs

CDC type	Super	Large	Medium	Small
Number of rows in DC	50	30	20	8
Number of racks in a row	60	30	30	20
Number of servers in a rack	20	20	10	10
Load (kW)	36000	10800	3600	960

For the design of cooling systems and air management, it normally assumes a uniform operation status for all of servers and homogenous temperature in data centres. Nevertheless, the operation status is quite different from server to server. To reduce excessive cooling supply, cooling demand should be determined according to the operation status of servers, or in other words IT load. To investigate the energy saving potential when regulating the cooling supply according to the power consumption of servers, five scenarios are designed including a reference scenario.

Scenario 1. Reference case: In data centres, there could be thousands of servers which operating statuses are not uniform due to their divergent functions. Therefore, the hot spot keeps moving. Even though many servers may not operate at full load, to guarantee all of servers operate in the desired range of temperature, the supplied cooling is normally fixed at a high level and much excessive cooling is supplied. The cooling demand can be calculated by assuming all of servers are running at full load:

$$P_{cooling\_1} = N_{servers} \cdot P_{full} \quad (6)$$

where P_{full} is the power consumption of server in running at full load, and $N_{servers}$ is the number of servers in the entire data centre. This represents the case of the highest power consumption.

Scenario 2. Cooling demand response at room level: The change of server operation status results in the change of power consumption. In this scenario, instead of assuming all of processors always running at full load, the cooling demand is determined by the server which consumes the most power:

$$P_{cooling\_2} = N_{servers} \cdot Max(P_{i,j,h}) \quad (7)$$

where $P_{i,j,h}$ is the power consumption of the h^{th} server in the i^{th} row and the j^{th} rack.

Scenario 3. Cooling demand response at row level: The cooling demand response at row level takes the row of server as a cooling object for adjusting the cooling demand. The cooling demand of each row is, therefore, determined by the server consuming the maximum power in that row:

$$P_{cooling\_3} = \sum_{i=1}^{I} N_{racks\_in\_row} \cdot Max(P_{i,j,h}) \quad (8)$$

where $N_{racks\_in\_row}$ is the number of racks in a row, I is the number of rows in a room.

Scenario 4. Cooling demand response at rack level: Considering the rack of servers as the cooling object, the cooling demand of each rack is determined by the server consuming the maximum power in that rack:

$$P_{cooling\_4} = \sum_{j=1}^{J} \sum_{i=1}^{I} N_{servers\_in\_rack} \cdot Max(P_{i,j,h}) \quad (9)$$

where $N_{servers\_in\_rack}$ is the number of servers in a rack, J is the number of racks in a row.

Scenario 5: Cooling demand response at server level: Cooling demand response at server level determines the cooling demand based on the power consumption of each server, which is calculated by:

$$P_{cooling\_5} = \sum_{h=1}^{H} \sum_{j=1}^{J} \sum_{i=1}^{I} N_{servers\_in\_rack} \cdot P_{i,j,h} \quad (10)$$

where $P_{i,j,h}$ is the power consumption of the h^{th} server in the i^{th} row and the j^{th} rack, H is the number of servers in a rack.

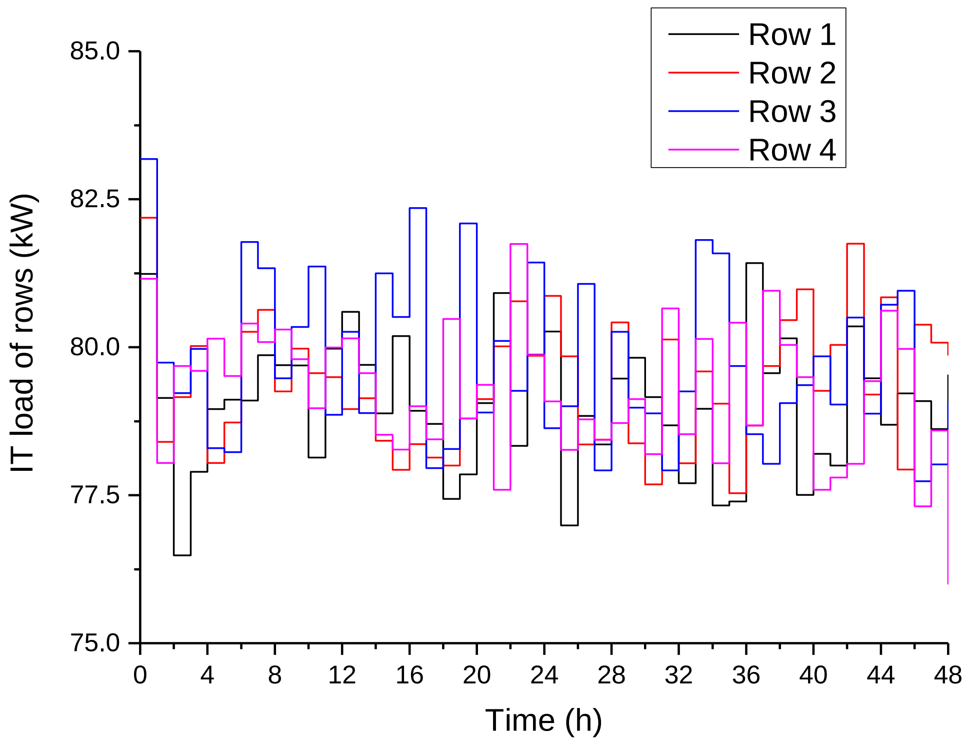
Although the processor accounts for most of the power consumption of a server, there are some other components such as hard disk and network component, which also consume power [37]. To estimate the cooling demand more accurately, it is assumed that the power consumption of hard disk and network component are 80W and 20W respectively, and each server contains 20 processors. Therefore, the cooling demand of a server can be corrected as:

$$P_{i,j,h} = P_{disk} + P_{net} + \sum_{n=1}^{N} P_{processor} \quad (11)$$

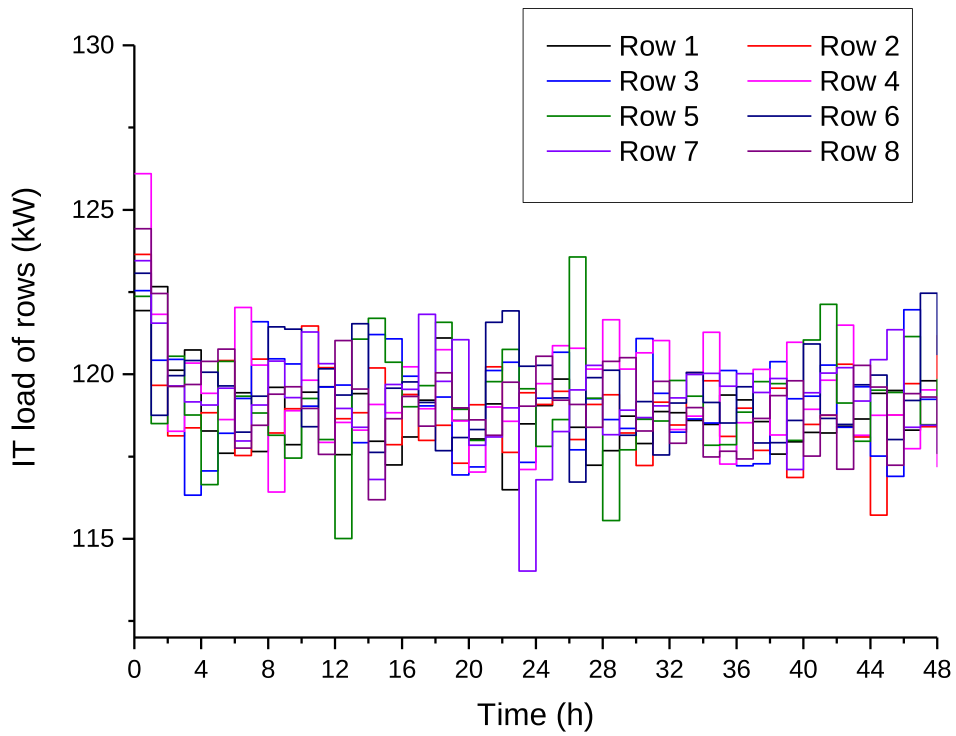
where $P_{processor}$ and P_{disk} and P_{net} are the power consumptions of processor, hard disk and network component, respectively, N is the number of processors in a server.

3.2. Energy saving potential for the 5 scenarios

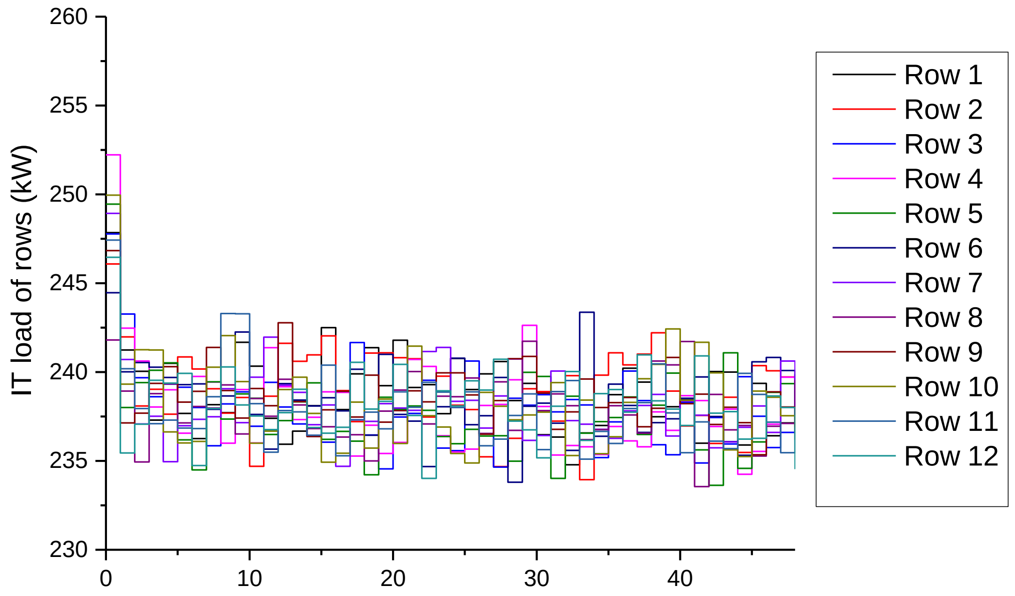
To calculate the cooling demand for different scenarios, a C++ program was designed to simulate the IT loads of every server in a CDC for each hour of the 48 hours. The simulated IT loads of different rows are shown in Fig.7. The dynamic hourly cooling demand is shown in Fig.8.



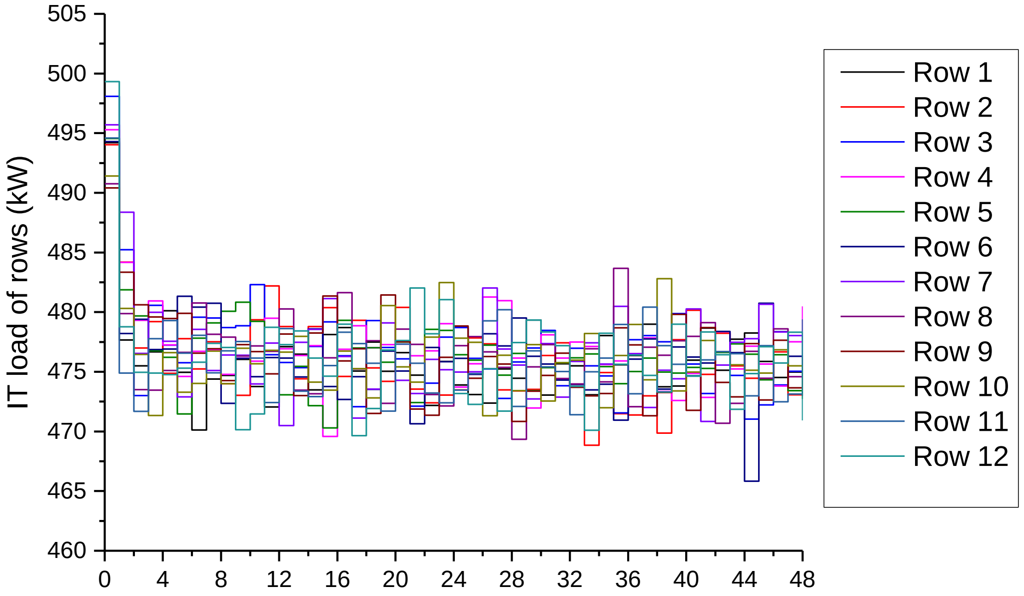
(a) Small DC



(b) Medium DC

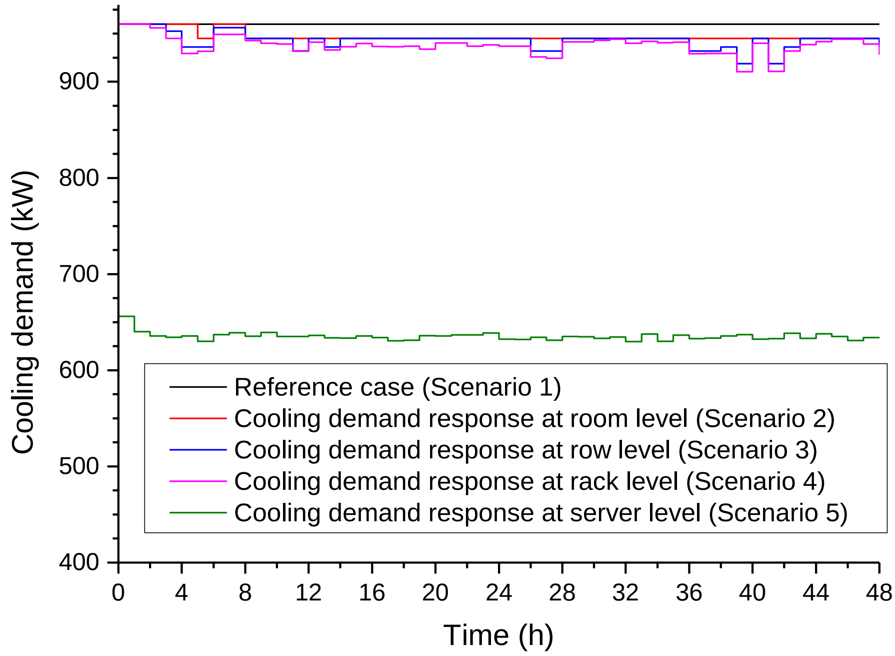


(c) Large DC

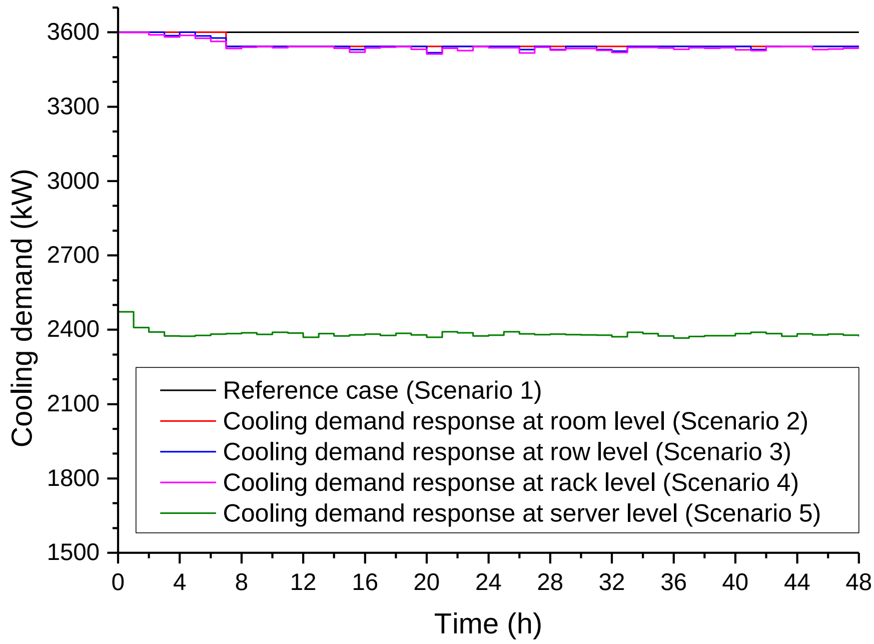


(D) Super DC

Fig. 7. IT load of different rows in four types of CDCs



(a) Small DC



(b) Medium DC

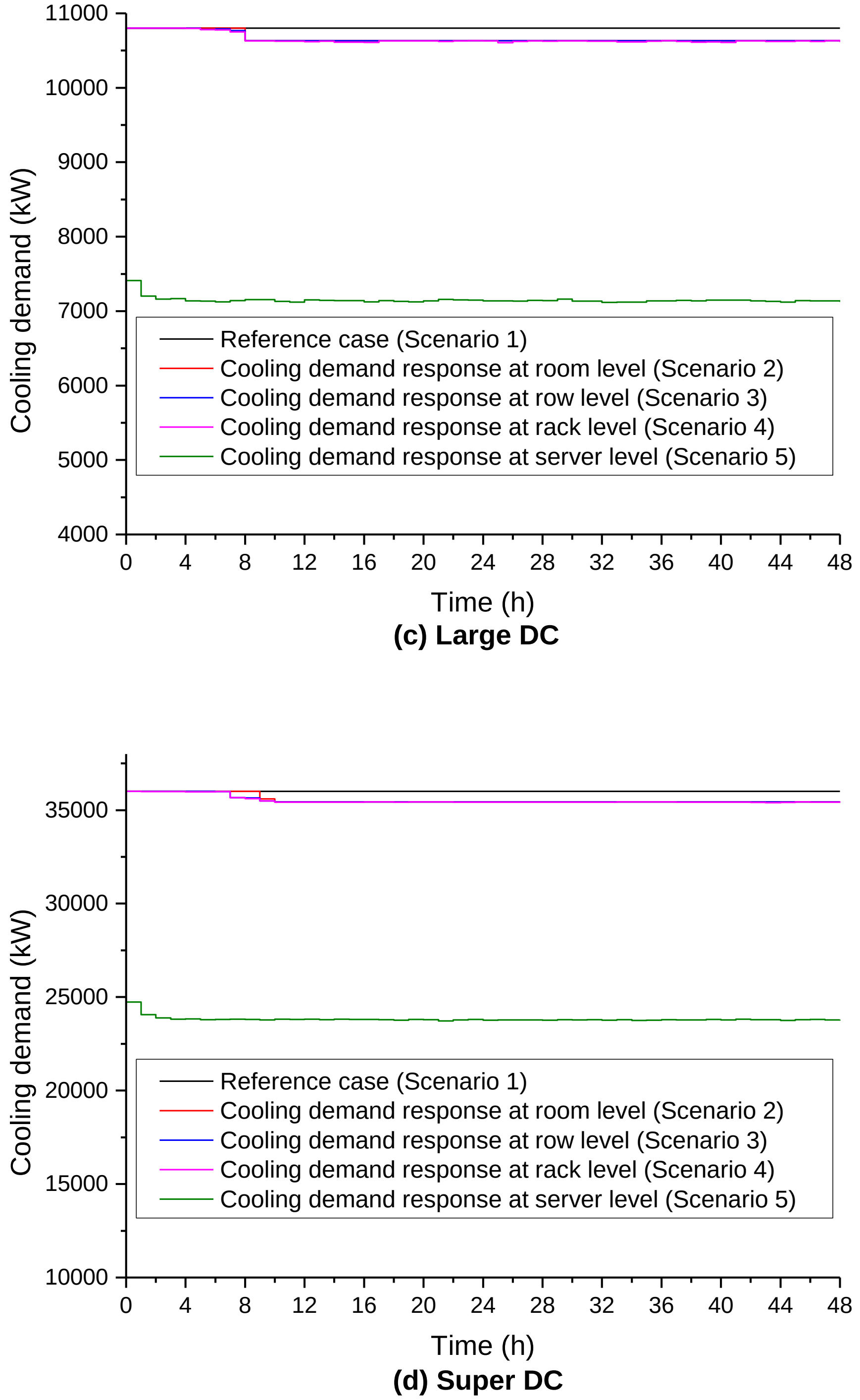


Fig.8. Cooling demand of different scenarios in four types of CDCs

Table 6 depicts that compared to reference case (Scenario 1), the total cooling demand of Scenario 2, Scenario 3, Scenario 4, Scenario 5 is reduced by 2.38%, 4.12%, 4.99% and 33.85% respectively for small CDC, 1.53%, 2.27%, 2.78% and 33.70% for medium CDC, 1.28%, 1.64%, 1.97% and 33.87% for large DC, 1.36%, 1.40%, 1.50% and 33.82% for super CDC, respectively.

Table 6. Total cooling demand of different scenarios in four types of CDCs in 48 h.

Cooling demand response	Small	Medium	Large	Super
reference case (MW·h)	5.88	23.52	52.92	235.2
room level / reference case	97.62%	98.47%	98.72%	98.64%
row level / reference case	95.88%	97.73%	98.36%	98.60%
rack level / reference case	95.01%	97.22%	98.03%	98.50%
server level / reference case	66.15%	66.30%	66.13%	66.18%

Compared with reference case, which calculates the cooling demand at a high level by assuming the most of servers are in running status, it has great potential to save energy to use dynamic IT load to determine the cooling demand. The scale of CDCs slightly affects the saving of cooling demand, the smaller the CDC, the higher proportion of cooling demand would be saved. Corresponding to 4 ways of cold air supply, the saved cooling demand increases following the order of cooling demand response at room level, row level, rack level and server level. For the randomly simulated 48 hours, the total cooling demand is reduced by 6.7%, 8.5%, 9.3% and 34.2% respectively for small DC; 1.5%, 2.0%, 2.6% and 33.8% for medium DC; 1.3%, 1.4%, 1.6% and 33.8% for large DC; 1.3%, 1.3%, 1.3% and 33.8% for super DC, respectively.

3.3 Energy saving potential of the super performance dew point air cooler

The energy saving potential of super dew point cooling was analyzed by comparing the PUEmechanical of CDCs using traditional cooling systems and super dew point cooling system. The Coefficient of performance (COP) of an air conditioning system is defined by:

$$COP = \mathrm{Q/W} \tag{12}$$

where Q is the useful heat load of IT equipment, and W is the work required by the air conditioning system.

The IT equipment power PIT converts into the heat load for air conditioning system, so in ideal conditions,

$$PUE_{mechanical} = 1/COP \tag{13}$$

The COP of traditional cooling systems is around 3.0, and the COP of the super performance dew point air cooler investigated by Peng Xu et al. [38] achieved as high as 37.4. COPs of the super performance dew point air cooler at various climatic conditions are depicted in Fig. 9.

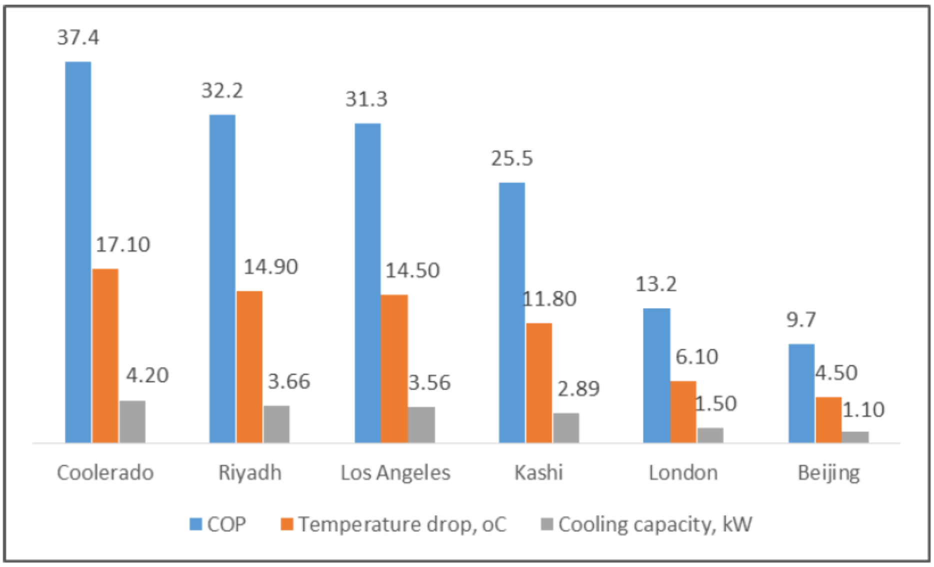
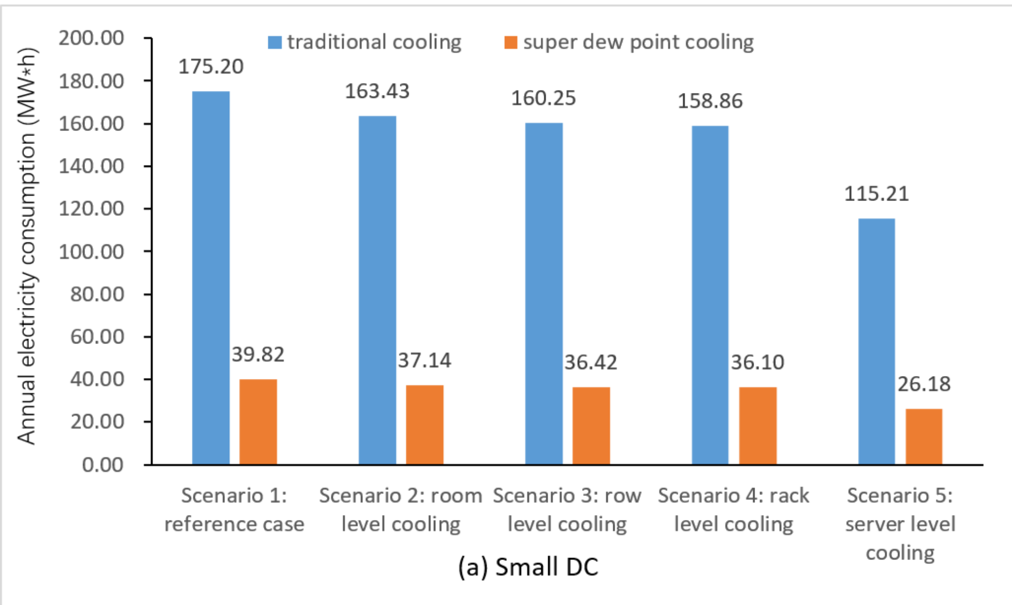


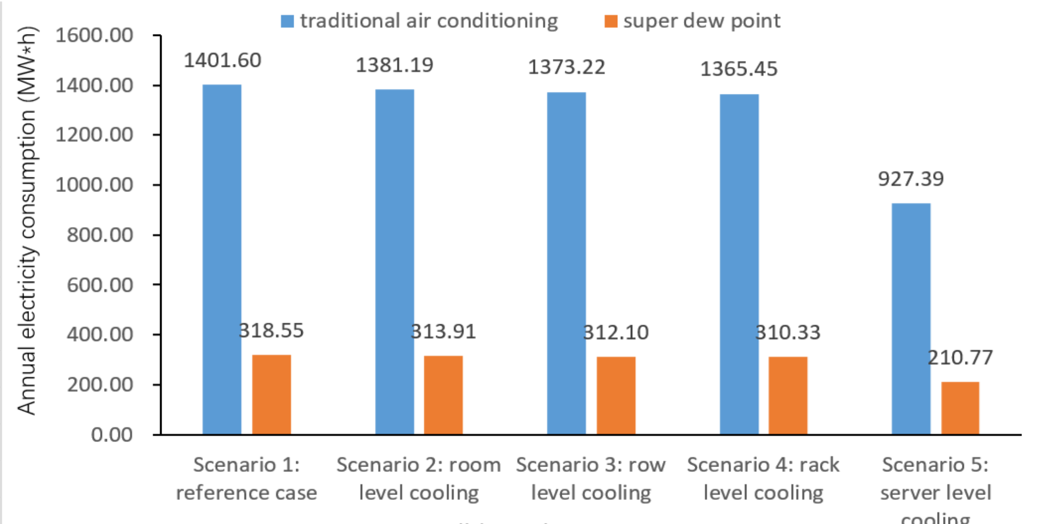
Fig. 9. COP of the super performance dew point cooler at various climatic condition [38]

Assuming the COP of the super performance dew point air conditioning system to be 13.2 (in London's summer climates) and the COP of traditional air conditioning system to be 3.0, the annual electricity consumption for the two kinds of air conditioning systems could be calculated for 4 types of CDCs in the 5 scenarios.

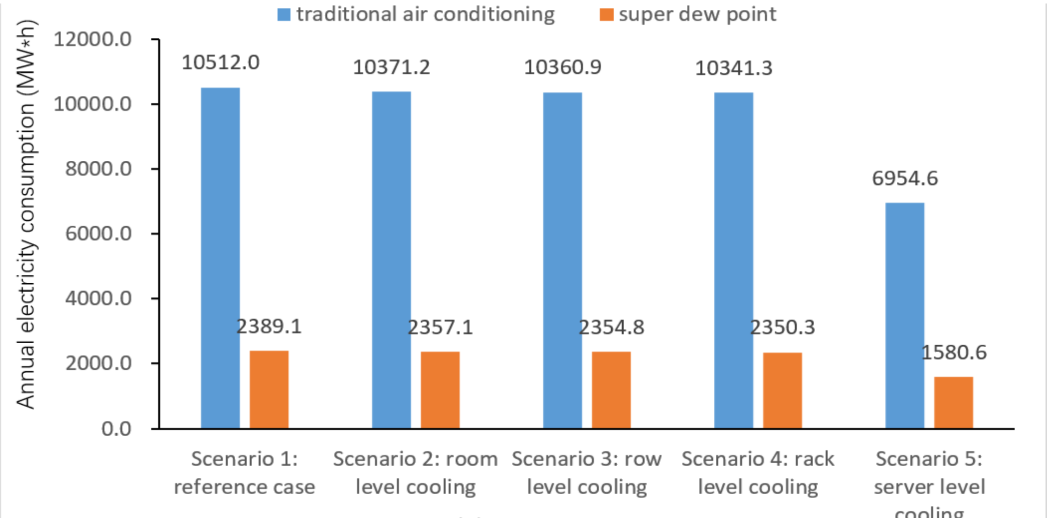
$$E = P_{cooling} \cdot t/COP \tag{13}$$

Where E is the electricity consumption for air conditioning systems, Pcooling is the cooling demand for a CDC, t is the time. The results are shown in Fig. 10.

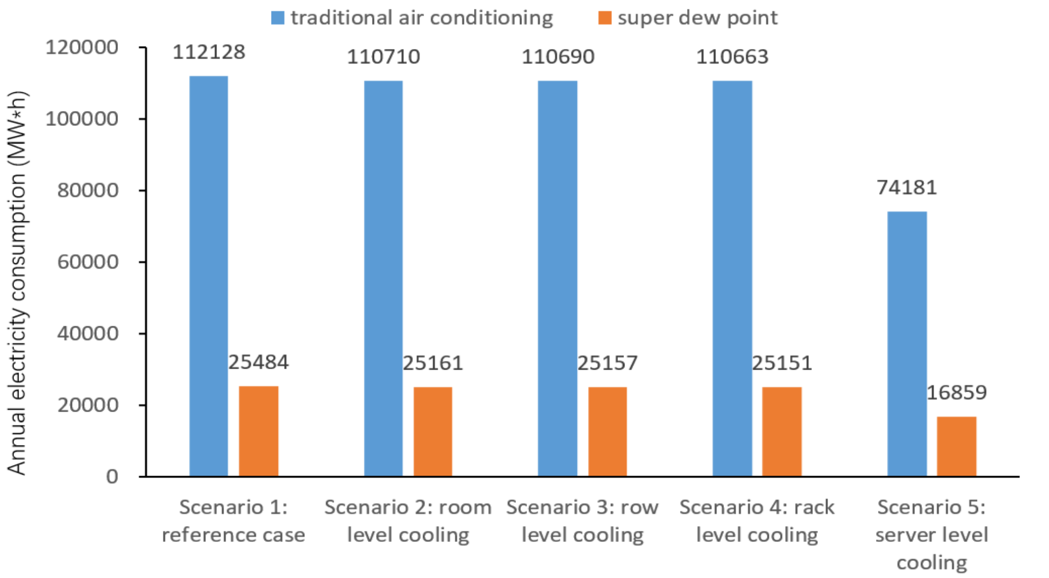




(b) Medium DC



(c) Large DC



(d) Super DC

Fig. 10 Annual electricity consumption for the two kinds of air conditioning systems

Table 7 Annual electricity saving by using the super dew point air conditioning system instead of traditional system

Annual electricity saving	reference	room level	row level	rack level	server level
Small CDC （MWh）	2166.1	2137.1	2127.9	2116.5	1433.1
Medium CDC （MWh）	8122.9	8014.1	8006.7	7992	5376.6
Large CDC （MWh）	24368.7	24050.1	24047.4	24031.2	16123.8
Super DC （MWh）	81229.1	80200.3	80164.3	80143	53737

Table. 7 depicted the annual electricity saving by using the super dew point air conditioning system instead of traditional air conditioning system in 4 types of CDCs with the 5 kinds of cooling method. The advantage of the super dew point air conditioning system is verified by the calculation results. The bigger the CDC the more electricity energy would be saved by applying super dew point air conditioning system. The average annual electricity saving is 1196.1 MWh for small DC, 7502.5 MWh for medium DC, 22524.2 MWh for large DC, and 75.94.7 MWh for super DC, respectively.

4. Conclusions

4.1 Technical conclusion

The details of CDCs are investigated, they can be classified into 4 types in terms of IT equipment load capacity: super, large, medium and small. The energy saving potential in super, Large, medium and small CDCs when managing cold air supply at the room level, row level, and rack level is studied and the cooling demand based on the simulated dynamic IT load is calculated. In addition, Annual electricity consumptions for super dew point air conditioning system and traditional system air conditioning systems were compared to further explore the energy saving in CDCs.

Compared with reference case, it has great energy-saving potential to use dynamic IT load to determine the cooling demand. The scale of CDCs slightly affects the saving of cooling demand, the smaller the DC the higher proportion of cooling demand would be saved. Corresponding to the 4 ways of cold air supply, the saved cooling demand increases following the order of cooling demand response at room level, row level, rack level and server level.

The energy saving potential of the super dew point cooling were analyzed by comparing the $PUE_{mechanical}$ of DCs using traditional cooling systems and super dew point cooling system, and the annual electricity consumption for the two kinds of air conditioning systems. The annual electricity saving by using the super dew point air conditioning system instead of traditional air conditioning system is huge. The average annual electricity saving is 1196.1 MWh for small

DC, 7502.5 MWh for medium DC, 22524.2 MWh for large DC, and 75.94.7 MWh for super DC, respectively. The advantage of the super dew point air conditioning system is verified.

4.2 Task conclusion

In this task, (1) the details of CDCs design have been investigated and CDCs are classified into several types therefore the energy saving methods for each type of CDCs could be studied. (2) The energy saving potential in various types of CDCs are theoretically investigate by using IT load to determine the cooling demand and introducing cold air supply management. (3) The feasibility of applying super dew point cooling system in CDCs is explored. The energy-saving potential of the super dew point cooling is analysed by comparing the $PUE_{mechanical}$ of DCs using traditional cooling systems and super dew point cooling system respectively and calculating the annual electricity consumption for the two kinds of air-conditioning systems. The outcomes of this task will be used in the following task 1.2 and task 1.3 as the technical foundation of CDC dew point cooling systems analysis and CDC cooling design database. The valuable outcomes will also provide insights regarding the selection of technologies to improve the energy performance of CDCs in work-package 2 to work-package 7.

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