*Revised Manuscript with No Changes Marked

# A Simplified Power Consumption Model of Information Technology (IT) Equipment in Data Centers for Energy System Real-time Dynamic Simulation

**Abstract**

Due to the rapid rise of power consumption of data centers in recent years, much work has been done to develop energy-efficient design, controls and diagnosis of their cooling systems, while the energy system simulation is used as an effective tool. However, existing models of information technology (IT) equipment of data centers cannot well represent the effects of IT equipment design and operation status on the data center cooling demand, and this hinders the development of the energy saving cooling technologies of data centers. To address this issue, this paper introduces a power consumption model of IT equipment in data centers with coefficients and modeling script provided for immediate use in data center energy system simulation. This energy model can be used to simulate energy performance of typical IT equipment in data centers under real-time dynamic operation conditions conveniently and effectively without the need of data other than the specifications of a data center design and IT equipment manuals. Its use with a commonly used building simulation program is demonstrated with a building model of a typical large office in a subtropical area. The results show that the model can represent the change of power consumption of data centers with different IT equipment designs and operation appropriately.

*Keywords:* Data center; energy consumption modeling; building simulation; energy efficiency

## 1. Introduction

Energy consumption of data centers is increasing every year. In 2010, their electricity consumption was around 1.3% of the total of the whole world [1], and Shehabi et al. estimated their energy consumption would be tripled in a decade if the demand on their services continued to increase and their energy efficiency remained unchanged [2]. Since the top two energy consumers in data centers have been its information technology (IT) equipment and cooling systems and each consumes around 30% to 60% of total electricity use of the data centers [3]–[5], many researchers have developed technologies to reduce energy use of these two components in data centers rapidly in recent years [6]–[13], [60].

**Nomenclature**

| | |
|---|---|
| $a_i$ | i[th] empirical coefficient [unit varies] |
| $C$ | Network traffic load [Gbit/s or Gbps] |
| $E$ | Annual electricity consumption [kWh] |
| $LF$ | Load factor |
| $N$ | Number of data points |
| $P$ | Power consumption [W] |
| $Q$ | Total cooling delivered in a year [kWh] |
| $S$ | Average speed [MHz] |
| T | Time variable [s] |

The short version of the paper was presented at ICAE 2017, Aug 21-24, Cardiff, UK. This paper is a substantial extension of the short version of the conference paper.

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| | |
|---|---|
| $u$ | Utilization rate [dimensionless] |
| $y$ | Dependent variable of a model [unit varies] |
| **Subscript** | |
| $ac$ | air conditioning system |
| $dist$ | power distribution |
| $cpu$ | Processor |
| $dc$ | data center |
| $ethernet$ | the Ethernet layer |
| $full$ | full capacity |
| $idle$ | Idle |
| $IP/MPLS$ | Internet protocol/multiprotocol label switching layer |
| $IT$ | Information technology |
| $link$ | links between routers |
| $measured$ | Measured |
| $network$ | network equipment |
| $op$ | operating |
| $otn$ | optical transport network |
| $predicted$ | Predicted |
| $rat$ | rated capacity |
| $router$ | routers |
| $server$ | server |
| $supply$ | rated power supply |
| **Acronyms** | |
| COP | Coefficient of performance |
| IP/MPLS | Internet protocol/multiprotocol label switching |
| IT | Information technology |
| OTN | Optical transport network |
| PDU | Power distribution unit |
| PUE | Power usage effectiveness |
| UPS | Uninterruptible power supply |

Before applying these technologies to a design of a data center, one needs to ensure that the technologies can provide sufficient cooling to maintain the reliability of operation of the data center. This is done by estimating the power consumption of its IT equipment and its cooling load. In the literature, the modeling is usually performed in three ways:

- Constant thermal load density model
- Using actual cooling data
- Detailed modeling of thermal load of IT equipment in data centers

Constant thermal load density model: Building engineers usually estimate the cooling load required in data centers based on their functions and the manufacturing year of the equipment as shown in Table 1 [14]–[16].

*Table 1 Constant thermal load densities used in building simulation software [14-16]*

| Year of construction | Core data center (space full of server racks) | Server racks in a computer room (space with IT equipment and office desks) |
|---|---|---|
| Before 2014 | 646 W/m$^2$ | 232 W/m$^2$ |

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| | | |
|---|---|---|
| After 2014 | 484 W/m$^2$ | 215 W/m$^2$ |

While energy system engineers can easily apply this method in their projects because the method does not require additional knowledge and information of the IT equipment in a data center, the method may overestimate the thermal load in the data center significantly and leads to oversizing of cooling equipment [17]. It also does not model the changes of power consumption of data centers due to the changes of operation statuses of the computing equipment [5, 65], removing the possibility to design cooling systems and the related control systems to cope with these changes. In other words, the model does not allow optimal design and control of cooling systems in data centers.

Using actual cooling data: Studies have also shown that energy system engineers can use actual cooling load profiles of a data center to forecast its performance in the future [18] and to avoid oversizing of cooling equipment [19]. However, the designers can only use this approach after the operation of a data center begins, and they cannot use this method to design data center cooling systems that have not yet been operational.

Detailed modeling of thermal load of IT equipment in data centers: Multiple studies have also been conducted to examine the relationship between the thermal load of the IT equipment and their operating status, and they have discovered that the on/off status of the IT equipment and the utilization rate of the processors has a significant effect to their power consumption and hence the thermal load ([5], [20]–[24], [65]). To avoid overestimating the thermal load of a data center, engineers can model the effect of processor utilization rate and on/off status of equipment to the thermal load through detailed models of IT equipment (i.e. modeling servers, server fans, processors, memory, network, uninterrupted power supply (UPS) and power distribution units (PDUs) separately). While the mathematical models of the equipment are available [24]–[26], the models require detailed specification from each IT equipment or parameters beyond what are usually available in the specification. Since energy system engineers may not have sufficient understanding in these subjects, they need to work closely with IT engineers to use these models which seldom occurs in data center energy system design projects. Some of these models even require extra tests of equipment to define their inputs. There are other models that estimate power consumption based on workload of data and web traffic, but these models also require a variety of inputs such as web and data usage of servers that is difficult to be accessed by data center energy system engineers at the design stage of a data center [61-63]. Due to the difficulty to gather the inputs required by these models, these modeling approaches are rarely used for actual data center design.

The modeling approach may also need engineering judgement of the IT engineers on the operating status of the IT equipment and may be too subjective for engineering designs [27]. For example, IT engineers may use the power supply rating in the specifications of servers to estimate the maximum power consumption of the servers, but a study of server testing data of their actual maximum power consumption, as shown in Figure 1, can easily show that the rating overestimates the power consumption.

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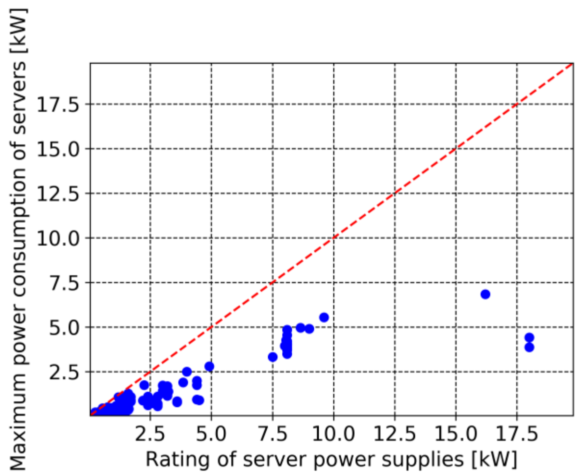


*Figure 1 Comparison of the maximum power consumption of servers and their power supply rating*

Figure 1 shows a comparison of the rated power of server power supplies and their actual maximum power consumption from the Standard Performance Evaluation Cooperation (SPEC) for 492 servers [28]. The results show that the actual maximum power consumption values of servers are much lower than that of the values of their rated power supplies in the specifications. Using the specification of IT equipment to model the data center power consumption in details would oversize cooling equipment and reduce data center operation efficiency.

Because the existing modeling methods are difficult or ineffective to optimize data center design, engineers seldom consider the profiles of actual IT equipment operation status and cooling load in their data center cooling and energy system designs. The cooling systems in data centers run in prolonged period of part load operation [29, 30] and consume more energy than expected. The ignorance of the changes of operating status of IT equipment in cooling and energy system designs results in excessive use of energy for data center cooling.

This study aims at addressing this issue by developing a model of the power consumption of IT equipment in data centers that satisfy the following criteria.

a) The model parameters and inputs should be available and accessible before the operation of the data centers, unlike most existing methods which inputs can only be retrieved after the operation of a data center;
b) The model parameters and inputs can be obtained from the specification without any extra testing, unlike most existing models which need extra testing data in addition to the information in the equipment specification;
c) The model should consider the effect of the design and the operation status of the IT equipment on their equipment power consumption to describe the actual energy needs of a data center;
d) The model provides sufficient information for non-IT experts to estimate the effect of IT equipment operation status on data center energy consumption for energy system designs.

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To develop the method, this study first identifies typical large power consumers among IT equipment in data centers. It introduces models of the major power consumers and validates them with data from the manufacturers and in the literature. It combines the models to form a model of IT equipment power consumption and tests the model on a case study in a building model. At the end, it evaluates the effects of different operation status and design of the IT equipment on the building energy consumption.

## 2. Model development and validation

### *2.1. Identification of major power consumers among IT equipment*

To generate a power consumption model of a typical data center for cooling and energy system designs, this study identified the major power consumers that dissipate heat to the indoor space in a data center based on previous surveys summarized in Table 2.

*Table 2 Summary of the percentage of energy use of major power consumers in data centers from different studies*

| **Sources** | **Network between servers** | **Data storage** | **Server** | | | **Power distribution** | | | **Lighting** | **Cooling** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Processor** | **Other server electronics** | **Server power supply** | **UPS** | **PDUs** | **Building electricity switchgears** | | |
| Emerson Network Power [3] | 4% | 4% | 15% | 15% | 14% | 5% | 1% | 3% | 1% | 38% |
| Mitchell-Jackson et al. [17] | 48% | | | | | 11% | | | 3% | 38% |
| Koomey [31] | 5% | 5% | 40% | | | 50% | | | | |
| Info-tech [32] | 10% | 26% | | | 11% | | | | | 50% |
| Pelley et al. [33] | 5% | 56% | | | | 8% | | | 1% | 30% |

Ignoring the cooling system that usually does not dissipate its heat to the data center, Table 2 shows that major power consumers and thermal load contributors in a data center are servers, storage equipment, network facilities and power distribution equipment. Lighting is not major power consumers in data centers and can be ignored. Storage equipment can be considered as storage servers which is a type of servers. Thus, this study modeled the power consumption of a data center by modeling the three major power consumers – servers, network equipment and power distribution equipment – as shown in Figure 2.

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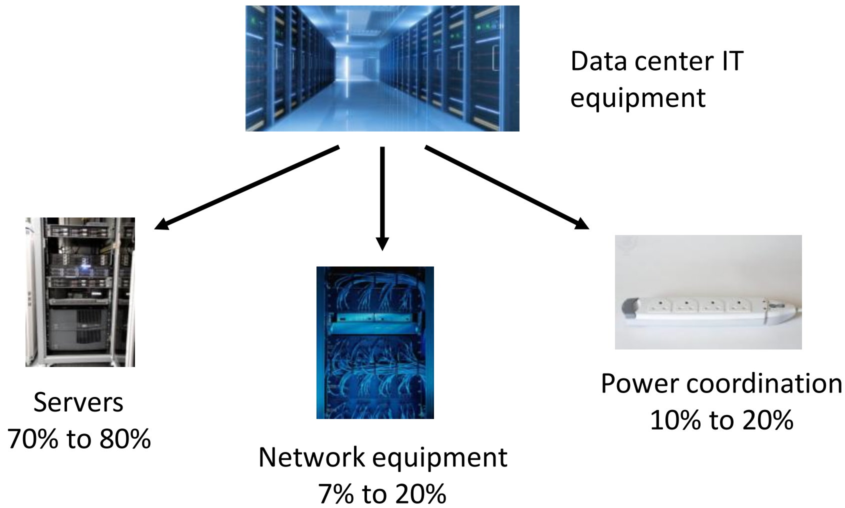


*Figure 2 Illustration showing the percentage of energy use of the major power consumer to be modeled relative to the total energy use of IT equipment in a data center estimated from Table 2 (Photos from [34]–[37])*

Some studies did not consider power distribution equipment as IT equipment [3]. However, power consumption of power distribution equipment varies with the operation status of the IT equipment, and building simulation programs usually do not model power distribution equipment separately from other IT equipment [38]. The equipment may also contribute to the cooling load of the data center because they may be installed in the indoor space together with other IT equipment. Power consumption of power distribution equipment is thereafter considered as part of the power consumption of IT equipment in this paper and is modeled as part of the overall IT equipment model.

### *2.2. Power consumption model of servers*

Servers in data centers are responsible to produce the computational outputs desired by users of data centers. When data center users want to finish a computational job, they submit the job to the data center and the data center allocates the job to servers. The server processors follow the computational instructions of the job to finish the computation. Since they are responsible for completing the computational part of the jobs, most space inside a data center is occupied by servers, and they are the major energy consumer in data centers [17].

There are a variety of models for servers. Alan et al. modeled server power consumption as a linear equation of the utilization rates of processors, network equipment, storage and memory inside the servers [39]. Ham et al. [23] and Garraghan et al. [25] modeled the power consumption of servers and their fans by the temperature of the processors, fan curves and Newton's law of cooling. There are also other models of power consumption of components inside servers [5, 65] but they are all too complex to be used in building simulation programs and energy system designs. Beloglazov et al. [40] modeled the power consumption of servers as a function of the processor utilization rate only as Equation (1).

$$P_{server} = P_{server,idle} + \left(P_{server,max} - P_{server,idle}\right)u_{cpu}(\tau) \tag{1}$$

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Equation (1) models the power consumption of a server if a user knows its processor utilization rate, its maximum power consumption and its idle power consumption. Servers run at their maximum power consumption when their processors are fully utilized at 100%, and run at their idle power consumption when its processors are not utilized. However, specifications of servers usually do not include their maximum power consumption and idle power consumption. To facilitate the use of Equation (1) based on processor utilization rate and specification data only, this study created Equations (2) and (3) to estimate server's maximum and idle power consumption.

$$P_{server,max} = a_0 + a_1 P_{server,supply} + a_2 N_{cpu} S_{cpu} \quad (2)$$

$$P_{server,idle} = a_3 + a_4 P_{server,supply} + a_5 N_{cpu} S_{cpu} \quad (3)$$

Equations (2) and (3) estimate the maximum and idle power consumption of a server based on its rating of power supply $P_{server,rat,supply}$, average rated processor speed of all servers in a data center $S_{cpu}$ in MHz and its number of processors $S_{cpu}$. These values, unlike the maximum and idle power consumption of servers, are usually available in the server's specifications.

The empirical coefficients inside Equations (2) and (3) are estimated by linear regression using the maximum and idle power consumption data of 491 different models of servers from various manufacturers submitted to the SPECpower2008 database between 2007 and 2017 [28]. Since the data come from servers of 491 different models, they should well represent the performance of servers in the market. Although Fuch et al. [41] reported other sources of server data, they do not contain the maximum power consumption data of any server and hence are not used to estimate the coefficients in Equations (2) and (3). The estimated coefficients are tabulated in Appendix A.

Since the SPECpower2008 database also contains data of server power consumption at processor utilization rates between 10% and 90% and these data were not used to build the server power consumption model, the model was validated by comparing the results of Equations (1), (2) and (3) with the measurement. The results are shown in Figure 3.

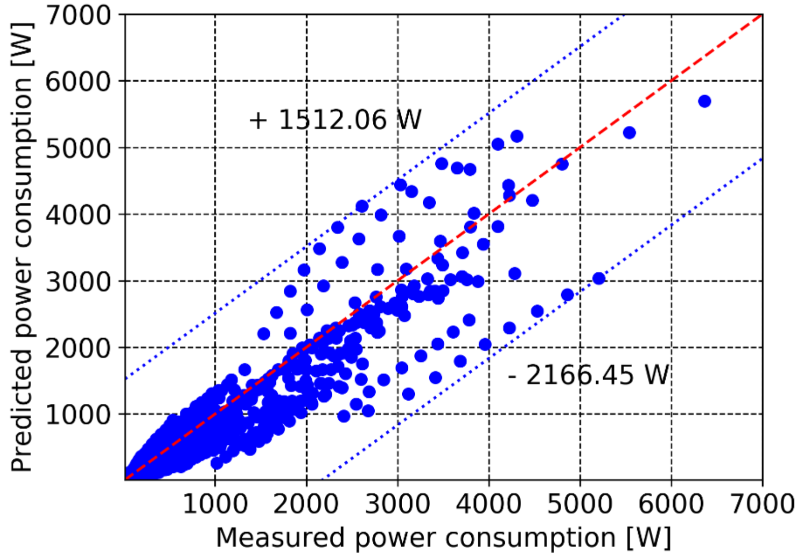


*Figure 3 Comparison of estimated power consumption from Equations (1), (2) and (3) and measured server power consumption in SPECpower2008 database*

Figure 3 shows that the estimation of power consumption is unbiased and does not overestimate server power consumption as the rated power supply values in Figure 1. However, due to the large amount of data points clustered between 0 and 1,000W, it is unclear how accurate the estimation is relative to other existing methods used by energy system engineers from Figure 3. The accuracy of the estimation is quantified based on the mean average percentage error (MAPE) calculated by Equation (4).

$$MAPE = \frac{1}{N}\sum \left|\frac{y_{predicted,i} - y_{measured,i}}{y_{measured,i}}\right| \text{x } 100[\%] \tag{4}$$

Table 3 compares the results of the proposed method with other alternative modeling methods of data center power consumption for energy system designs.

*Table 3 Comparison of MAPEs of various estimation method of server power consumption*

| **Method** | **MAPE** |
|---|---|
| Proposed method | 25.7% |
| Using rated power supply from specification as shown in Figure 2 | 154.3% |
| Using the design power consumption of the data center [17] | 282% |

Table 3 shows that the proposed method, despite the outliers in Figure 3, is a better method to estimate server power consumption than other alternative methods that estimate power consumption based on specification data only.

Based on the model of power consumption of a server, this study proposed Equations (5), (6) and (7) to model the power consumption of all servers in a data center.

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$$P_{server,dc} = P_{server,dc,idle} + \left(P_{server,dc,max} - P_{server,dc,idle}\right)u_{server,dc}(\tau) \quad (5)$$

$$P_{server,dc,max} = a_0 N_{server,dc} + a_1 \sum_{1}^{N_{server,dc}} P_{server,supply,i} + a_2 N_{cpu,dc} S_{cpu,dc} \quad (6)$$

$$P_{server,dc,idle} = a_3 N_{server,dc} + a_4 \sum_{1}^{N_{server,dc}} P_{server,supply,i} + a_5 N_{cpu,dc} S_{cpu,dc} \quad (7)$$

where $u_{server,dc}(\tau)$ is the utilization rate of processors in a data center which is the ratio of the number of processors being utilized to the total number of processors in a data center and is time-variant, $N_{server,dc}$ is the number of operating servers, $\sum_{1}^{N_{server,dc}} P_{server,supply,i}$ is the total rated power supply of all server in a data center, $N_{cpu,dc}$ is the number of processors in a data center, and $S_{cpu,dc}$ is the average rated speed of all processors from their specifications in a data center.

Since Equations (5), (6) and (7) are built based on server data from 2007 to 2017, the accuracy of the model may be lowered than the one suggested in Table 3 if the models are used to predict power consumption of servers manufactured beyond the period of time.

One can calculate the processing unit utilization rate needed by Equation (5) from the operation log of a data center by Equation (8).

$$u_{server,dc}(\tau) = \frac{N_{cpu,dc,op}(\tau)}{N_{cpu,dc}} \quad (8)$$

where $N_{cpu,dc,op}(\tau)$ is the number of operating processors in a data center at time $\tau$.

If the log is unavailable, users can use the utilization rate of a typical data center to approximate the utilization rate of a data center. The statistics of utilization rate of typical data centers are made from data in [42] and are attached in Appendix B for readers' reference.

### *2.3. Power consumption model of network equipment*

Network equipment in data centers transmits data between servers and between the servers and the outside of data centers. Since data centers can run a single computing job across multiple servers, it is important for network equipment to maintain the communication between the servers to complete the job, and a model of network equipment power consumption should consider the effect of the communication to the power consumption. When the servers host web services, the network equipment connects the servers to the Internet, and a model of its power consumption can help to explain the effect of web services to the data center power consumption.

Network equipment power consumption was modeled by various methods. Hlavacs et al. modeled network equipment power consumption to be directly proportional to the logarithm of the network traffic load of network switches [43]. Widjaja et al. recommended a model of power consumption that is directly proportional to the network traffic load of the switches in a manner similar to Equation (1) [44]. There are other models which estimate the network equipment power consumption by components [5, 65].

Among these models, Van Heddeghem et al. modeled the power consumption of a network between data centers across Europe and North America [45].. Since the model was used to estimate the power consumption of network equipment of multiple data centers in [45], this study could use the model to estimate power consumption of network equipment without validating the model again. The model contains three component models of network equipment inside a data center: the Internet protocol/multiprotocol label switching (IP/MPLS) layer model, the Ethernet layer model and the optical transport network (OTN) layer model. To model the power consumption of network equipment in a typical data center, this study extracted these models from the overall network power consumption model in [46] by ignoring the models of the power consumption of the cooling system of the network and the network equipment outside the data center. The resultant model of the network equipment is shown in Equation (9).

$$P_{network,dc} = C_{network}(\tau)\left(2 + 4\sqrt{\frac{N_{router} - 2}{\frac{2N_{link}}{N_{router}} - 1}}\right)\left[10[W/Gbps] + \frac{7[W]}{C_{network,rat}}\left(\frac{C_{nework,rat}}{1[Gbps]}\right)^{0.7347} + \frac{6.4196[W]}{C_{network,rat}}\left(\frac{C_{nework,rat}}{1[Gbps]}\right)^{0.8551}\right] \quad (9)$$

Equation (9) estimates the power consumption of network equipment in a data center based on the time-variant network traffic load $C_{network}(\tau)$ in Gbit/s (Gbps), the number of routers in the data center $N_{router}$, the number of links between the routers $N_{link}$, the power consumption per load of routers 10 W/Gbps and the power consumption per load of the Ethernet and OTN as empirical functions of the rated network traffic capacity $C_{network,rat}$ in Gbit/s (Gbps). The parameters in Equation (9) are constants, except for $C_{network}(\tau)$ whose value depends on the operation of the network equipment and is time-variant. Van Heddeghem et al. [45] calculated the constants based on their studies of network equipment from various manufacturers and practices from various data centers, and thus no additional validation is presented in this paper. Part of the model depends on the network traffic load, and this part describes the effect of network traffic load on power consumption of network equipment. The other part of the model estimates how the network power consumption changes with the specification of the network equipment.

When engineers use the model, they can consult the IT engineers for the log of network traffic and the specification of the network equipment and use Equation (17) in the Appendix C to calculate the network traffic load from the log. If the IT engineers cannot give the data of network traffic load, the network traffic load profiles of 3 data centers from the literature in Appendix C can be used to represent the network traffic load in a data center.

### *2.4. Power consumption of power distribution equipment*

Power distribution equipment in data centers maintains and distributes electricity to the equipment in a data center. Their major components include power distribution units (PDUs) which distribute electricity to various equipment in a server rack and uninterruptible power supplies (UPSs) which act as emergency power supplies to data center equipment during power interruption events. They are important because they sustain the power supply to other equipment in data center and are critical to the service reliability of data centers. Their connections to the equipment in a data center are one of the criteria for the reliability rating of data centers [46].

Various studies assumed that the efficiency of the power distribution equipment is a constant. Mitchell-Jackson et al. [17] reported a 95% UPS efficiency and a 98% PDU efficiency for the data center in the study. Pelly et al. [33] assumed the efficiency of UPS to be 91% and the efficiency of 97% in its model. Zhang et al. [22] measured the

UPS efficiency of their data center and found that the efficiency of their UPS was similar to that of [17]. Some studies modeled the PDU and UPS efficiency as a function of the ratio of input power to rated power supply [64].

In this study, the efficiency of the PDU follows that of [33] and is assumed to be 97% despite studies that PDU efficiency should be load-dependent [64]. Emerson Power System [3] reported that the electricity consumption of PDU is only 1% of the entire data center [3], and the variation of the PDU power consumption with the load is too insignificant to justify the introduction of an extra parameter (i.e. the total rated power input of the PDU from their specification) in order to model the variation in the proposed model. However, UPS consumes more energy, and this study proposed to model its efficiency based on the manufacturer data in [47] and a quadratic equation of the dependence of UPS efficiency with its input load [64]. Greenberg et al. [47] found that the efficiency of an UPS depended on its type and the load factor of the UPS. They found that the efficiency of the UPS can drop by approximately 5% if the load of the UPS varies from 100% to 25%. By conducting regression of the efficiency data with the percentage of load provided in [47], this study proposed Equations (10) to calculate the efficiency of UPS..

$$\eta_{UPS} = [a_6(LF_{UPS})^2 + a_7 LF_{UPS} + a_8] \text{x}\, 100[\%] \tag{10}$$

Equation (11) gives the load factor, which is the ratio of the UPS input power to the rated power input of the UPS/

$$LF_{UPS} = \frac{P_{server,dc}(u_{server,dc}(\tau)) + P_{network,dc}(C_{network}(\tau))}{P_{UPS,rated}} \tag{11}$$

The description of the training data in [47] are given in Table 4.

*Table 4 Description of training data for UPS efficiency estimation from different types of UPS*

| **Type** | **Number of UPSs tested in [47]** | **Range of load factor** | **Average efficiency** |
|---|---|---|---|
| Flywheel (rotary) | 2 | 30% to 100% | 97.2% |
| Delta connection | 2 | 25% to 100% | 96.6% |
| Double connection | 32 | 25% to 100% | 88.3% |

The empirical coefficients in Equation (10) are different for different types of UPS, and the empirical coefficients of Equation (10) for different types of UPS are given in the Appendix A. Detailed information of various types of UPS can be found in [48] for reference.

To examine how accurate the averages are to estimate the efficiency of UPS at different conditions, the deviations between the averages and the efficiency of UPS under different loading conditions are shown in Figure 4.

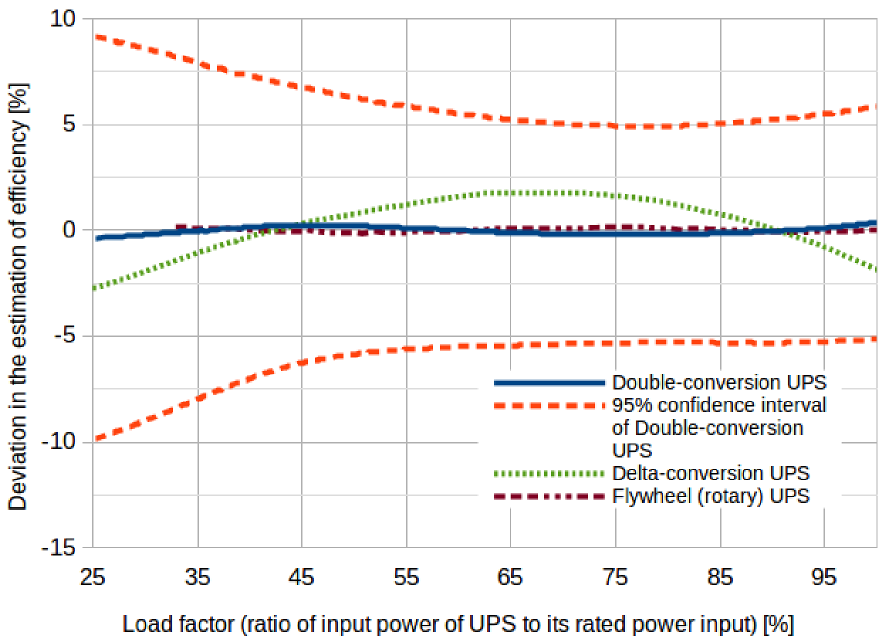


*Figure 4 Deviations between the average efficiencies in Table 4 and the efficiency of UPS at different loading conditions*

Figure 4 shows that the efficiencies of delta-conversion UPS and flywheel UPS are well estimated with a deviation less than 2.5%. However, the deviations between the estimated and measured efficiency of double-conversion UPS are much larger. This is caused by the large difference of efficiencies of double-conversion UPS in the data in [47]. The maximum and minimum efficiencies of the samples at 25% loading condition in [47] are 93% and 74% respectively. This large difference results in the large deviation and confidence interval in Figure 4 regardless of which mathematical formulae is used to model the UPS efficiency.

With the efficiencies of typical UPSs and PDUs, the power consumption of power distribution equipment in a data center can be modeled. The model follows [33] which assumes that the efficiencies of PDU and UPS are calculated as ratios of the power consumption of the PDU and UPS to the power input to these devices. Considering that both PDU and UPS are installed in the indoor space of a data center, the power consumption model of the power distribution equipment can then be defined as Equations (12) and .

$$P_{dist,dc} = \left( \frac{1}{\eta_{PDU}\eta_{UPS}\left(P_{server+netowrk,dc}(\tau)\right)} - 1 \right) P_{server+netowrk,dc}(\tau) \tag{12}$$

$$P_{server+netowrk,dc}(\tau) = P_{server,dc}(u_{server,dc}(\tau)) + P_{network,dc}(C_{network}(\tau)) \tag{13}$$

where the PDU efficiency is fixed at 97% and the UPS efficiency depends Equation (10). Power consumption of the servers and network equipment in the data center are estimated by Equations (5) and (9).

*2.5. Overall model*

The overall model of the power consumption of a data center is formed by summing up the results of Equations (5), (9) and (12) as shown in Equation (14).

$$P_{IT,dc} = \frac{1}{\eta_{PDU}\eta_{UPS}\left(P_{server+netowrk,dc}(\tau)\right)} P_{server+netowrk,dc}(\tau) \tag{14}$$

The method to use the model is illustrated in Table 5.

*Table 5 Step-by-step guide showing how to use the data center power consumption model*

| Step | Procedure |
|---|---|
| 1 | Gather the following specification data of the data center:<br>• Number of servers<br>• Total rated power supply in W<br>• Average processor speed in MHz<br>• Number of cores in servers<br>• Number of routers<br>• Number of links between routers<br>• Rated network traffic load of the network equipment in Gbit/s<br>• Type of UPS<br>• Rated power input of the UPS |
| 2 | Gather or estimate the following time profiles:<br>• Processor utilization rate<br>• Network traffic load in Gbit/s<br>If data are unavailable, the processor utilization rate or network traffic load in Appendices B and C can be used for reference. |
| 3 | Use the type of UPS and UPS rated input power to estimate the UPS efficiency by Equations (10) and (11). |
| 4 | Use the utilization rates and specification of servers to estimate the server power consumption using Equations (5), (6) and (7). |
| 5 | Use the network traffic load and the specification of routers and links to estimate the power consumption of network equipment by Equation (9). |
| 6 | Set $\eta_{PDU}$ to be 97% and use the UPS efficiency and the power consumption values of servers and network equipment to estimate the total power consumption by Equation (14). |

## 3. Case study integrating the model in a building simulation program

*3.1. Description of the case study*

To examine how the design and operation of the IT equipment affect the building energy consumption and to demonstrate the use of models in building simulation programs, the proposed model is applied to the EnergyPlus model of the typical 2013 large office model in Florida, U.S.A. in [49] after some modification. The area is the subtropics, and the building requires much more cooling than buildings in cold area. The original model contains a data center with a floor area at 780m$^2$ at the basement of the model is consuming power constantly at a power consumption density at 484W/m$^2$. The data center uses a single-speed water-sourced heat pump with a rated cooling capacity at 332kW without free cooling to cool the indoor space. EnergyPlus models the power consumption and the efficiency of the heat pump at different cooling load, including ones at part load operation, according to a model of water-sourced heat pumps in [59]. EnergyPlus also uses other factors such as the thermal conductance of the building material, the occupancy of each room in the building and the weather of the building location to simulate the instantaneous power consumption and cooling load throughout a year. The details of the simulation steps using empirical models of energy systems, heat transfer models, thermodynamic principles and other models can be found in the documentation in EnergyPlus [38]. To replace the constant power density model with the power consumption model in this paper, the data center IT equipment model is written in custom model script according to instructions in EnergyPlus and replaces the constant power density inputs as shown in the Supplementary Material. In the modified EnergyPlus model, the power consumption of the data center depends on the model in Equation (14) with the specification of its IT equipment as Table 6

*Table 6 Specification of the IT equipment in the data center in the case study*

| Component | Specification | Value |
|---|---|---|
| Server | Total rated power supply | 260,480 W |
| | Total size of servers | 2,220 U |
| | Average processor speed | 2,500 MHz |
| | Total number of processors | 2,960 |
| | Average processor utilization rate | 0.7 |
| Network equipment | Number of routers | 42 |
| | Number of links between routers | 60 |
| | Rated network traffic load of the network equipment | 100 Gbit/s |
| | Average network traffic load between routers during operation | 25 Gbit/s |
| Power distribution equipment | Type of UPS | Delta connection |
| | Rated power of the UPS | 320,000 W |

To imitate the real situation, the specification of the equipment in Table 6 is set by the following rules.

- The density of the servers and routers is similar to the data center in [17];
- The number of processors per server, the speed per processor and the amount of storage per server are similar to the servers in [28];
- Average utilization rate following the Whale cluster data in the Appendix B with similar number of processors;
- The link per router is similar to that in [45];
- The network traffic load approximately follows the network traffic in data centers in [50].
- The UPS and PDU of the data center are installed in the cooling space of the data center;
- The power consumption of the servers, network equipment and power distribution equipment all contribute to the cooling load of the building.

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The IT equipment model of the basement data center is the only part of the EnergyPlus model that is changed from the original building model. The rating of the other electric, heating and cooling equipment in the building, including their rated power consumption, their rated cooling and heating capacity, their rated airflow and their rated water flow remains unchanged from the original model. For example, its ventilation also remains to be maintained by a 31kW single-speed fan as that in the original model.

### *3.2. Simulation results under the rated operating condition*

Since the model of data center IT equipment power consumption estimates the power consumption of servers, network equipment and power distribution equipment separately, the proportion of the estimated power consumption of each component relative to the total IT equipment power consumption of the case study can be calculated, and they can be compared with that obtained in the literature to examine if the estimated results are reasonable. The results are shown in Figure 5.

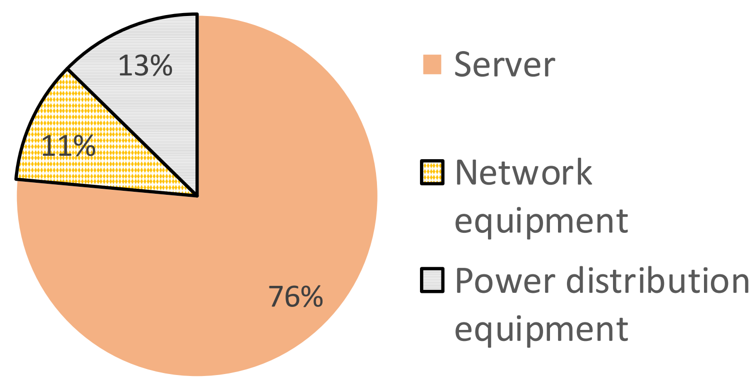


*Figure 5 Proportions of the annual energy use of each IT equipment component relative to the annual energy use of the IT equipment in the case study*

Figure 5 shows that the proportions of the energy use of all equipment are similar to that of Figure 2. The energy use of servers is estimated to be 76% which is between the server energy use ranging from 70% to 80% in Figure 2, the energy use of network equipment is 11% which is between 7% and 20% for the energy use of network equipment in Figure 2, and the energy use of power distribution equipment is 13% which also falls between the 10% to 20% range for the energy use of power distribution equipment in Figure 2. This shows that their estimation is reasonable.

### *3.3. Parametric study for effects of configuration of IT equipment to building performance*

To examine how the configurations and operation of the IT equipment in the data center affects the building energy performance, the case study is also simulated by changing the following conditions from -50% to +100% at 25% intervals:

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- Total processor speed
- Number of servers with the same power rating, number of processors and processor speed per server
- Number of links between routers
- Rated network traffic load of the network equipment
- Average processor utilization rate
- Average network traffic load between routers during the operation

To understand the performance of the data center due to the changes of the design and operation of the IT equipment, this study calculated the coefficient of performance (COP) of the cooling equipment of the data center and the power usage effectiveness (PUE) of the data center [51] from the simulation results of the case study by Equations (15) and (16).

$$COP_{dc} = \frac{Q_{ac,dc}}{E_{ac,dc}} \tag{15}$$

$$PUE_{dc} = \frac{E_{dc}}{E_{IT,dc}} \tag{16}$$

A higher COP implies a more efficient cooling system, and a lower PUE implies a more efficient data center.

The total cooling delivered in a year $Q_{ac,dc}$, the energy use of the air conditioning system $E_{ac,dc}$, the energy use of the data center $E_{dc}$ and the energy use of the IT equipment $E_{IT,dc}$ of each case are all estimated by running the simulation of the modified EnergyPlus model for a year using the typical meteorological year weather data in Florida, U.S.A. [58]. The results of the simulation are plotted in Figure 6.

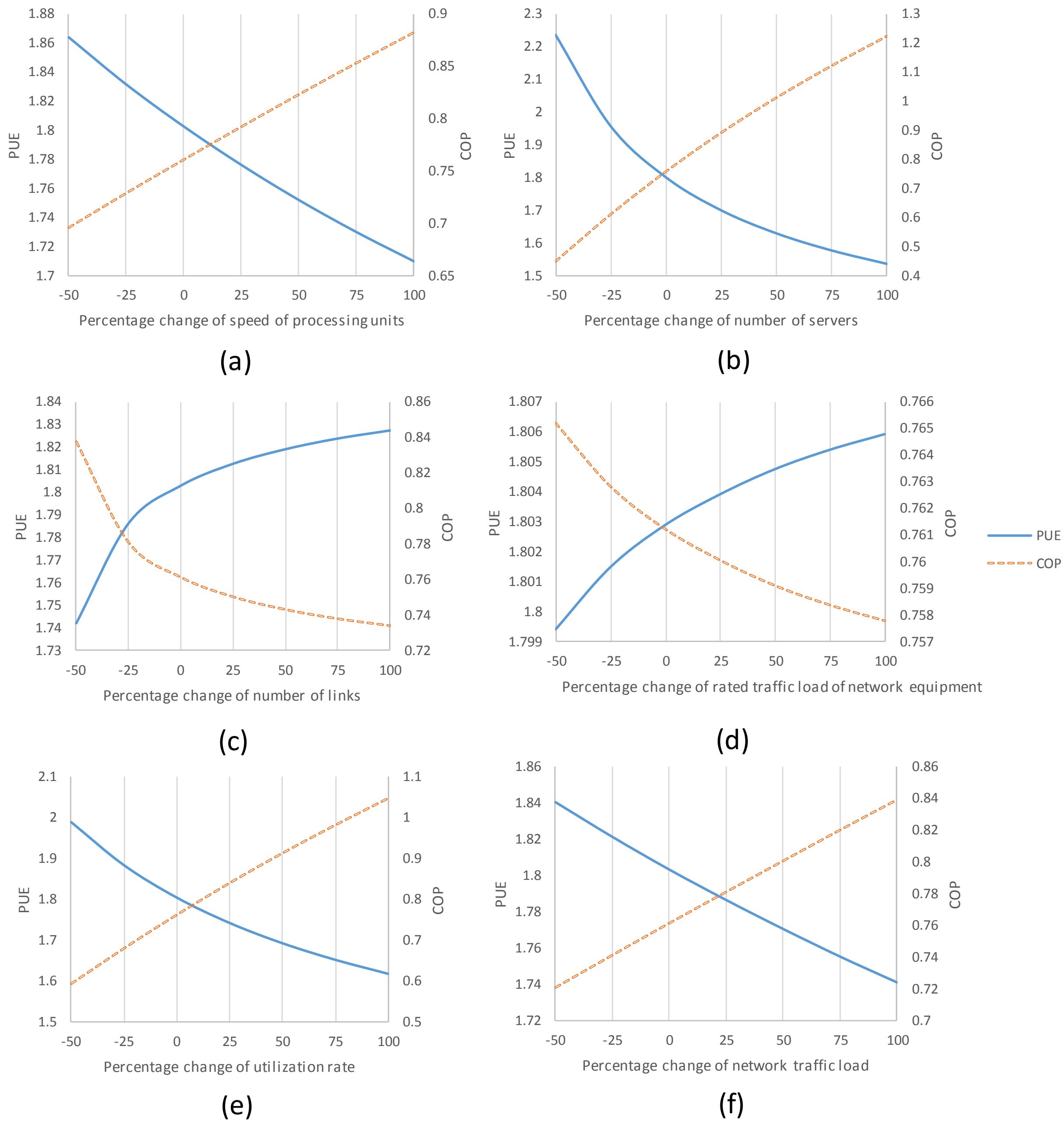


*Figure 6 Change of PUE and COP with percentage change of (a) speed of processing units, (b) number of servers, (c) number of links, (d) rated traffic load of network equipment, (e) utilization rate and (f) network traffic load*

Figure 6 shows that the data center PUE drops with an increase of processor speed, an increase of number of servers, a reduction of the number of links, a reduction of the rated network traffic load of the equipment, an increase of processor utilization rate and an increase of average traffic load between routers. An increase of processor speed, an increase of number of servers, an increase of processor utilization rate and an increase of traffic load between routers mean more computation in the data center. This increases the amount of IT equipment

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electricity use and lower the data center PUE. However, a reduction of number of links and rated network traffic load do not imply less computation. Their reduction causes longer travel time of data between routers, longer operation time of the network equipment and an increase of IT equipment and building electricity use. Hence the data center PUE can be increased by lower processor speed, fewer servers, more links between servers, higher rated network traffic load of the network equipment, lower processor utilization rate and lower network traffic load between routers.

Figure 6 also shows how the energy efficiency of the cooling system in the data center changes with the design of the IT equipment. The cooling system, a 332kW heat pump, is oversized relative to the cooling load of the data center because the cooling load of the data center is on average 74.6kW according to the simulation result. The cooling load of the data center is much lower than the cooling capacity of the heat pump. Most of the time, the cooling system runs at part load operation, and its COP remains low. When the IT equipment energy use increases, the part load ratio of the cooling system and the COP of the cooling system of the data center increases. The increase of cooling system COP leads to a lower PUE and hence a more efficiency data center operation. Hence a smaller load at the IT equipment does not imply that a higher efficiency of a data center, especially if the cooling system is oversized.

Figure 6 also shows the significance of the factors to the energy performance of a data center (i.e. PUE and COP). The energy performance of a data center is most sensitive to the number of servers, followed by the processor utilization rate, the speed of processing units, network traffic load, the number of links and the rated traffic load of network equipment. The energy performance of a data center is always affected by servers more significantly than the network equipment. This is reasonable because the server power consumption is higher than that of network equipment in a data center as shown in Figure 2 and Figure 5. The more important observation is the higher sensitivity of the energy performance with the processor utilization rate than the speed of processing unit and the higher sensitivity of the energy performance with the network traffic load than other network equipment design factors. This observation shows that the controls of IT equipment operation may change a data center energy performance more significantly than its design specification, and the operation status of the IT equipment can be a more important consideration factor in energy-saving data center design than the specification of the IT equipment.

### *3.4. Case study of the power consumption model with time profiles of processor utilization rate and network traffic load*

To demonstrate how the power consumption model can simulate the effect of time-variant processor utilization rate and network traffic load in a building simulation program, scenarios 1 and 2 in Table 7 are imposed to the case study.

*Table 7 Scenarios with different time profiles of processor utilization rate and network traffic load*

| **Scenarios** | **Description of the time profiles** |
|---|---|
| 1 | Processor utilization rate is 1 in the morning on every day in the year and drops to 0.4 in the afternoon. |
| 2 | Network traffic load is 5 Gbit/s in the morning on every day in the year and drops to 45 Gbit/s in the afternoon. |

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While the average processor utilization rate and network traffic load of these scenarios are the same as that of the test case, their time profiles are different as illustrated by Figure 7 and Figure 8.

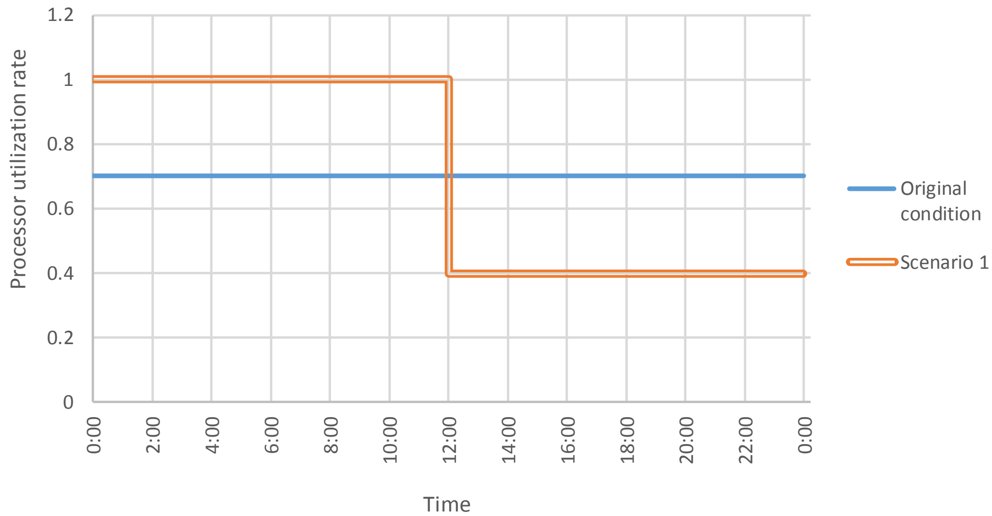


*Figure 7 Comparison of daily time profiles of processor utilization rate between Scenario 1 and the original condition of the case study*

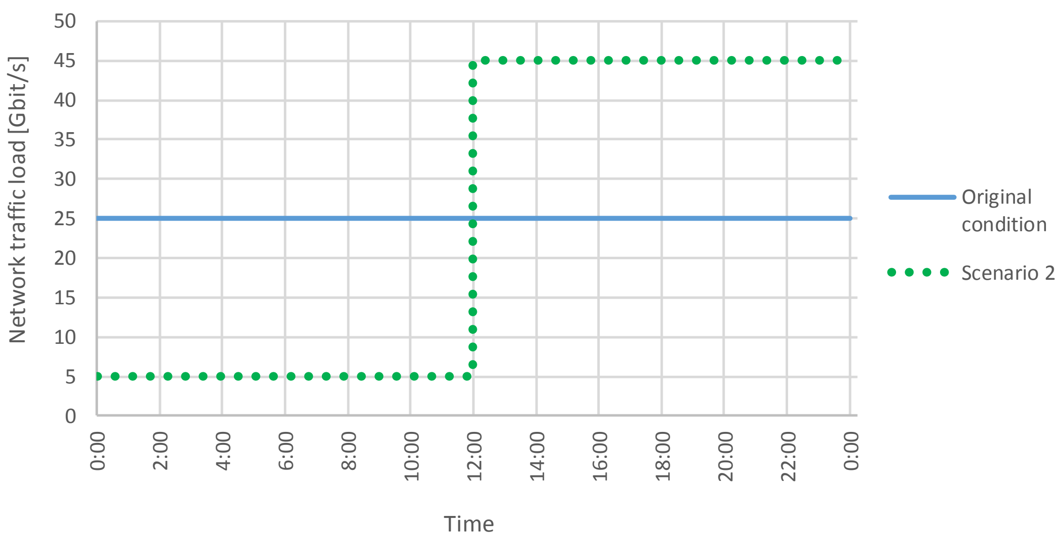


*Figure 8 Comparison of daily time profiles of network traffic load between Scenario 2 and the original condition of the case study*

To simulate the effects of time-variant processor utilization rate and network traffic load to building performance in a building simulation program, in each scenario, the time profile replaces its corresponding constant value in the test case and is used to model the instantaneous power consumption of the IT equipment at different times of the year. The time profile of the power consumption is used to simulate the instantaneous cooling load of the data center throughout the year. Example time profiles of the cooling load in the two scenarios are compared with that of the original test case as shown in Figure 9 and Figure 10.

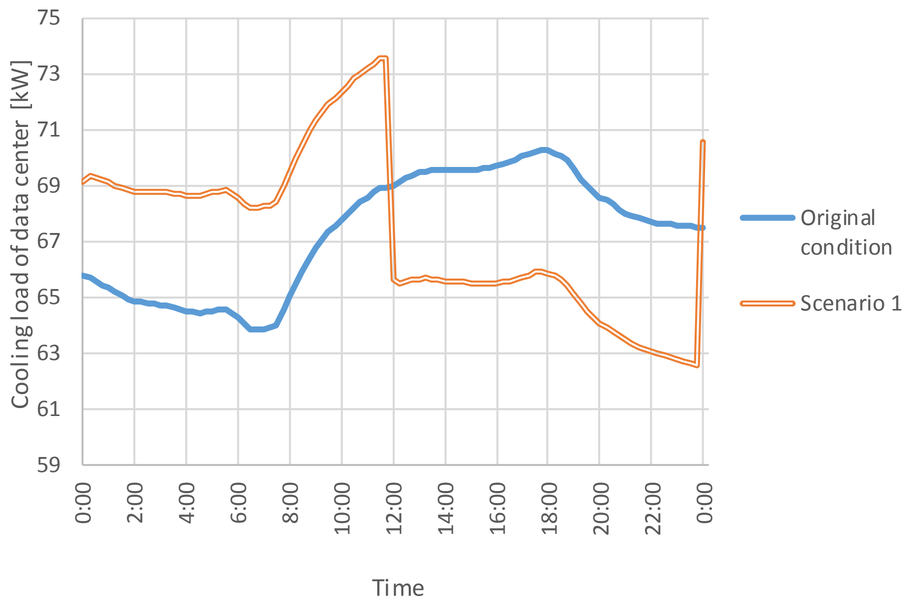


*Figure 9 Estimated cooling load of the data center in the original test case and Scenario 1 on 1st April*

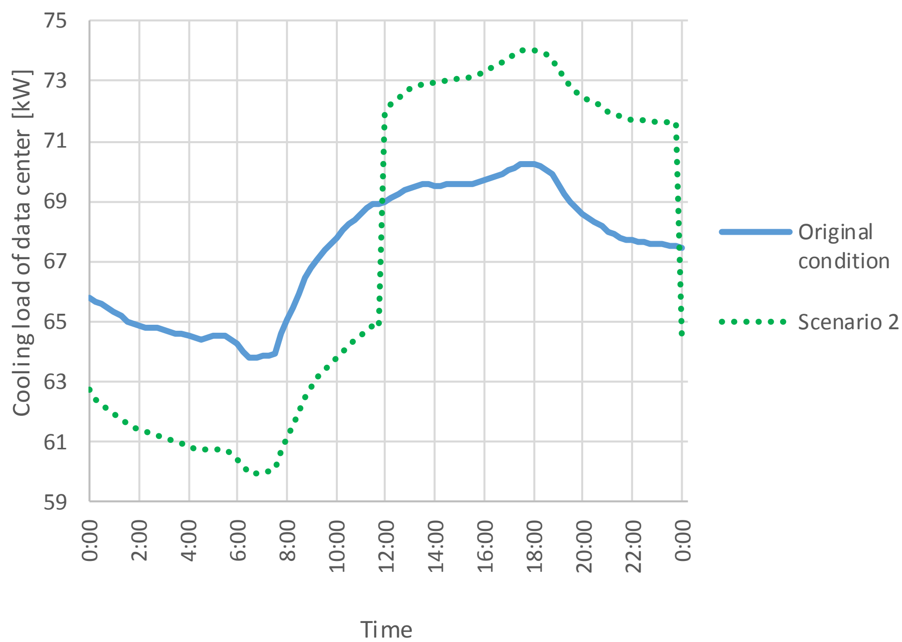


*Figure 10 Estimated cooling load of the data center in the original test case and Scenario 2 on 1st April*

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Figure 9 and Figure 10 show the cooling load of the data center changes following the hourly changes of processor utilization rate and network traffic load in Figure 7 and Figure 8. A higher processor utilization rate or a higher network traffic load implies a higher cooling load of the data center. Hence the proposed power consumption model can be used to model the change of data center energy performance due to the time-variant processor utilization rates and network traffic load.

## 4. Conclusions

In summary, this study develops a model of power consumption of information technology (IT) equipment for building simulation program. The model consists of three component models: the model of servers, the model of network equipment and the model of power distribution equipment. The component models are built based on performance data of the equipment and some existing models in the literature, and the resultant models fulfill the following criteria:

- The model can be used with building simulation programs for energy system designs;
- Model inputs can be obtained easily from the design of a data center and manufacturer specification of the equipment, unlike the existing models that require extra testing data or expert IT knowledge;
- The model can estimate the change of power consumption with data center IT equipment design and the IT equipment operation status;
- The model provides statistics of data center operation status for energy system engineers to predict IT equipment operation status for energy system designs in the absence of IT engineers;
- The model can simulate the change of building performance due to different processor utilization rates and network traffic load at different times of the year.

To demonstrate the use of the IT equipment power consumption model in a building simulation program, this study uses the proposed data center model in a building model of a typical large office with a data center in its basement under a tropical climate condition. The result shows that the model is able to estimate a reasonable server, network and power distribution load like the ones in the literature. The result also shows the effect of various designs and operation status of a data center affect its operation efficiencies, including the efficiencies of its cooling systems.

## Acknowledgements

This research is financially supported by The Hong Kong Polytechnic University Postdoctoral Fellowship (G-YW2B) of The Hong Kong Polytechnic University.

The authors would also like to acknowledge the following people for the collections of workload logs at [42] : Dan Dwyer and Steve Hotovy for the log at Cornell University; Dalibor Klusáček and Czech National Grid Infrastructure MetaCentrum for the MetaCentrum Czech National Grid log; Hui Li, David Groep and Lex Wolters for the log from University of Amsterdam; Joseph Emeras for the log from the University of Luxemburg; Ciaron Linstead for the log from Potsdam Institute for Climate Impact Research; Reagan Moore and Allen Downey for the

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log from San Diego Supercompter Center (SDSC) Paragon; Travis Earheart and Nancy Wilkins-Diehr for the log from SDSC Blue Horizon; Lars Malinowsky for the log from the Swedish Royal Institute of Technology; Motoyoshi Kurokawa for the log from RIKEN Integrated Cluster of Clusters; Fabrizio Petrini for the log from the Los Alamos National Laboratory; Moe Jette for the logs from the Lawrence Livermore National Lab; Ake Sandgren for the log from the High-Performance Computing Center North; John Morton and Clayton Chrusch for the SHARCNET log; Joseph Emeras for the CEA Curie log; Susan Coghlan, Narayan Desai and Wei Tang for the Argonne Leadership Computing Facility log.

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## Appendix A. Empirical coefficients in models

The empirical coefficients for the server model in Equations (2) and (3) are tabulated in Table 8.

*Table 8 Empirical coefficients in server model*

| Equation (2) | | Equation (3) | |
|---|---|---|---|
| **Coefficient** | **Values** | **Coefficient** | **Values** |
| $a_0$ | -5.607 W | $a_3$ | -5.679 W |
| $a_1$ | 0.2101 W/W | $a_4$ | 0.1123 W/W |
| $a_2$ | 0.002499 W/MHz | $a_5$ | -0.0001593 W/MHz |

The empirical coefficients of the UPS efficiency model Equation (10) for different types of UPS is are shown in Table 9.

*Table 9 Empirical coefficients in the efficiency model of UPS for different types of UPS*

| Coefficient | Flywheel (rotary) | Delta connection | Double connection |
|---|---|---|---|
| $a_6$ | -0.08936 | -0.3610 | -0.1680 |
| $a_7$ | 0.1510 | 0.4969 | 0.2761 |
| $a_8$ | 0.9160 | 0.8161 | 0.7847 |

## Appendix B. Statistics of utilization rate in data centers

This section tabulates the statistics of processor utilization rate of data centers from [42] for reference. Feitelson et al. collected the logs of processors workload from different data centers around the world, and the workload logs can be converted to utilization rate profile following the procedure in [42]. They are listed in Table 10 for building simulation users' reference if they need a realistic processor utilization profile to model the servers in data centers.

*Table 10 Processor utilization rate in different data centers*

| Location of the data center | Mean | Sample standard deviation | Starting time of the log | Duration of data | Number of processors |
|---|---|---|---|---|---|
| Cornell University, Ithaca, New York, USA [52] | 0.8522 | 0.2327 | 06/1996 | 333 days | 338 |
| Vrije Univsiteit Amsterdam, Amsterdam, Netherlands [53] | 0.1493 | 0.2143 | 01/2003 | 364 days | 144 |
| Leiden University, South Holland, Netherlands [53] | 0.1194 | 0.2124 | 01/2003 | 359 days | 64 |
| University of Amsterdam, Amsterdam, Netherlands [53] | 0.1957 | 0.2729 | 01/2003 | 364 days | 64 |
| Delft Univ. of Technology, Delft, Netherlands [53] | 0.1079 | 0.2250 | 01/2003 | 362 days | 64 |
| Utrecht University, Utrecht, Netherlands [53] | 0.1447 | 0.2546 | 02/2003 | 332 days | 64 |
| University of Luxemburg Gaia Cluster, Luxemburg [54] | 0.4716 | 0.2428 | 05/2014 | 84 days | 2004 |
| MetaCentrum Czech National Grid, the Czech Republic | 0.3709 | 0.1862 | 01/2009 | 172 days | 806 |
| Potsdam Institute for Climate Impact Research (PIK), Germany | 0.3797 | 0.3055 | 04/2009 | 1188 days | 2560 |
| San Diego Supercompter Center (SDSC) Paragon, San Diego, U.S.A. [55] | 0.7159 | 0.2470 | 01/1995 | 364 days | 400 |
| SDSC Blue Horizon, San Diego, U.S.A. | 0.7681 | 0.2618 | 04/2000 | 974 days | 1152 |

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| | | | | | |
|---|---|---|---|---|---|
| Swedish Royal Institute of Technology, Stockholm, Sweden | 0.7042 | 0.2952 | 10/1996 | 331 days | 100 |
| RIKEN Integrated Cluster of Clusters, Japan | 0.8766 | 0.2437 | 05/2010 | 152 days | 8192 |
| Los Alamos National Lab Nirvana cluster, U.S.A. | 0.6914 | 0.2207 | 12/1999 | 127 days | 2048 |
| Lawrence Livermore National Lab BlueGene/L system, U.S.A. | 0.5591 | 0.3724 | 11/2006 | 222 days | 2048 |
| High-Performance Computing Center North, Sweden | 0.6016 | 0.2293 | 07/2006 | 1264 days | 240 |
| SHARCNET cluster for several universities in Ontario, Canada | 0.4355 | 0.3442 | 12/2005 | 391 days | 6828 |
| Lawrence Livermore National Lab Atlas cluster, U.S.A. | 0.7046 | 0.2775 | 11/2006 | 193 days | 9216 |
| Lawrence Livermore National Lab Thunder cluster, U.S.A. | 0.8649 | 0.2597 | 02/2007 | 150 days | 4008 |
| Argonne Leadership Computing Facility, Argonne National Laboratory, U.S.A. [56] | 0.5969 | 0.3278 | 01/2009 | 239 days | 163840 |
| San Diego Supercompter Center (SDSC) Paragon, San Diego, U.S.A. [55] | 0.7572 | 0.2797 | 01/1996 | 366 days | 400 |
| Curie supercomputer, CEA, France | 0.6313 | 0.2955 | 02/2011 | 251 days | 93312 |
| Whale cluster within SHARCNET in Ontario, Canada | 0.7192 | 0.3157 | 12/2005 | 203 days | 3072 |
| Laboratoire de Physique Corpusculaire, Université Blaise-Pascal, France [57] | 0.2440 | 0.2770 | 08/2004 | 239 days | 140 |

## Appendix C. Network traffic load of some data centers

Benson et al. [50] include profiles of the logs of network activities for network traffic situation from 3 data centers as shown in

*Table 11 Specification of data centers in Benson et al. [50]*

| Data center | Function | Number of routers | Number of servers |
|---|---|---|---|
| EDU 1 | University | 22 | 500 |
| EDU 2 | | 36 | 1093 |
| EDU 3 | | 1 | 147 |

However, the logs contained the distributions of size of network flow in bytes, duration of flow in seconds and number of simultaneous flows in the network only and were not directly related to the network traffic load in Gbit/s required in Equation (8). To facilitate their uses in the equation, this study conducted a Monte Carlo simulation as shown in Figure 11 to calculate the network traffic load from the data in [51] by Equation (17).

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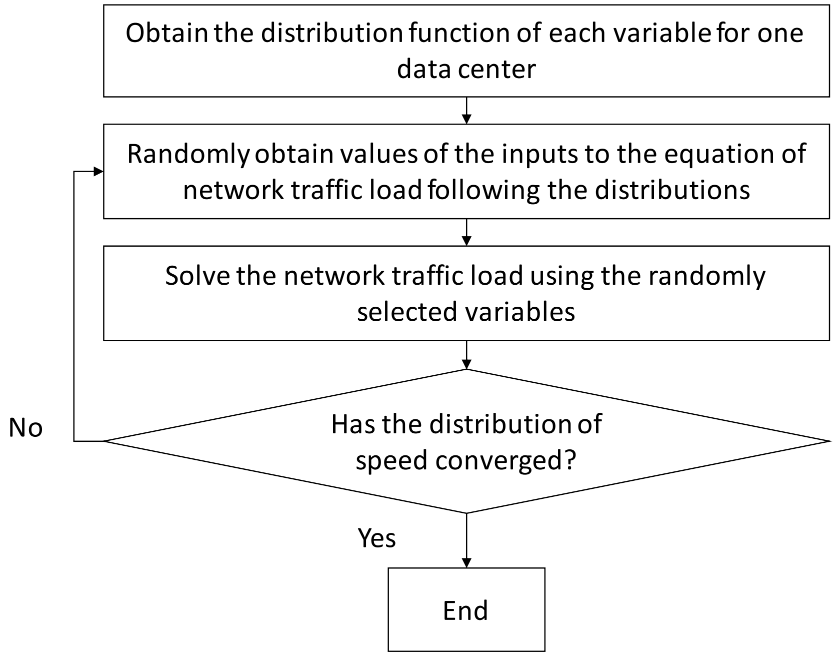


*Figure 11 Flowchart for Monte Carlo simulation to calculate the distribution of network traffic load*

$$\text{Network traffic load [Gbit/s]} = \left(\frac{1[Gbit]}{125[\text{byte}]}\right) \cdot (\text{Number of simultaneous flow}) \left(\frac{\textit{Average size of flow } [\text{byte}]}{\textit{Length of flow [s] + Time between flow [s]}}\right) \tag{17}$$

The statistics of the calculated network traffic loads of each data center is summarized in Table 12.

*Table 12 Statistics of the simulated network traffic load*

| **Data center** | **Mean network traffic load [Gbit/s]** | **Sample standard deviation of the network traffic load [Gbit/s]** |
|---|---|---|
| EDU 1 | 28.74 | 450.56 |
| EDU 2 | 11.97 | 254.39 |
| EDU 3 | 8.49 | 132.73 |

The cumulative distribution diagrams of the data centers are plotted in Figure 12, Figure 13 and Figure 14.

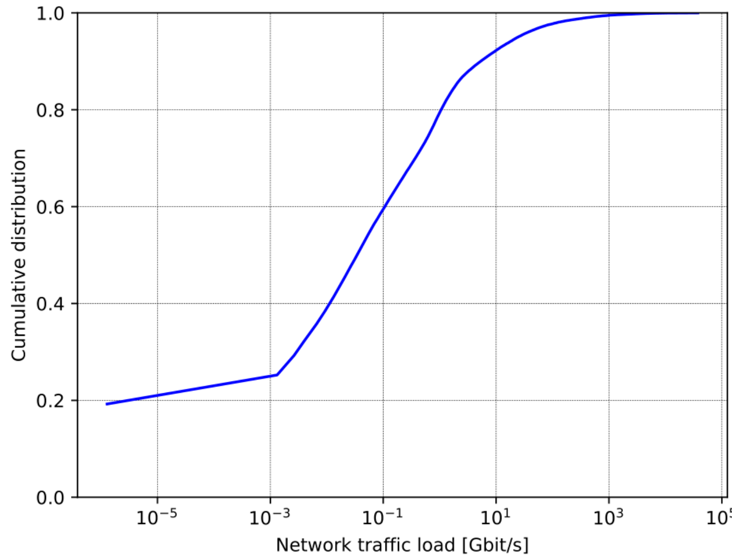


*Figure 12 Cumulative distribution of network traffic load of data center EDU 1*

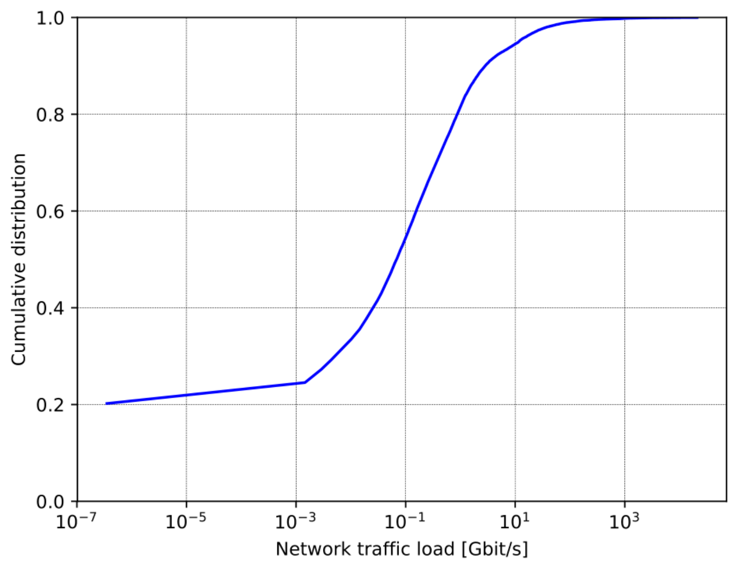


*Figure 13 Cumulative distribution of network traffic load of data center EDU 2*

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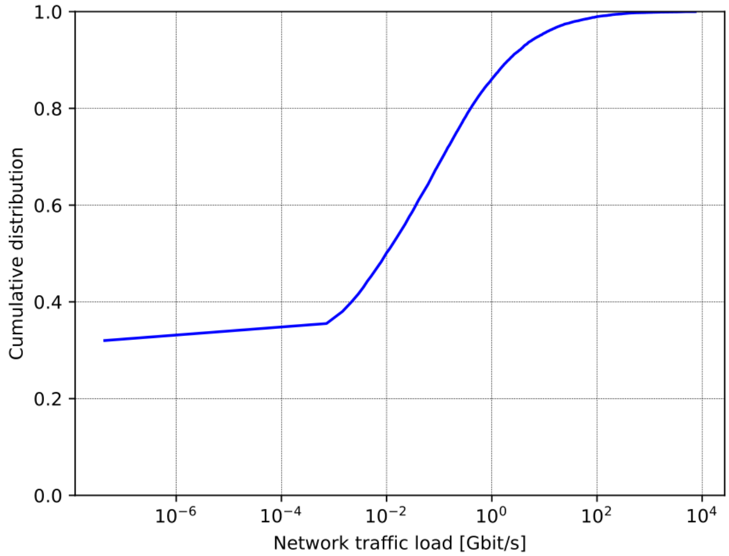


*Figure 14 Cumulative distribution of network traffic load of data center EDU 3*

The short version of the paper was presented at ICAE 2017, Aug 21-24, Cardiff, UK. This paper is a substantial extension of the short version of the conference paper.

Revision 1 to Applied Energy

# Supplementary material of "A Simplified Power Consumption Model of Information Technology (IT) Equipment in Data Centers for Energy System Real-time Dynamic Simulation"

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This document describes how the original large office model from [15] is modified to replace the original constant power density model with the proposed model of power consumption to estimate the power consumption of IT equipment in data centers.

## 1. Lines to be deleted from the model

The following lines of codes should be deleted from the original large office model.

```
ElectricEquipment,
  DataCenter_Basement_MiscPlug_Equip,  !- Name
  DataCenter_basement_ZN_6,!- Zone or ZoneList Name
  ALWAYS_ON,               !- Schedule Name
  Watts/Area,              !- Design Level Calculation Method
  0,                       !- Design Level {W}
  484.423246742185,        !- Watts per Zone Floor Area {W/m2}
  ,                        !- Watts per Person {W/person}
  0.0000,                  !- Fraction Latent
  0.5000,                  !- Fraction Radiant
  0.0000,                  !- Fraction Lost
  DataCenter_PlugLoads;    !- End-Use Subcategory
```

## 2. Lines to be added into the model

The following lines of codes should be added to estimate the power consumption of the IT equipment in the basement data center by the proposed model.

```
ElectricEquipment,
  DataCenter_Basement_MiscPlug_Equip,  !- Name
  DataCenter_basement_ZN_6,!- Zone or ZoneList Name
  ExtPowerFile,            !- Schedule Name
  EquipmentLevel,          !- Design Level Calculation Method
  379632.810006915,        !- Design Level {W}
  ,                        !- Watts per Zone Floor Area {W/m2}
  ,                        !- Watts per Person {W/person}
  0.0000,                  !- Fraction Latent
  0.5000,                  !- Fraction Radiant
  0.0000,                  !- Fraction Lost
  DataCenter_PlugLoads;    !- End-Use Subcategory

Schedule:Constant,
  ExtPowerFile,            !- Name
  Any Number,              !- Schedule Type
  0.5;                     !- Value

EnergyManagementSystem:ProgramCallingManager,
  ExtPowerEstimationProcedure,    !- Name
  BeginTimestepBeforePredictor,   !- EnergyPlus Model Calling Point
  ExtPowerServerPowerEstimation,  !- Program Name 1
  ExtPowerNetworkPowerEstimation, !- Program Name 2
  ExtPowerCorrdPowerEstimation,   !- Program Name 3
  ExtPowerFileEstimation;         !- Program Name 4
```

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```
EnergyManagementSystem:GlobalVariable,
  ServerPowerConsumption;         !- Name of object

Schedule:File,
  ServerURateFile,         !- Name
  fraction,                !- ScheduleType
  URate.csv,               !- Name of file
  1,                       !- Column Number
  0,                       !- Rows to Skip at Top
  8760,                    !- Number of Hours of Data
  Comma,                   !- Column Separator
  Yes,                     !- Interpolate to Timestep
  15;                      !- Minutes Per Item

EnergymanagementSystem:Sensor,   !- For use in EMS program
  ServerURateFile,         !- Name
  ServerURateFile,         !- Output:Variable Index Key Name
  Schedule Value;          !- Output:Variable Name

EnergyManagementSystem:Program,
  ExtPowerServerPowerEstimation,  !- Name of program
  Set NumServer = 740,            !- Number of servers
  Set AvgRatedPowerSupply = 352,  !- Average rated power supply per server in W
  Set AvgProcessorSpd = 2500,     !- Average processor speed in MHz
  Set NumCore = 2960,             !- Number of cores
  Set MaxPower = -5.607,          !- Start using the equations. Should not be changed
onwards
  Set MaxPower = MaxPower * NumServer,
  Set MaxPower = MaxPower + 0.2101 * AvgRatedPowerSupply * NumServer,
  Set MaxPower = MaxPower + 0.002499 * AvgProcessorSpd * NumCore,
  Set MinPower = -5.679,          !- Calculating idle power
  Set MinPower = MinPower * NumServer,
  Set MinPower = MinPower + 0.1123 * AvgRatedPowerSupply * NumServer,
  Set MinPower = MinPower - 0.0001593 * AvgProcessorSpd * NumCore,
  Set ServerPowerConsumption = MaxPower - MinPower,
  Set ServerPowerConsumption = ServerPowerConsumption * ServerURateFile,
  Set ServerPowerConsumption = ServerPowerConsumption + MinPower;

EnergyManagementSystem:GlobalVariable,
  NetworkPowerConsumption; !- Name of object

Schedule:File,
  NetworkTrafficFile,      !- Name
  Any Number,              !- ScheduleType
  NetworkTraffic.csv,      !- Name of file
  1,                       !- Column Number
  0,                       !- Rows to Skip at Top
  8760,                    !- Number of Hours of Data
  Comma,                   !- Column Separator
  Yes,                     !- Interpolate to Timestep
  15;                      !- Minutes Per Item

EnergymanagementSystem:Sensor,  !- For use in EMS program
  NetworkTrafficFile,      !- Name
  NetworkTrafficFile,      !- Output:Variable Index Key Name
  Schedule Value;          !- Output:Variable Name

EnergyManagementSystem:Program,
  ExtPowerNetworkPowerEstimation, !- Name of program
  Set NumRouter = 42,             !- Number of routers
  Set NumLink = 60,               !- Number of links
  Set RatedLoad = 100.0,            !- Rated network traffic load of equipment in Gbit/s
  Set RatNetworkOne = RatedLoad ^ 0.7347,
  Set RatNetworkOne = RatNetworkOne * 7.0 / RatedLoad,
  Set RatNetworkTwo = RatedLoad ^ 0.8551,
  Set RatNetworkTwo = RatNetworkTwo * 6.4196 / RatedLoad,
  Set RatNetwork = ( 2.0 * NumLink / NumRouter ) - 1.0,
  Set RatNetwork = ( NumRouter - 2.0 ) / RatNetwork,
  Set RatNetwork = RatNetwork ^ 0.5,
  Set RatNetwork = 2.0 + ( 4.0 * RatNetwork ),
```

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```
    Set NetworkPowerConsumption = 10.0 + RatNetworkOne + RatNetworkTwo,
    Set NetworkPowerConsumption = NetworkTrafficFile * NetworkPowerConsumption,
    Set NetworkPowerConsumption = RatNetwork * NetworkPowerConsumption;

  EnergyManagementSystem:GlobalVariable,
    CoordPowerConsumption; !- Name of object

! Program to calculate power consumption of power coordination equipment
  EnergyManagementSystem:Program,
    ExtPowerCorrdPowerEstimation,   !- Name of program
    Set PDUEff = 0.97,              !- Efficiency of PDU
    Set UPSType = 1,                !- Type of UPS. 0 for Rotary, 1 for Delta and 2 for Double
    Set UPSInputPower = 320000.0,   !- UPS rated input power in W
    Set CompPowerConsumption = NetworkPowerConsumption, !- Start using the equations
    Set CompPowerConsumption = CompPowerConsumption + ServerPowerConsumption,
    Set LoadFactor = CompPowerConsumption / UPSInputPower,
    IF (UPSType == 0),              !- Start calculating UPS efficiency
    Set UPSEff = -0.08936 * LoadFactor * LoadFactor,
    Set UPSEff = UPSEff + 0.1510 * LoadFactor,
    Set UPSEff = UPSEff + 0.9160,
    ELSEIF (UPSType == 1),          !- Delta connection
    Set UPSEff = -0.3610 * LoadFactor * LoadFactor,
    Set UPSEff = UPSEff + 0.4969 * LoadFactor,
    Set UPSEff = UPSEff + 0.8161,
    ELSE,                           !- UPS type is double connection by default
    Set UPSEff = -0.1680 * LoadFactor * LoadFactor,
    Set UPSEff = UPSEff + 0.2761 * LoadFactor,
    Set UPSEff = UPSEff + 0.7847,
    ENDIF,
    Set CoordPowerConsumption = CompPowerConsumption / UPSEff / PDUEff,
    Set CoordPowerConsumption = CoordPowerConsumption - CompPowerConsumption;
!- Program to finalize the schedule value to be used for total DC IT power consumption

  EnergyManagementSystem:Actuator,
    ExtPowerFile_OVERRIDE,          !- Name of object
    ExtPowerFile,                   !- Name of schedule to be overridden
    Schedule:Constant,              !- Type of schedule
    Schedule Value;                 !- Type of actuator

  EnergyManagementSystem:Program,
    ExtPowerFileEstimation,                                !- Name
    Set TotalPower = ServerPowerConsumption + NetworkPowerConsumption,
    Set TotalPower = TotalPower + CoordPowerConsumption,   !- Program Line 2
    Set ExtPowerFile_OVERRIDE = TotalPower / NormLevel;    !- Program Line 3

  EnergyManagementSystem:OutputVariable,
    Normalized Data Center IT Power Consumption,  !- Name
    ExtPowerFile_OVERRIDE,   !- EMS Variable Name
    Averaged,                !- Type of Data in Variable
    ZoneTimeStep,            !- Update Frequency
    ,                        !- EMS Program or Subroutine Name
    ;                       !- Units

  EnergyManagementSystem:InternalVariable,
    NormLevel,               !- Name
    DataCenter_Basement_MiscPlug_Equip, !- Internal Data Index Key Name
    Plug and Process Power Design Level;         !- Internal Data Type
```

Please notice that the code requires two files Urate.csv and NetworkTraffic.csv to run. They are text files containing the processor utilization rates and network traffic loads throughout the year respectively. They contain the values at 15-minute intervals and hence contain 35,040 entries to describe the changes of the values in a year. To illustrate the format of the files, the first 5 rows of the files are shown below:

URate.csv:

```
0.7,
0.7,
0.7,
0.7,
0.7,
```

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NetworkTraffic.csv:

```
25,
25,
25,
25,
25,
```

The short version of the paper was presented at ICAE 2017, Aug 21-24, Cardiff, UK. This paper is a substantial extension of the short version of the conference paper.