Using Network Modeling to Test for ASHRAE 90.4 Standard Compliance

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ABSTRACT

The ASHRAE 90.4 Standard provides important guidelines to justify data center design standards to meet energy efficiency criteria. As a building, a data center heat load due to the contained IT equipment far overshadows thermal gains and losses of traditional buildings that house people. In addition, one approach to being energy efficient is to evaporate water to achieve latent cooling, which can consume significant quantities of water, creating another potential environmental issue. Also, importantly, energy modelling tools assume mixing for thermal comfort, whereas data centers operate better with segregation of cold supply and warm return air. Thus, traditional energy modeling tools for general buildings are not ideally designed for evaluating data center performance. Designers therefore often resort to ad-hoc assessment approaches using the like of spreadsheets or other bespoke calculation approaches. The risk is that calculations are not very standardized and so methods and outcomes may not be very consistent, which is a disincentive for states to adopt the Standard. Therefore, general computational tools for design justification to the Standard are needed. The most useful tools contain a broad capability to model a variety of cooling and power systems and an underlying framework to calculate the corresponding MLC and ELC metrics associated with the Standard. One approach that accomplishes this task is to use network modeling to connect various cooling system component models into a system-wide framework, with a similar approach for the electrical system. Both systems are modeled under a single umbrella to account for system-system dependencies. This study describes an approach used to predict MLC and ELC metrics, and the associated compliance with the Standard, for a direct expansion cooling system and a non-redundant power configuration for a 1 MW data center. The study demonstrates that compliance checking predictions are both feasible and flexible when using a network modeling approach that connects various electrical and mechanical components in a systematic framework.

INTRODUCTION

Data centers consume large quantities of electricity. Recent estimates of data center energy consumption include 1.8% of U.S. electricity consumption in 2014 (A. Shehabi et al. 2016), 1% of worldwide electricity usage in 2018 (Jones 2018), and a projection of 73 billion kWh of consumption in 2020 (A. Shehabi et al. 2016). While some investigators predict massive increases in data center global electricity usage (Andrae 2017), others point out that increases in energy consumption have been mitigated recently in part to improvements in energy efficiency (Masanet et al. 2020). Such improvements in energy efficiency have financial and environmental benefits, so ASHRAE has implemented its 90.4 Standard (American Society for Heating, Refrigerating, and Air Conditioning Engineers 2019, 4) for ensuring that data center cooling and power system designs meet minimum criteria for energy efficiency.

Different metrics are used to evaluate data center resource consumption. The most well-known metric is the dimensionless power usage effectiveness (PUE) (ISO/IEC 2016), defined as

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$$PUE = \frac{P_{tot}}{P_{IT}} \tag{1}$$

where P_{tot} and P_{IT} are the annual electricity consumption for the entire data center and the IT equipment, respectively. One issue associated with the PUE metric is its intention to be evaluated for data centers currently in operation. Many studies (e.g., (Wemhoff and Ahmed 2022; Khalid and Wemhoff 2019b; Khalid, Wemhoff, and Joshi 2017; Shehabi et al. 2011)) have applied predictions of PUE for given data center cooling system and power distribution system configurations. However, PUE is not intended for design compliance checking. Therefore, ASHRAE Standard 90.4 was developed to establish metrics associated with for data center designs. The Standard focuses on whether data center designs are compliant through evaluation of two metrics: the Mechanical Load Component (MLC) and Electrical Loss Component (ELC). Compliance is achieved when the metrics are below maximum allowable values as set by the climate zone associated with the data center's location (MLC) and power distribution equipment efficiencies (ELC). Compliance paths include mechanical only, electrical only, or combined, depending on which system is involved in the design. This study focuses on all three approaches.

Accurate calculations of MLC and ELC are therefore essential to determining the viability of data center designs to meet the Standard, yet no universal Standard modeling approach has been adopted by ASHRAE, perhaps because of the diversity of data center cooling and power system design configurations (especially cooling system designs). Myriad cooling designs include, for example, traditional air-based cooling using supply and return plenums, hot aisles and cold aisles; air-based cooling using an open return, ducted supply or return directly to the rack, air-based cooling via fan walls, cold-plate water-based cooling, immersion-based liquid cooling, and pumped refrigerant cold plate-based cooling (ASHRAE TC9.9 Committee 2021). These cooling designs can include air-side (with or without direct or indirect evaporative cooling) or one of many water-side economization schemes (Li Chen and Aaron P. Wemhoff 2022). Furthermore, new cooling designs continue to be approached, including, for example, passive refrigerant-based two-phase cooling in enclosed racks (Khalid et al. 2019). Therefore, a universal standard should be able to account for both current cooling approaches and be flexible enough to handle future cooling technologies.

This study illustrates the flexibility of applying network modeling for cooling and power distribution systems in an example 1 MW data center in Ashburn, VA. The study shows how to calculate metrics (MLC & ELC). The approach is applied on a simple direct expansion-based cooling system and one non-redundant power distribution solution. It should be noted that although a 1 MW data center is illustrated here to indicate the feasibility of implementing network modeling for 90.4 compliance, the process can be easily extended to examine data centers of any size and configuration, enabling sensitivity analyses of data center size and system parameters on MLC and ELC predictions.

METHOD

The ASHRAE 90.4 Standard

ASHRAE 90.4 Standard ensures that data center cooling and power distribution designs meet minimum energy efficiency requirements. MLC and ELC are metrics used to ensure that the standard is met, so the focus of this study is on compuatational tools that can provide reliable calculations of MLC and ELC. The Standard defines compliance using the sum of MLC and ELC as compared to the sum of allowable design limits. The MLC calculation, defined as "annualized MLC" in the Standard, can be performed using hourly calculations or a binning approach (1°C bins) and requires examination at four ITE loads: 100%, 75%, 50%, and 25%. The use of bins or hourly calculations can be achieved with TMY3 climate data for a given location (Khalid and Wemhoff 2019a).

The Design Mechanical Load Component (MLC) is calculated as

$$MLC = \frac{E_{mech,25\%} + E_{mech,50\%} + E_{mech,75\%} + E_{mech,100\%}}{E_{ITE,25\%} + E_{ITE,50\%} + E_{ITE,75\%} + E_{ITE,100\%}} \tag{2}$$

where E is power consumption, and the subscripts *mech* and *ITE* represent mechanical cooling and information technology equipment (ITE) (American Society for Heating, Refrigerating, and Air Conditioning Engineers 2019, 4).

The mechanical cooling energy is calculated as

$$E_{mech} = E_{cool} + E_{pump} + E_{fan} + E_{AHU} \quad (3)$$

where the subscripts *cool*, *pump*, *fan*, and *AHU* indicate cooling, pump, heat rejection fan, and air handling unit (AHU), respectively. The Standard notes that the cooling energy encompasses that required for cooling, humidification, and dehumidification, whereas the pump, fan, and AHU energies are for prime movers in the cooling system. Waste heat recovery and/or onsite renewable energy generation can be used to reduce E_{mech}, which in turn, reduces MLC.

The Design Electrical Load Component (ELC) is calculated as

$$ELC = L_{is} + L_{UPS} + L_{id} \quad (4)$$

where L_{is}, L_{UPS}, and L_{id} are the percentage losses associated with the incoming electrical service segment efficiency, uninterruptible power supply (UPS) segment efficiency, and ITE distribution segment efficiency, respectively, using worst-case conditions. The segment efficiencies are defined as 100% minus the losses. The incoming electrical service segment includes all equipment and line losses upstream of the UPS to the utility service point. This segment therefore generally includes a medium-voltage transformer and its associated immediate inlet and outlet line losses. The segment efficiency can be calculated as the product of individual line loss and equipment efficiencies.

The UPS segment efficiency is modeled using a manufacturer-specified efficiency and power factor. The Standard recommends that this segment be considered the initial phase of ELC calculations since the UPS output power is designed to handle the ITE load. Knowledge of this UPS output power and efficiency enable calculations of the UPS input power, enabling calculations associated with the upstream incoming electrical service segment. Similarly, knowledge of the UPS output power enable calculations of the downstream ITE distribution segment. A holistic network modeling tool, however, does not restrict ELC calculations to progress in this manner since complex power is solved for simultaneously in the entire network.

The use of UPS redundancy is addressed in the Standard as either N+1, 2N, or 2(N+1). In the case of N+1 and 2(N+1) redundancy, the only variation is the operational load percentage, which is defined based on the percentage of operational design load times the potential maximum load with redundancy. This adjusted operational load percentage then influences the UPS efficiency. For 2N or 2(N+1) redundancy, only one system is considered for purposes of efficiency calculations, however the percentages of operational load differ: for N or N+1 systems, the percentages are 100% and 50%, whereas these percentages are 50% and 25% for 2N and 2(N+1) systems. Note that system ELC calculations are required for one of (100%, 50%) or (50%, 25%) operational load combinations based on UPS redundancy conditions.

The ITE distribution segment considers line losses between the UPS and power distribution unit (PDU), and PDU to ITE, and PDU loss (modeled as a 480V to 208 V transformer in example calculations in the Standard). The segment loss is 100% minus the segment efficiency, defined as the product of line loss and PDU efficiencies.

Network Modeling

Network modeling approaches enable the required flexibility to perform Standard 90.4 MLC and ELC calculations, enabling flexible, rapid predictions of MLC and ELC compliance through built-in calculations. Network modeling consists of creating models of individual components in the data center that capture the physical behavior of the equipment in the cooling and power systems. These components then interact with each other via a computational framework that ensures energy and mass balances (Wemhoff et al. 2013). An example of the modeling of a cooling system containing a single computer room air conditioning (CRAC) unit with airside economization and evaporative cooling is shown in Fig. 1 (Khalid and Wemhoff 2019b). The individual components of the cooling system include the computer room air conditioner, data center whitespace, and evaporative cooler, which are all connected via a fluid loop containing control dampers.

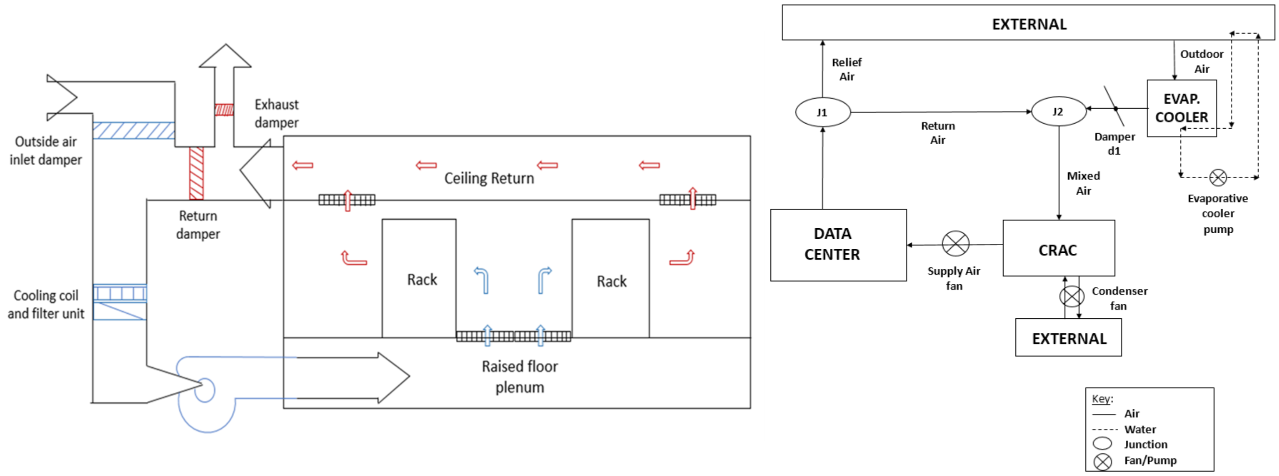

Fig. 1 Network model (right) of cooling system containing direct expansion-based cooling with airside economization and evaporative cooling (left) (Khalid and Wemhoff 2019b). Major components of the cooling system include the data center whitespace, the CRAC, the evaporative cooler, fans/pumps, and external reservoir.

In network modeling, the fluid flow patterns within the system are reduced to one-dimensional representations with uniform conditions approximated for plenae. In the whitespace, flow patterns can be modeled, with decreasing order of accuracy, directly using computational fluid dynamics simulations (Kamran Fouladi, Schaadt, and Wemhoff 2017), approximated using interpolation between different flow field conditions for different inputs as generated using computational fluid dynamics models (K. Fouladi et al. 2017), or approximated using a one-dimensional representation (Bhalerao, A. et al. 2016). Fan performance can be estimated, with decreasing order of accuracy, using pipe/duct energy equations with known duct dimensions and minor loss factors, or estimates for fan/pump power requirements to achieve a desired flow rate. In the latter case, the flow rate can be determined based on known data center ITE load, supply air temperature, and return air temperature.

One issue with modeling to test Standard compliance is the differing performance with different loads. The Standard calls for modeling at 25%, 50%, 75%, and 100% loads. Here, part-load coefficient of performance data for the Liebert DA085 computer room air conditioning unit are multiplied by an ambient temperature multiplier for generic direct expansion systems (L. Chen and A. P. Wemhoff 2022). A series of steady-state simulations are performed using Typical Meteorological Year (TMY3) hourly data for Dulles International Airport (approximated as conditions for nearby Ashburn, VA), which is located in ASHRAE Climate Zone 4A. Pumps and fans are assumed to have a fixed efficiency of 70%.

Network modeling is feasible for power distribution systems as well even though the number of components in the model generally vastly exceeds that for the cooling system. While less variability is generally seen in power distribution systems compared to cooling systems, variations are still seen in different power systems as related to Uptime Institute Tiers (Uptime Institute 2018), and research has examined the viability of DC-based power distribution systems (Wemhoff and Ahmed 2022). Figure 2 shows a generic AC-based power distribution system that is modeled in this study. The primary benefit with network modeling for power systems are the inherent line loss calculations that add complexity when performing ELC hand calculations. Here, the incoming service segment is defined at the outlet of then electric grid, which is connected to an AC transformer that drops the voltage from 13.8 kVAC to 480 VAC. The segment also features a transformer for dropping the voltage from 480 VAC to 208 VAC and line losses between the high voltage transformer outlet – including feeds to mechanical equipment – and the UPS input. The efficiency of the UPS is the product of two components: a rectifier and an inverter. Finally, the ITE distribution segment features line losses downstream of the UPS through four power distribution units PDUs into the racks. The PSU losses are not included in the ELC calculations.

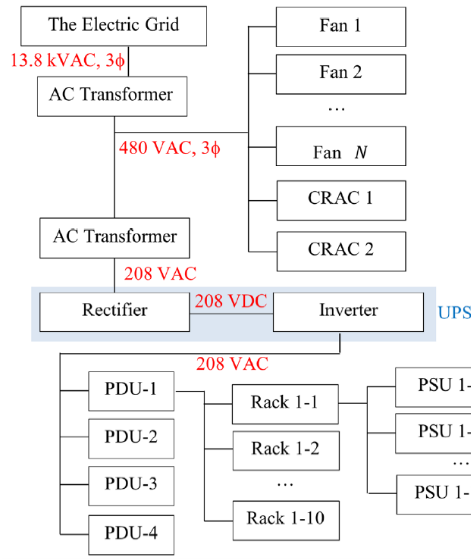

Fig. 2 Network modeling representations of an AC-based power distribution system. Major components of the electrical system include power distribution units (PDUs), two AC transformers, an uninterruptible power supply (UPS) containing a rectifier and inverter, CRAC units, power supply units (PSUs), and the electric grid (Wemhoff and Ahmed 2022).

Data Center Model

A CRAC-based model is used in this study. Each CRAC is designed for 250 kW of cooling, all air flow paths are approximated as 1 m in diameter and 1 m in length to impose an assumption that the CRAC compressor power is far larger than CRAC fan power. MLC calculations are performed at a given load percentage by defining the predicted annualized PUE at that load as the ratio of mechanical energy divided by IT energy. Therefore,

$$E_{mech} = (PUE - 1) \cdot E_{ITE} \quad (5)$$

The AC-based power distribution systems modeled here is a non-redundant system as seen in Fig. 2. The wire gauges used in the lines are Gauge 00 upstream of the split between mechanical equipment and ITE, and Gauge 1 elsewhere. The ELC is calculated at the peak hour of external cooling demand, defined as highest enthalpy of ambient moist air, for simplicity. Finally, it should be noted that if a redundant system were to be used, then the effects of the redundancy, per the Standard, would be that the part loads on the UPS components (rectifier and inverter) are reduced from 100% and 50% to 50% and 25% for compliance evaluation. The segment losses are calculated by multiplying component (individual equipment or line loss) efficiencies within a segment. These efficiencies are calculated as

$$\eta = \frac{S_{out}}{S_{in}} \quad (6)$$

where the component efficiency and complex power magnitude are η and S, respectively.

RESULTS

The hourly simulations for cooling system design took about one hour to process on a standard laptop for each load percentage. Table 1 provides the annualized PUE predictions using the network modeling tool for a known ITE load, enabling the calculation of the MLC metric for compliance. The annualized ITE load is calculated as the ITE load times the number of hours in a year (8,760) per the Standard, whereas the annual mechanical energy is derived from the predicted annualized PUE. The tables show that the CRAC-based system does not meet compliance.

Table 1. MLC Calculation – CRAC-Based System

Load Percentage	Annual ITE Load, kWh	Annualized PUE Prediction	Annual Mechanical Energy, kWh*
100%	8,760,000	1.33	2,890,800
75%	6,570,000	1.31	2,036,700
50%	4,380,000	1.31	1,357,800
25%	2,190,000	1.33	722,700
*Mechanical Energy is calculated as (Annual ITE Load) × (PUE-1)			
Sum of Annual Mechanical Energy = 7,008,000 kWh Sum of Annual ITE Load = 21,900,000 kWh Calculated annualized MLC = (7,008,000 kWh)/(21,900,000 kWh) = 0.32 Maximum allowable MLC for ASHRAE Climate Zone 4A (ITE Design Power above 300 kW) = 0.18 The above system is not in compliance with Standard 90.4-2019.			

Tables 2 and 3 demonstrate the calculation of the ELC using data from electrical system calculations for the worst case weather scenario. In the ELC calculations, the line loss is handled as the percentage of initial power lost in a branch as defined as the relative reduction in power in the branch between the branch inlet and outlet. This study assumes that losses downstream in the mechanical equipment branch are smaller than those associated with the branch serving the ITE due to the higher number of power conversions in the latter branch, however network modeling can test this assumption since all power losses are calculated simultaneously.

Table 2. ELC Calculation – Non-Redundant Power; CRAC-Based System, 100% Load

Component	Segment	Inlet Power, kVA	Outlet Power, kVA	Percent efficiency
Grid-to-480V transformer line loss	Incoming electrical service	2256.29	2256.29	100.00%
480V transformer	Incoming electrical service	2256.29	2099.98	93.07%
480V transformer to 480V junction line loss	Incoming electrical service	2099.98	2095.19	99.77%
480V junction to 208V transformer line loss	Incoming electrical service	1483.63	1479.60	99.73%
208V transformer	Incoming electrical service	1479.60	1377.60	93.11%
208V transformer to UPS line loss	Incoming electrical service	1377.60	1374.16	99.75%
Overall incoming electrical service segment efficiency = (100.00%)(93.07%)(99.77%)(99.73%)(93.11%)(99.75%) = 86.01% Overall incoming electrical service segment loss = L_{is} = 100% - 86.01% = 0.1399				
Rectifier loss	UPS	1374.16	1282.08	93.30%
Rectifier to inverter line loss	UPS	1282.08	1282.08	100.00%
Inverter loss	UPS	1282.08	1186.60	92.55%
UPS segment efficiency = (93.30%)(100.00%)(92.55%) = 86.35% UPS segment loss = L_{UPS} = 100% - 86.35% = 0.1365				
Inverter to PDU-main line loss	ITE distribution	1186.60	1184.12	99.79%
PDU-main to PDU-row	ITE distribution	1184.12	1183.56	99.95%
PDU-row to rack	ITE distribution	11.84	11.84	100.00%

ITE distribution segment efficiency = (99.79%)(99.95%)(100.00%) = 99.74% ITE distribution segment loss = LITE = 100% - 99.74% = 0.0026 ELC = 0.1399 + 0.1365 + 0.0026 = 0.2790 Maximum allowable ELC for single-feed UPS (N), IT design load ≥ 100 kW, 100%: 0.265 The above system is not in compliance with Standard 90.4-2019.

Table 3. ELC Calculation – Non-Redundant Power; CRAC-Based System, 50% Load

Component	Segment	Inlet Power, kVA	Outlet Power, kVA	Percent efficiency
Grid-to-480V transformer line loss	Incoming electrical service	1092.13	1092.13	100.00%
480V transformer	Incoming electrical service	1092.13	1016.16	93.04%
480V transformer to 480V junction line loss	Incoming electrical service	1016.16	1015.10	99.90%
480V junction to 208V transformer line loss	Incoming electrical service	729.80	728.73	99.85%
208V transformer	Incoming electrical service	728.73	678.24	93.07%
208V transformer to UPS line loss	Incoming electrical service	678.24	677.39	99.88%
Overall incoming electrical service segment efficiency = (100.00%)(93.04%)(99.90%)(99.85%)(93.07%)(99.88%) = 86.27% Overall incoming electrical service segment loss = L_{is} = 100% - 86.27% = 0.1373				
Rectifier loss	UPS	677.39	631.20	93.18%
Rectifier to inverter line loss	UPS	631.20	631.20	100.00%
Inverter loss	UPS	631.20	585.69	92.79%
UPS segment efficiency = (93.18%)(100.00%)(92.79%) = 86.46% UPS segment loss = L_{UPS} = 100% - 86.35% = 0.1354				
Inverter to PDU-main line loss	ITE distribution	585.69	585.08	99.90%
PDU-main to PDU-row	ITE distribution	585.08	584.59	99.92%
PDU-row to rack	ITE distribution	5.85	5.85	100.00%
ITE distribution segment efficiency = (99.90%)(99.92%)(100.00%) = 99.81% ITE distribution segment loss = LITE = 100% - 99.74% = 0.0019 ELC = 0.1373 + 0.1354 + 0.0019 = 0.2745 Maximum allowable ELC for single-feed UPS (N), IT design load ≥ 100 kW, 50%: 0.189 The above system is not in compliance with Standard 90.4-2019.				

The combined ELC and MLC results for the CRAC-based cooling system at both 100% and 50% electrical loads are 0.60 and 0.59, respectively, which are higher than the combined limits of 0.45 and 0.37 for these electrical loads, respectively. Therefore, the overall system design does not meet compliance.

The above approach indicates the possibility of using network modeling as a tool for determining 90.4 compliance, opening the opportunity for development of commercial software for compliance checking on various data center cooling nad power delivery designs. It should be noted that the confidence in compliance calculations is highly dependent on the accuracy of the component models, so the use of manufacturer's data is essential for component creation, and these components need thorough validation to ensure reliable assessment of 90.4 metrics.

CONCLUSIONS

This study demonstrates the ability for network modeling to perform the calculations necessary for MLC and ELC calculations in a straightforward manner. Network modeling has the flexibility to model different cooling and power distribution systems within the data center, and internal software calculations can be used to predict MLC and ELC for compliance.

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NOMENCLATURE

AHU	=	Air handling unit
CFD	=	Computational fluid dynamics
CRAC	=	Computer room air conditioner
E	=	Energy consumption
ELC	=	Electrical loss component
L	=	Loss
MLC	=	Mechanical load component
N	=	Number of equipment
P	=	Power
PDU	=	Power distribution unit
PUE	=	Power usage effectiveness
S	=	Complex power magnitude
UPS	=	Uninterruptible power supply
η	=	Component efficiency

Subscripts

AHU	=	air handling unit
cool	=	cooling
fan	=	fan
id	=	*ITE distribution*
is	=	*incoming electrical service*
ITE	=	information technology equipment
mech	=	mechanical
pump	=	pump
tot	=	total
UPS	=	*uninterruptible power supply*

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