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Article

Determining the Outdoor Air Intake Dry-Bulb Temperature Range for Economizer Applications in Data Centers

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Abstract

This study aimed to identify the optimal outdoor air (OA) intake temperature range for the application of a dry-bulb temperature-based air-side economizer in data centers. To this end, a series of parametric simulations was conducted using EnergyPlus (version 24.1.0) and a previously validated small-to-medium-scale data center model situated in Daejeon, South Korea (ASHRAE Climate Zone 4A). A parametric analysis was performed by varying the maximum allowable OA intake dry-bulb temperature from 10 to 18 °C in 2 °C increments. The simulation results indicated that OA intake was limited during the summer due to high humidity levels, whereas it was more viable during the winter and interseason period. However, when the maximum OA intake dry-bulb temperature exceeded 14 °C, the increase in latent heat load caused humidity increased overall energy consumption. To expand the applicable range for air-side economizer operation, the cooling system capacity was adjusted. The scenario with a 14 °C OA threshold demonstrated the most favorable balance between energy efficiency and compliance with operating environmental criteria. The findings of this study provide a technical basis for establishing OA intake guidelines in dry-bulb temperature-based economizer control. However, further field-based validation is required to verify the effectiveness of these simulation results under real-world operating conditions.

Keywords: outdoor air; dry-bulb temperature; air-side economizer; data center; cooling system

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1. Introduction

Data centers are facilities that house IT (Information technology) equipment such as communication systems, computer systems, and storage devices, serving critical functions such as data storage, processing, and transmission. With the rapid growth of the AI market, the volume of internet data has surged, leading to an increase in the number of data centers in South Korea, which grew from 156 in 2020 to 187 in 2022 [1]. Consequently, the total energy consumption of South Korean data centers is projected to rise from 1762 MWh in 2022 to 49,397 MWh by 2029 [2]. As energy demand continues to grow, the need for effective energy-saving strategies in data centers has become increasingly urgent. The primary contributors to energy consumption in data centers are Information Technology (IT) equipment and the cooling system [3]. The cooling system plays a critical role in dissipating the heat generated by IT equipment, which, if not adequately managed, can lead to equipment malfunction, data loss, and decreased operational reliability [4]. Accordingly, cooling systems are essential for maintaining stable data center operation. However, these systems account for approximately 40% of the total energy consumption in data centers, highlighting the importance of strategies to reduce cooling energy use [5].

In response to this, outdoor air (OA)-based cooling strategies, commonly known as economizer systems, have been widely adopted in data centers to improve energy efficiency. The purpose of introducing OA in data centers is to take advantage of favorable OA temperature and humidity conditions to minimize the operation of mechanical cooling systems. This approach helps reduce energy consumption while maintaining the thermal safety and reliability of IT equipment. These systems are generally categorized into air-side or water-side economizers [6]. Air-side economizers directly introduce OA into the indoor environment (direct type) or use heat exchangers to indirectly cool return air (RA) (indirect type) [7]. Although air-side economizers can significantly reduce mechanical cooling demand, their performance is affected by variations in OA humidity and air quality [7]. Water-side economizers, typically employed in large-scale data centers, utilize OA to lower the temperature of chilled water, which is then used to cool the indoor environment through heat exchangers [8]. While less sensitive to ambient air quality, water-side economizers require significant upfront investment due to the need for cooling towers and heat exchangers [7].

Previous studies have explored various economizer-based strategies to reduce energy consumption in data centers.

Kim et al. [9] evaluated the effects of supply air (SA) temperature and design airflow rate on energy consumption in a data center utilizing an air-side economizer. SA temperatures of 16, 20, and 24 °C were selected based on ASHRAE recommended conditions, with airflow rates of 230, 270, and 325 CMH/kW. The findings indicated that higher SA temperatures extended the duration during which OA could be utilized, thereby reducing cooling energy consumption. Additionally, reduced airflow resulted in lower fan energy demand. In this context, OA was introduced only when its temperature was lower than the RA temperature.

Kim et al. [10] assessed energy use under varying OA operation modes in water-side economizers across four Korean cities—Seoul, Busan, Daegwallyeong, and Chuncheon. Connecting chillers and heat exchangers in the series yielded energy savings of up to 20%. The operation was controlled based on OA wet-bulb temperature.

Ali et al. [11] examined air-side economizer performance using a dry-bulb temperature-based control across four distinct climates—Dubai, Stockholm, Singapore, and San Francisco. Substantial energy reductions were observed in Stockholm (86%) and San Francisco (76%), whereas energy consumption increased in Dubai (2%) and Singapore (4%) due to high ambient temperatures and humidity. The analysis was based on the criterion that OA is introduced only when the dry-bulb temperature is below 24 °C.

Kim et al. [12] conducted a comparative analysis of three economizer configurations—direct air-side, indirect air-side, and water-side—across 15 regions, reporting that the indirect air-side economizer exhibited the highest energy-saving potential, with reductions of up to 40%. In the case of direct air-side economizer systems, OA can only be utilized when the SA dry-bulb temperature is within the range of 18 to 27 °C and the dew point temperature remains below 15 °C.

Park and Chang [13] evaluated a multi-stage economizer system integrating both air-side and water-side economizers. The system was simulated across five major Korean cities, demonstrating energy savings of approximately 21% at a SA temperature of 13 °C and up to 32% at 25 °C. The air-side economizer was operated when the OA enthalpy was below 43.8 kJ/kg, the dry-bulb temperature was below 21.5 °C, and the dew point temperature was below 10.5 °C.

Lan et al. [14] analyzed the impact of SA temperature and airflow on IT equipment inlet conditions and energy consumption using a fan-wall cooling system. While increased airflow and power raised the inlet air temperature, overall energy use was reduced by up to 34% with the fan-wall configuration.

Fan and Zhou [15] proposed an optimized control algorithm for chillers and water-side economizers, demonstrating a 14.3% reduction in energy consumption relative to a baseline model, with the most effective scenario involving hourly control optimization.

Jin et al. [16] evaluated the feasibility of applying water-side economizer systems in 34 cities across China, based on a data center in Chongqing with an 8270 kW design load. Free cooling was applied when the OA wet-bulb temperature fell below a threshold defined by the chilled water supply temperature, the cooling tower approach (typically 5 °C), and the heat exchanger temperature difference (1 °C). Under chilled water temperatures range of 21 to 27 °C, full free cooling was available in all cities, resulting in energy savings 3.17 times higher than those at 12/18 °C. However, water consumption increased in 74% of the cities. Both energy and water consumption showed a geographical trend—lower in the western and northern regions, and higher in the eastern and southern regions.

Park and Seo [17] conducted a simulation study on a data center located in Seoul, South Korea, to evaluate the impact of exhaust air (EA) recirculation and SA temperature on the performance of air-side economizers. Thirteen cases were modeled by varying EA recirculation ratios (0%, 5%, 10%, and 15%) and SA temperature settings (13.5 °C, 18 °C, and 22 °C). The results showed that a 15% EA recirculation increased annual cooling energy consumption by up to 9% compared to the no-recirculation case, while raising the SA temperature to 22 °C reduced energy use by up to 67% compared to a central chilled-water system. OA was introduced based on temperature or enthalpy conditions, and was generally allowed when the OA temperature was below approximately 22 °C.

Previous studies have investigated various types of economizer systems, including air-side economizers [9,11,14,17], water-side economizers [10,15,16], and integrated or multi-stage systems [12,13].

However, most of these studies did not attempt to determine the optimal OA intake dry-bulb temperature range for air-side economizer operation, often relying on fixed thresholds or guideline values without optimization.

As shown in Table 1, the allowable OA intake temperature was either set equal to the RA temperature [9] or fixed within a range, such as 21.5 °C to below 24 °C [11–13,17]. In addition to dry-bulb temperature control, some studies applied humidity-related constraints, such as enthalpy or dew point limits. However, study [15] did not consider the inlet air temperature and humidity to IT equipment—factors critical for ensuring reliability and thermal safety. Moreover, studies [10–15] did not include analyses specific to ASHRAE Climate Zone 4A [18], where hot-humid summers and cold winters significantly influence air-side economizer performance.

To address these limitations, this study evaluated the performance of a dry-bulb temperature–based an air-side economizer system using a small-to-medium-scale simulation-validated data center model located in Daejeon, South Korea—representative of ASHRAE Climate Zone 4A [19]. This zone is classified as a mixed-humid region, characterized by at least 2000 heating degree days (base 18 °C), and hot, humid summers. The objective of this study is to identify the optimal OA intake dry-bulb temperature range and establish effective operational guidelines that improve energy efficiency while ensuring reliable environmental conditions for IT equipment.

Table 1. A review of the literature on data center economizer systems.

Ref.	Year	Economizer Type	Regions	Climate Zone	Consideration of IT Equipment Inlet Air Conditions	OA Intake Dry-Bulb Temp. Range
[9]	2019	Air-side (Direct)	Seoul, South Korea	4A	O	$T_{OA} \leq T_{RA}$
[10]	2022	Water-side	South Korea (Busan, Seoul, Chuncheon, and Daegwallyeong)	3–6A	O	-
[11]	2023	Air-side (Direct)	Stockholm, Dubai, San Francisco, and Singapore	7A, 1B, 3C, 1A	O	$T_{OA} \leq 24$ °C
[12]	2024	Air-side (Direct and indirect)	15 Asian cities (e.g., Bangkok, Abu Dhabi, Hanoi, and etc.)	0A–8	O	18 °C $\leq T_{SA} \leq$ 24 °C
[13]	2017	Combine air-side and water-side	South Korea (Seoul, Jeonju, Jecheon, Bonghwa, and Taebaek)	4A, 6A, 7A	O	$T_{OA} \leq 21.5$ °C
[14]	2023	Air-side	Guiyang, China	3A	O	-
[15]	2023	Water-side	Guiyang, China	3A	X	-
[16]	2024	Water-side	34 cities in China	3–5A	O	-
[17]	2018	Air-side (Direct and indirect)	Seoul, South Korea	4A	O	$T_{OA} \leq 22$ °C

2. Methodology

2.1. Research Procedure

This study aimed to determine the optimal dry-bulb temperature range for OA intake in an air-side economizer control by evaluating both energy consumption and the thermal conditions at the IT equipment inlet. The study employed a multi-objective assessment designed to simultaneously minimize annual energy consumption and ensure compliance with the ASHRAE TC 9.9 [20] environmental criteria, particularly regarding the allowable relative humidity at the IT equipment inlet. The methodology consisted of five distinct phases, as illustrated in Figure 1.

The first phase involved the development of a simulation model representing a small-to-medium-sized data center located in Daejeon, South Korea (ASHRAE Climate Zone 4A). A previously validated model, originally equipped with a Computer Room Air Conditioner (CRAC) system [19], was modified to incorporate an air-side economizer. To ensure that the indoor environment satisfied the ASHRAE TC 9.9 thermal and humidity requirements, a humidifier and a reheat coil were added to the system. Simulations were conducted using EnergyPlus version 24.1.0 [21], and the environmental thresholds were established according to ASHRAE classifications, as presented in Table 2.

Table 2. Data center operating conditions according to environmental class (temp.: temperature, RH: relative humidity).

Class	Dry-Bulb Temp. [°C]	Dew Point Temp. [°C]	RH [%]	Ref.
Recommended A1 to A4	18 to 27	−9 to 15	60	[20]
Allowed				
A1	15 to 32	−12 to 17	8 to 80	
A2	10 to 35	−12 to 21	8 to 80	
A3	5 to 40	−12 to 24	8 to 85	
A4	5 to 45	−12 to 24	8 to 95	

The second phase conducted preliminary simulations by varying the maximum allowable OA intake dry-bulb temperature, defined as the high-limit setpoint. Scenarios were created by decreasing this limit from 18 °C to 10 °C in 2 °C intervals, based on ASHRAE Standard 90.1 [22]. The minimum OA intake temperature, or low limit setpoint, was fixed at 5 °C in accordance with the Building Re-Tuning Training Guide published by the Pacific Northwest National Laboratory (PNNL) [23]. Meteorological data were sourced from the

IWEC2 dataset for Daejeon, South Korea [24] and hourly simulation was run for a full year under identical schedules and boundary conditions.

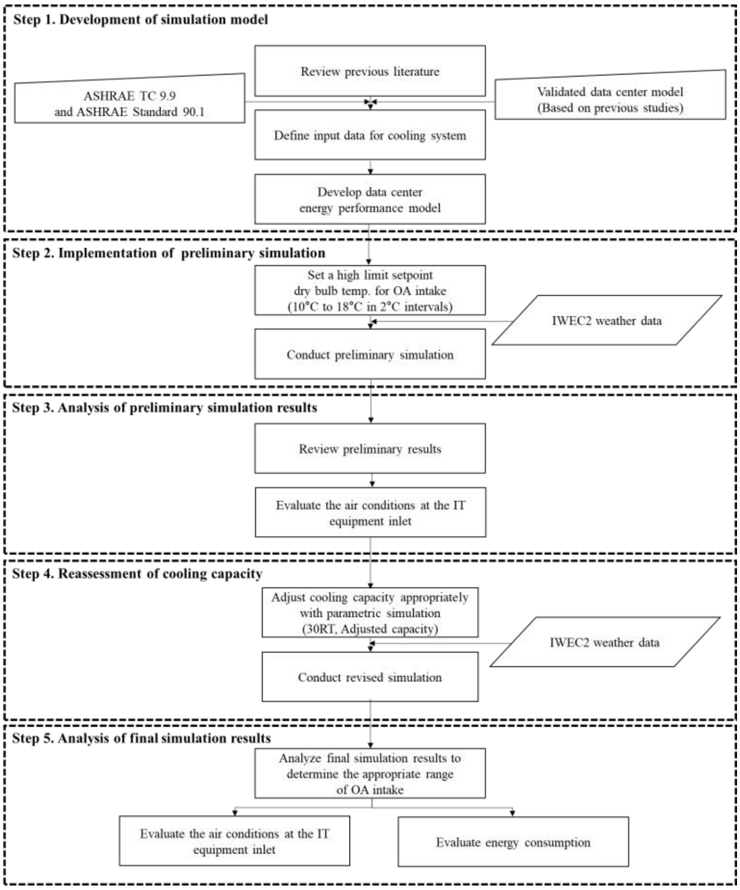


Figure 1. Overall research process.

The third phase focused on analyzing the preliminary simulation results. This analysis evaluated the thermal and humidity conditions at the IT equipment inlet. In multiple scenarios, the relative humidity exceeded the acceptable limits defined by ASHRAE TC 9.9, indicating that the base cooling capacity was inadequate to maintain indoor environmental compliance.

The fourth phase involved conducting revised simulations by adjusting the cooling capacity of the system. Instead of applying the autosizing feature in EnergyPlus version 24.1.0, a para-metric approach was used to increase the cooling capacity from the baseline value of 30 RT up to 56 RT in 2 RT increments. For each case, the capacity at which the relative humidity criteria were first met was identified and applied.

The fifth phase re-evaluated all humidity-compliant cases to assess their seasonal energy consumption. Subsequently, the annual energy consumption was compared between cases using the baseline and revised cooling capacities. This final analysis enabled the identification of the optimal OA intake high limit setpoint that offered the best trade-off between energy efficiency and indoor environmental compliance. Among the scenarios, the case applying a 14 °C high limit setpoint demonstrated the most favorable balance between minimizing energy use and maintaining allowable inlet conditions.

2.2. Data Center Simulation Modeling

To ensure the reliability of the simulation results, this study used a validated EnergyPlus simulation model [19]. The model was developed based on data from Research Institute 'A' in Daejeon, South Korea, which covers small and medium-sized data centers with computer room air conditioning (CRAC) systems. The model was validated by comparing simulated cooling energy use and internal heat gain with measured data under similar boundary conditions, including building area, internal heat gain, and operating schedule. In this study, a dry bulb temperature-based air-side economizer system was applied to a validated model to evaluate the impact of the economizer system on energy consumption and IT environment operating conditions to derive the optimal range of outside air introduction.

Figure 2 shows the schematic of the simulation model, and Table 3 summarizes the input parameters.

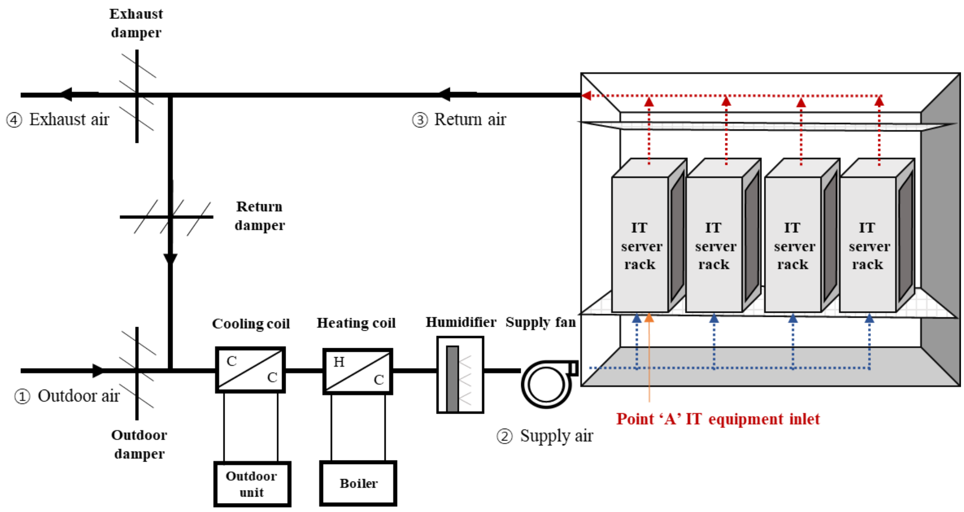


Figure 2. Schematic diagram for data center model.

Table 3. Simulation modeling parameters.

Input Parameters			Values	Refs.
Building		Type	Data center	[19]
	U-value	Wall	0.34 $W/m^2 \cdot K$	[19]
		Ceiling	0.21 $W/m^2 \cdot K$	[19]
		Floor	0.29 $W/m^2 \cdot K$	[19]
	IT space	IT equipment inlet temp.	18 + 1 °C	[20]
		IT equipment outlet temp.	33 ± 1 °C	[25–28]
	Surrounding space	Space setpoint temp.	24 °C	[19]
System		Operating hours	24/7 operation	
	Cooling	Type	Air cooled type CRAC	
		Capacity	30 RT	[19]
	Reheat (Boiler)	Capacity	Autosize	
	Humidifier	Capacity	Autosize	
	Fan	Type	Variable speed fan	
		Flow rate	7.25 m^3/s	[19]
		Efficiency	0.641	[19]
	IT equipment	Maximum IT equipment load	75.5 kWh	[19]
General		Location	Daejeon, South Korea	
		Weather data	IWEC2	[23]

The cooling system consisted of an air-cooled CRAC unit that supplied air through the raised floor. Dehumidification is achieved by overcooling the air using a cooling coil to reduce its absolute humidity. A heating coil is used to reheat the overcooled air to the desired SA temperature. The heat source for the heating coil is a boiler, and its capacity was determined using EnergyPlus's autosizing function based on the building's thermal load conditions. A humidifier was added to maintain a minimum dew point temperature of −9 °C, as recommended by ASHRAE TC 9.9. The heating coil and humidifier were newly added, and their capacities were determined using EnergyPlus's autosizing function based on internal load conditions. EnergyPlus provides functionality for automatically sizing

HVAC components—such as cooling/heating coils, fans, and boilers—based on internal thermal loads and user-defined design criteria. By simulating peak load conditions, the software determines appropriate equipment capacities without requiring manual input [25].

The dry-bulb temperature at the IT equipment inlet was set to 18 + 1 °C in accordance with ASHRAE TC 9.9 guidelines. The exhaust temperature of the IT equipment was set to 33 ± 1 °C, based on results from previous studies [26–29]. The surrounding temperature of the IT room was maintained at 24 °C, reflecting the actual operating conditions at Research Institute A. The thermal properties of the floor, ceiling, interior walls, and exterior walls were modeled identically to those of the validated reference model [19]. The maximum internal heat gain from the IT equipment was set to 75.5 kWh, based on field-measured data reported in previous studies, and applied as the peak sensible load in the simulation model. The IT equipment utilization rate was reflected through sensible heat gain, calculated from the average weekly IT heat output data.

In the simulation model, the airflow followed this path: OA entered and partially mixed with RA, while the remaining portion was exhausted as EA. The mixed air (MA) passed through the cooling coil, heating coil, humidifier, and supply fan, before being delivered into the underfloor plenum as SA. This air was supplied to the IT equipment, passed through it, and returned as RA, completing the circulation.

2.3. Simulation Cases Configuration

In Section 2.3, simulation cases were configured to determine the allowable range of OA dry-bulb temperatures for economizer operation. The base case represented a scenario in which the cooling system operated without OA intake, whereas Cases #2 through #6 applied the air-side economizer. Case #6 was based on ASHRAE Standard 90.1, which specifies 18 °C as the maximum allowable OA dry-bulb temperature for Daejeon, South Korea, which is located in Climate Zone 4A [22]. Cases #2 to #6 were configured by reducing the maximum intake temperature in 2 °C intervals from 18 °C. The minimum allowable OA intake dry-bulb temperature was set to 5 °C, following the guideline from the Building Re-Tuning Training Guide published by the Pacific Northwest National Laboratory (PNNL) [23].

When the OA temperature was between 5 °C and the SA setpoint temperature (approximately 17–18 °C), 100% OA was introduced for free cooling. In the range between the SA setpoint and the maximum allowable OA temperature (10–18 °C, depending on the case), partial OA intake was allowed by mixing with RA. This staged control strategy was implemented to ensure that the SA temperature could be maintained efficiently while maximizing the use of OA.

Table 4 summarizes the simulation cases used to analyze the impact of cooling system capacity on indoor air conditions and energy consumption.

Table 4. Preliminary simulation cases for selecting optimal OA intake conditions.

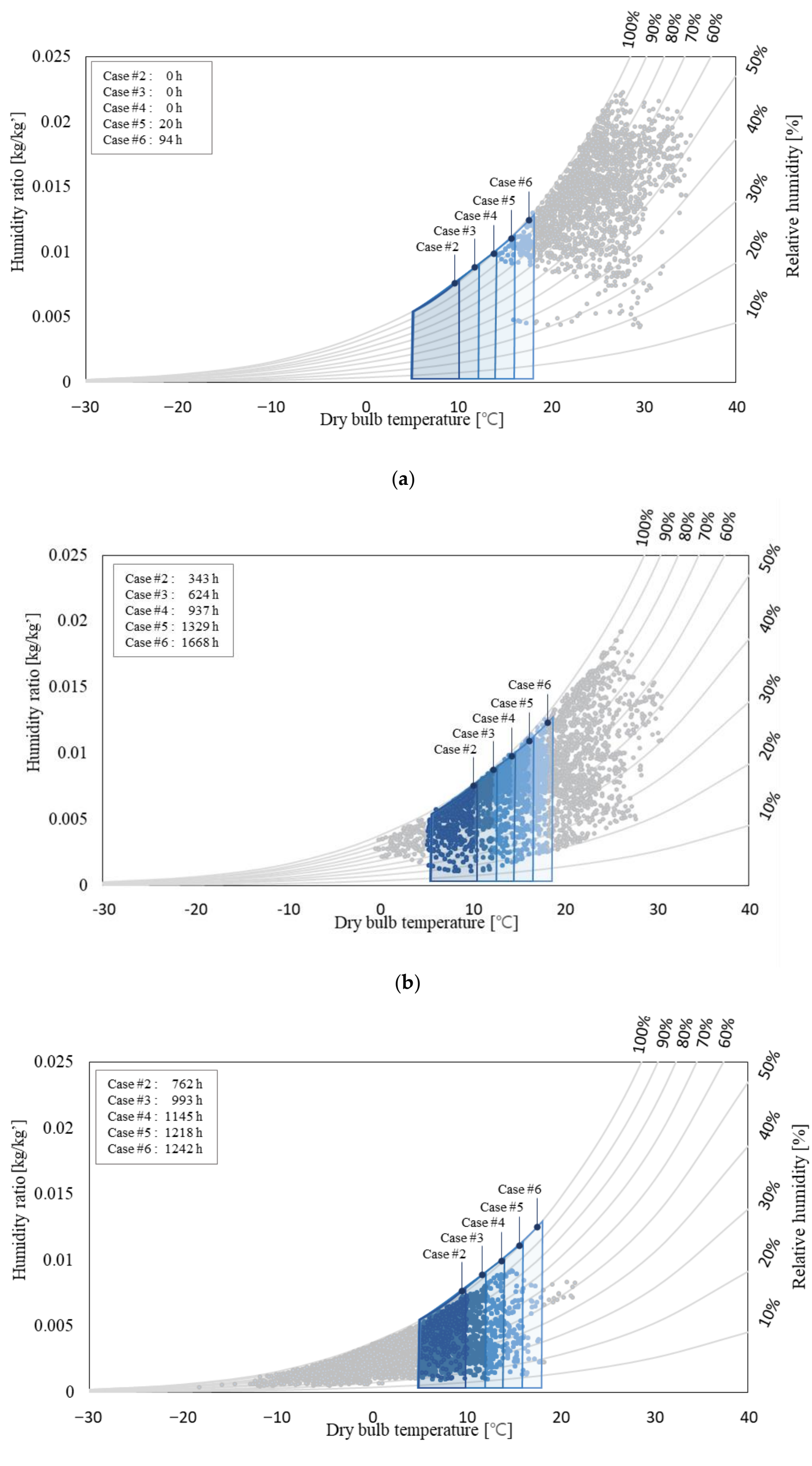
Simulation Cases	OA Intake Dry-Bulb Temp. Range
Case #1 (Basecase)	-
Case #2	5–10 °C
Case #3	5–12 °C
Case #4	5–14 °C
Case #5	5–16 °C
Case #6	5–18 °C

3. Simulation Results and Analysis

3.1. Evaluation of OA Applicability by Case

Section 3.1 analyzed the allowable OA intake time for each case based on hourly outdoor dry-bulb temperature data from the IWEC2 weather file for Daejeon, South Korea [22].

Figure 3 illustrated the OA conditions and the number of hours during which OA intake was allowed for each case across the summer season, interseason, and winter season periods. The summer season was defined as June to August (2208 h), the winter season as November to March (3624 h), and the interseason periods as April to May and September to October (2928 h).



(**a**) (**b**) (**c**)

Figure 3. OA intake availability hours in each case: (**a**) Summer; (**b**) interseason; (**c**) Winter.

In summer, the number of allowable hours intake was 94 for Case #6 and 20 for Case #5, out of 2208 total hours. No OA intake was allowed for Case #2 to Case #4 during this period. Only two cases permitted OA use in summer, suggesting the limited applicability of OA cooling in this season. This was because the OA temperatures rarely dropped below the upper intake thresholds (e.g., 14 °C or lower), which were defined for Cases #2 to #4, making OA intake infeasible under the given criteria.

In the interseason periods, Case #6 allowed 1668 h of OA intake, followed by Case #5 with 1329 h, Case #4 with 937 hours, and Case #3 with 624 hours. The percentage of allowable intake hours during the interseason period ranged from 11.71 to 45.39%.

In winter, Case #6 had 1,242 allowable hours, accounting for 56.25% of the total winter hours. Case #5 and Case #4 also showed more than 50% applicability, with 55.16% and 51.86%, respectively. Due to high dry-bulb temperatures, the OA intake potential in summer was limited, and the energy-saving effect was expected to be minimal. However, in the interseason periods and winter seasons, the allowable intake ratio ranged from 11 to 55%, indicating that OA could have significantly contributed to cooling energy reduction during these periods.

3.2. Analysis of Air Conditions at the IT Equipment Inlet

Section 3.2 evaluated the air condition at the inlet point of the IT equipment, which corresponds to Point 'A' in Figure 2. In the simulation, this location was represented by a designated node in EnergyPlus.

All simulation cases were configured to maintain the inlet air temperature for the IT equipment within the ASHRAE TC 9.9 recommended dry-bulb temperature range of 18–27 °C. Since this condition was satisfied in all cases, the analysis primarily focused on evaluating humidity control performance, which showed greater variability across scenarios.

The relative humidity at this node was directly obtained using the standard output variables available for each node in EnergyPlus. ASHRAE TC 9.9 recommends that the humidity level at the IT equipment inlet be maintained below a dew point temperature of 15 °C or within a relative humidity of 60%. In this study, the air conditions were assessed based on the relative humidity criterion.

Figure 4 was generated by plotting the relative humidity values at the IT equipment inlet node over the entire simulation year for each case. The box plots illustrate the distribution of relative humidity, including the maximum, 75th percentile, median, 25th percentile, and minimum values. This visualization enabled a clear comparison of humidity conditions across different OA intake cases and highlighted periods when the relative humidity exceeded or remained within the ASHRAE TC 9.9 recommended limit.

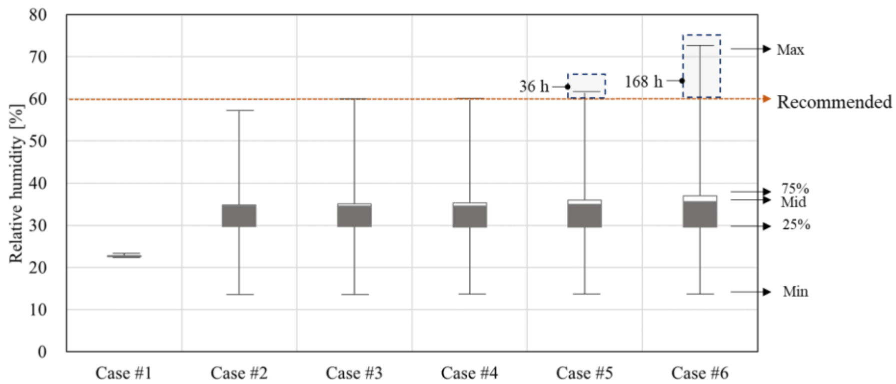


Figure 4. Distribution of humidity ratio for each case compared to the recommended threshold.

The results indicated that Case #2 through #4 met the ASHRAE TC 9.9 standard. However, in Case #5 and Case #6, the relative humidity exceeded the standard for 36 hours and 168 hours, respectively. This was attributed to insufficient dehumidification of the incoming OA. Therefore, a reassessment of the cooling system capacity is required to enhance the dehumidification performance in Case #5 and #6.

3.3. Determination of Appropriate Cooling Capacity by OA Intake Dry-Bulb Temperature

The simulation results indicated that the cooling coil significantly lowered the temperature of the incoming OA below its dew point to reduce humidity. This overcooling process was essential to dehumidify the humid OA before supplying it to the IT equipment.

As a result, in Case #5 and Case #6, the originally designed cooling system capacity (30 RT) was insufficient to handle the increased cooling demand, including the added latent load, under high-temperature and high-humidity OA conditions (refer to Figure 4). Consequently, the dry-bulb temperature and humidity at the IT equipment inlet did not meet the standards recommended by ASHRAE TC 9.9.

Increasing cooling capacity is generally considered an abnormal strategy from the perspective of energy efficiency, as it typically results in higher energy consumption. However, this study prioritized maintaining the thermal and humidity conditions required by ASHRAE TC 9.9 for stable IT equipment operation. Accordingly, the cooling capacity was adjusted to meet the environmental criteria even under humid OA conditions. Although this adjustment may increase energy use, it also enables a wider OA intake range, which can improve the potential for cooling energy savings through enhanced economizer operation.

In this study, the cooling capacities for Case #5 and Case #6 were redefined using a parametric approach to satisfy the environmental criteria set by ASHRAE TC 9.9. The capacities were incrementally increased until the conditions at the IT equipment inlet met the required standards. As shown in Table 5, the optimal cooling capacities were determined to be 45 RT for Case #5_adj and 56 RT for Case #6_adj. The simulation model had been previously validated under baseline load conditions, and only the cooling capacity was modified without altering the system configuration.

Table 5. Revised simulation cases for meeting ASHRAE TC 9.9 IT equipment operating environmental criteria.

Simulation Cases	OA Intake Dry-Bulb Temp. Range	Adjusted Cooling System Capacity
Case #1	-	30 RT
Case #2	5–10 °C	30 RT
Case #3	5–12 °C	30 RT
Case #4	5–14 °C	30 RT
Case #5_adj	5–16 °C	45 RT
Case #6_adj	5–18 °C	56 RT

3.4. Analysis of Thermal Conditions at the IT Equipment Intake with Adjusted Cooling Capacity

Section 3.4 analyzed the air conditions at the IT equipment intake when the cooling system capacity was appropriately configured for each case. Figure 5 presents the air condition at the intake point for each simulation case. The results showed that with appropriately adjusted cooling capacities, the relative humidity at the IT equipment intake in Case #5_adj and Case #6_adj remained below the ASHRAE TC 9.9 recommended limit of 60%.

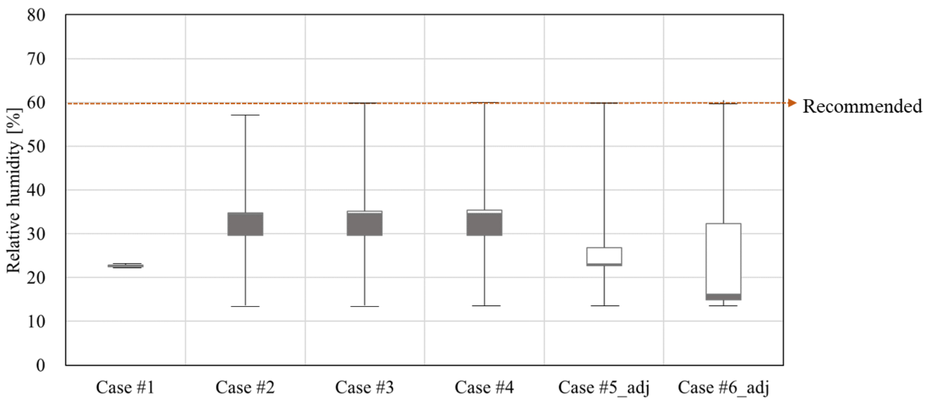


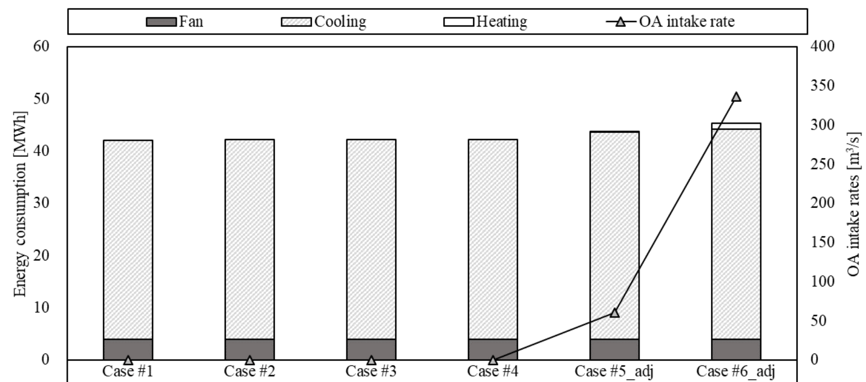
Figure 5. Air conditions at the IT equipment inlet section for each case.

These findings emphasize that when applying an economizer system in a data center, the cooling system capacity should be selected with consideration for its dehumidification capability. In this study, the adjustment of cooling system capacities was intended to examine the potential to expand the OA intake range while ensuring compliance with the relative humidity limits recommended by ASHRAE TC 9.9. By satisfying this criterion, it becomes possible to explore wider OA intake thresholds that may enhance energy-saving potential under favorable OA conditions. This modeling approach was not intended as a design recommendation but rather aimed at demonstrating that achieving humidity control performance is a prerequisite for enabling such expansion.

3.5. Energy Consumption

3.5.1. Seasonal Energy Consumption

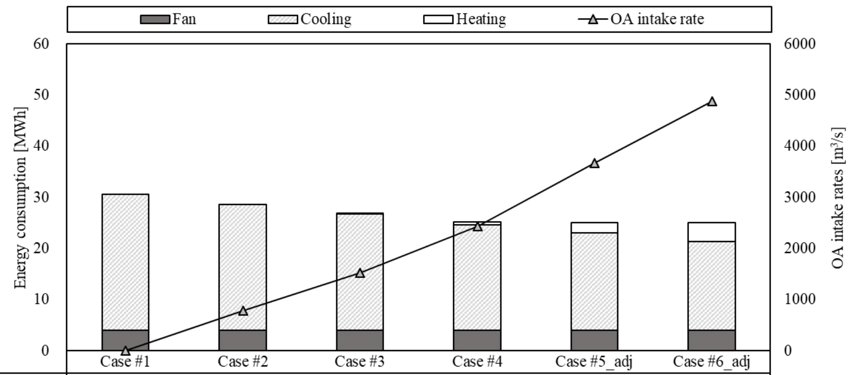
This section analyzed the impact of varying the allowable OA intake dry-bulb temperature range on energy consumption across three periods: summer (June to August), interseason (April to May and September to October), and winter (November to March). Figure 6 illustrated the hourly energy consumption for fan operation, cooling, and reheating, as well as the OA intake rate for each simulation case (Case #1 to Case #6). Figure 7 presented the hourly cooling coil energy consumption and OA humidity ratio during five weekdays around the autumnal equinox (22 September).



	Case #1	Case #2	Case #3	Case #4	Case #5_adj	Case #6_adj
Total	42	42	42	42	44	45
Heating	0	0	0	0	0	1
Cooling	38	38	38	38	40	40
Fan	4	4	4	4	4	4
OA intake rate	0	0	0	0	61	336

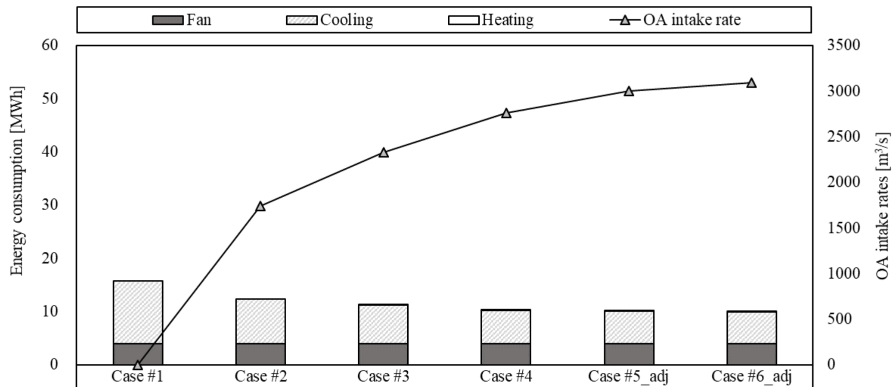
(**a**)

Figure 6. *Cont.*



	Case #1	Case #2	Case #3	Case #4	Case #5_adj	Case #6_adj
Total	31	29	27	25	25	25
Heating	0	0	0	1	2	4
Cooling	27	25	23	21	19	17
Fan	4	4	4	4	4	4
OA intake rate	0	781	1529	2438	3670	4887

(**b**)



	Case #1	Case #2	Case #3	Case #4	Case #5_adj	Case #6_adj
Total	16	12	11	10	10	10
Heating	0	0	0	0	0	0
Cooling	12	8	7	6	6	6
Fan	4	4	4	4	4	4
OA intake rate	0	1740	2332	2764	3002	3092

(**c**)

Figure 6. Hourly average energy consumption for each seasonal period: (**a**) Summer; (**b**) interseason; (**c**) Winter.

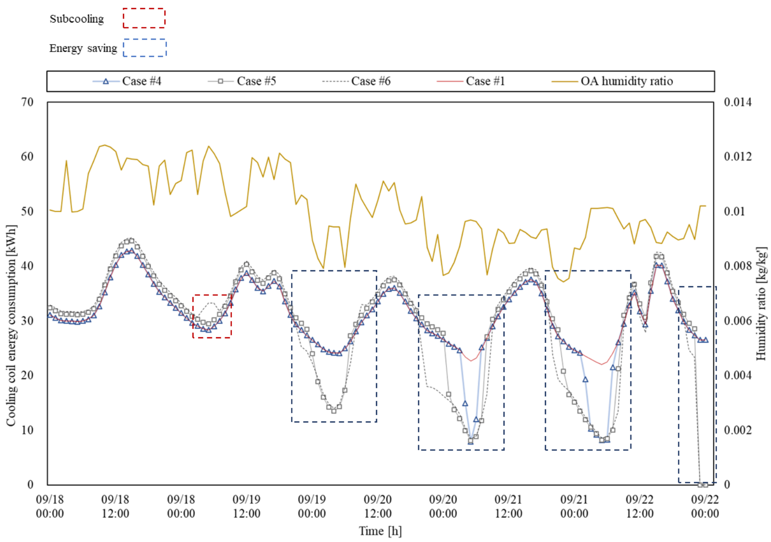


Figure 7. Weekday hourly cooling coil energy consumption and OA humidity ratio (Case #1, Case #4~Case #6).

Each case was evaluated with its corresponding cooling capacity: 30 RT for Cases #1 to #4, 45 RT for Case #5, and 56 RT for Case #6. In summer, as the OA intake increased from 0 m^3/s in Case #1 to 336 m^3/s in Case #6, and the hourly total energy consumption rose from 42 to 45 MWh. Case #5 also showed a 2 MWh increase compared to Case #1, primarily due to elevated energy use by the cooling and reheating coils. This increase resulted from overcooling to remove excess humidity in Daejeon's summer climate, followed by reheating to reach the desired SA temperature, thereby increasing energy use in both systems. Therefore, OA intake during summer was not recommended due to its inefficiency in terms of energy consumption.

During the interseason, energy consumption was reduced by 2 to 6 MWh from Case #1 to Case #6, as the increased OA intake shortened the operating time of the cooling system. Although the OA intake in Case #6 was 4887 m^3/s greater than that in Case #2, the total energy savings were similar from Case #4 to Case #6. This was because the over-cooled air in Case #6 required reheating for dehumidification, which increased energy usage 4 MWh. An hourly analysis conducted from 18 to 22 September indicated that energy savings were most prominent after 7:00 p.m., with Case #6 demonstrating a maximum reduction of up to 30 kWh. Conversely, during the early morning period between 5:00 a.m. and 6:00 a.m. on 19 September, the energy consumption in Case #6 increased by approximately 15–17% compared to Case #1. This increase was attributed to additional subcooling required for humidity control. Therefore, it can be concluded that, during interseason periods with low ambient humidity, the allowable OA intake temperature threshold may be reasonably extended up to the level defined in Case #6.

In winter, energy consumption in Cases #5 and #6 was approximately 6 MWh lower than that in Case #1. Although OA intake increased by 1529 m^3/s from Case #2 to Case #6, the magnitude of increase was smaller than in the interseason. This was likely due to the generally low temperatures during winter and the limited OA intake duration of only 482 hours from Case #2 to Case #6 (refer to Figure 3c, Winter). Therefore, the OA intake ranges defined in Cases #5 and #6 were considered effective for reducing energy consumption during the winter season.

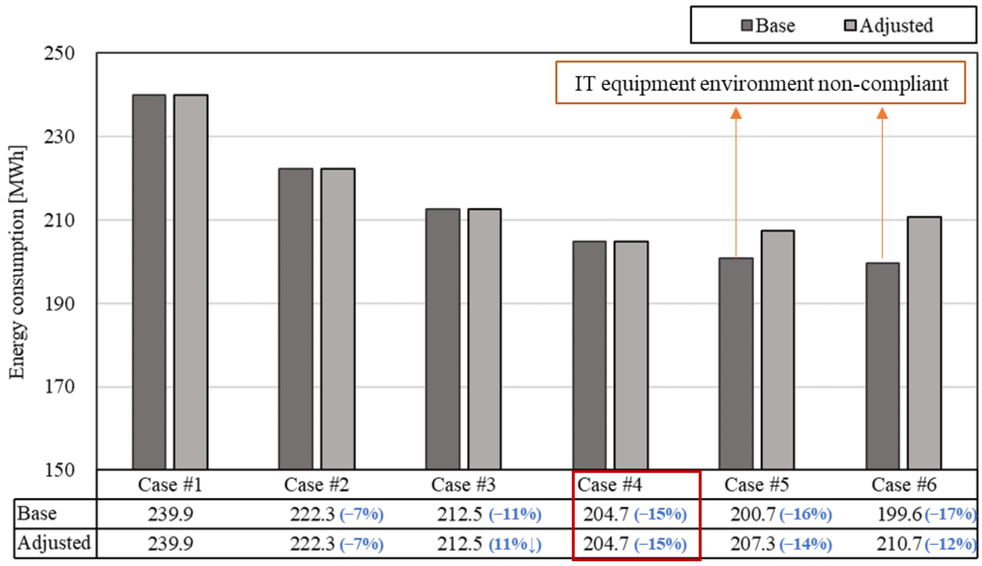
These findings suggested that data center economizer systems should apply seasonally optimized OA intake ranges based on climate conditions and external air characteristics.

3.5.2. Annual Energy Consumption

Section 3.5.2 analyzed the annual energy consumption of the design-sized cooling system (30 RT) and the adjusted systems. The total energy use included cooling, dehumidification, reheating, humidification, and supply fan operation. Figure 8 presents the annual energy consumption for each simulation case according to cooling system capacity.

The results showed that with adjusted cooling capacities, energy consumption from Case #1 to Case #6 was reduced by up to approximately 15% compared to the baseline (Case #1). A gradual decrease in energy use was observed from Case #2 to Case #5, while in Case #6, the reduction rate declined by 2.9% compared to Case #5. This decrease in efficiency was attributed to increased energy use in cooling and reheating caused by overcooling, which was necessary to meet the humidity standard at the IT equipment inlet when high-humidity air was introduced.

Based on the annual cumulative energy consumption analysis, Case #4 (5 to 14 °C) was identified as the optimal allowable OA intake dry-bulb temperature range under adjusted cooling capacities.



	Case #1	Case #2	Case #3	Case #4	Case #5	Case #6
Base	239.9	222.3 (−7%)	212.5 (−11%)	204.7 (−15%)	200.7 (−16%)	199.6 (−17%)
Adjusted	239.9	222.3 (−7%)	212.5 (11%↓)	204.7 (−15%)	207.3 (−14%)	210.7 (−12%)

Figure 8. Annual energy consumption for each case according to capacity.

4. Conclusions

This study aimed to determine the optimal OA intake dry-bulb temperature range for a data center located in Daejeon, Republic of Korea (ASHRAE Climate Zone 4A), by applying a dry-bulb temperature–based economizer system. For this purpose, simulation scenarios were established based on allowable OA temperature thresholds, and simulations were conducted after determining and applying the appropriate cooling system capacities. The analysis focused on the air condition at the IT equipment inlet and the corresponding energy consumption to evaluate system performance.

The key findings are summarized as follows:

(1) The analysis of allowable OA intake durations revealed a significant seasonal variation in OA utilization. In summer, high temperature and humidity limit the intake potential, whereas in winter and interseason periods, longer intake durations allowed for greater cooling energy savings.

(2) When the maximum OA intake dry-bulb temperature exceeded 16 °C, the baseline cooling capacity (30 RT) was insufficient to maintain the relative humidity at the IT equipment inlet within the ASHRAE TC 9.9 limits. Simulation-based adjustments revealed that cooling capacities between 30 RT and 56 RT were required depending on the case, and all scenarios satisfied the humidity criteria after adjustment.

(3) The energy consumption analysis showed that the effectiveness of OA intake varied depending on climatic conditions. In summer, the introduction of humid OA led to overcooling and subsequent reheating, resulting in increased total energy use. Conversely, during the interseason and winter periods, the economizer operation significantly reduced cooling energy consumption. The annual energy analysis confirmed energy savings in most scenarios with adjusted cooling capacities, with Case #4—defined by a 14 °C intake threshold and 30 RT capacity—achieving the greatest reduction of approximately 15%.

Based on the simulation results, Case #4 was identified as the most balanced configuration for applying a fixed year-round OA intake strategy, achieving both energy efficiency and compliance with IT equipment environmental standards. Furthermore, seasonally adjusting the OA intake dry-bulb temperature may allow for slightly higher thresholds during interseason periods. Under favorable nighttime conditions with low humidity, extending the threshold to the level defined in Case #6 appears feasible.

While increasing the cooling system capacity helped meet the humidity control requirements under expanded OA intake conditions, it inevitably results in higher capital expenditure (CAPEX). Nevertheless, this cost increase may be offset by operational expenditure (OPEX) savings enabled through extended economizer operation. Although an in-depth economic assessment was beyond the scope of this study, such trade-offs are critical for practical implementation and should be considered in future research.

For data centers located in Daejeon, South Korea (ASHRAE Climate Zone 4A), it is recommended to implement a flexible OA control strategy that reflects seasonal and annual climatic variability to maximize energy savings while maintaining a stable thermal environment for IT equipment.

The simulation model was developed in accordance with ASHRAE TC 9.9 guidelines and based on a previously validated data center model. However, following the incorporation of the economizer control strategy, no experimental or field-based validation was conducted. Therefore, future research should aim to implement the proposed control strategy in an operational data center to evaluate its real-world applicability. Additionally, several technical challenges must be addressed for practical deployment, including the optimization of sensor placement for accurately monitoring OA and IT equipment inlet conditions, integration of control logic with existing BMS platforms, and the development of real-time feedback mechanisms for dynamic OA regulation. Although these aspects were beyond the scope of this study, they are essential for practical implementation and should be explored in future work.

While the findings are based on the climatic conditions of Daejeon, South Korea, they may be extended to other regions within ASHRAE Climate Zone 4A due to shared climatic characteristics. However, climatic and operational variability across different regions, even within the same climate zone—may, influence the performance of the proposed strategy. Therefore, further comparative studies across diverse geographic contexts, including locations beyond Daejeon, are required to evaluate the robustness and generalizability of the results.

Although the proposed approach in this study was developed and validated using a small- to medium-scale data center model, the core concept—controlling OA intake based on dry-bulb temperature—can be applied to larger facilities with appropriate adjustments. However, when scaling the strategy to larger data centers, new challenges may arise, such as increased internal heat loads, more complex airflow distribution, and the need for coordinated control across multiple zones. Therefore, to assess the scalability and practical applicability of the proposed strategy, future research should involve high-fidelity simulations or pilot-scale implementations in large and multi-zone data centers.

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Abbreviations

The following abbreviations are used in this manuscript:

OA	Outdoor air
IT	Information technology
RA	Return air
SA	Supply air
EA	Exhaust air
MA	Mixed air
IWEC2	International weather for energy calculation 2.0
CRAC	Computer room air conditioner
RT	Refrigeration ton

References

1. Korea Data Center Council. *Korea Data Center Market 2023–2026*; Korea Data Center Council: Seoul, Republic of Korea, 2023.
2. Ministry of Trade, Industry and Energy. *Measures to Mitigate the Concentration of Data Centers in the Metropolitan Area*; MOTIE: Sejong, Republic of Korea, 2023.
3. Huang, J.; Chen, C.; Guo, G.; Zhang, Z.; Li, Z. A calculation model for typical data center cooling system. *J. Phys. Conf. Ser.* **2019**, *1304*, 012022. [CrossRef]
4. Lin, M.; Shao, S.; Zhang, X.S.; VanGilder, J.W.; Avelar, V.; Hu, X. Strategies for data center temperature control during a cooling system outage. *Energy Build.* **2014**, *73*, 146–152. [CrossRef]
5. Oh, S.S. *District Cooling and Heating Utilization Cases of Data Center Waste Heat and Policy Implications*; Research Report No. 19-01; Korea Energy Economics Institute: Ulsan, Republic of Korea, 2019. Available online: https://www.dbpia.co.kr/journal/articleDetail?nodeId=NODE09329676 (accessed on 15 December 2022).
6. Zhang, H.; Shao, S.; Xu, H.; Zou, H.; Tian, C. Free cooling of data centers: A review. *Renew. Sustain. Energy Rev.* **2014**, *35*, 171–182. [CrossRef]
7. ASHRAE. *Best Practices for Datacom Facility Energy Efficiency*, 2nd ed.; ASHRAE: Atlanta, GA, USA, 2009; pp. 53–66.
8. Stein, J. Waterside economizing in data centers: Design and control considerations. *ASHRAE J.* **2009**, *155*, 192.
9. Kim, J.H.; Aum, T.Y.; Jeong, C.S. Energy performance of air-side economizer system for data center considering supply temperature and design airflow rate of CRAH. *J. Archit. Inst. Korea Struct. Constr.* **2019**, *35*, 181–188.
10. Kim, Y.J.; Ha, J.W.; Lim, W.W.; Kim, H.Y.; Song, Y.H. Analysis of energy efficiency according to free cooling modes of water-side economizer system in data centers. *J. Korean Soc. Living Environ. Syst.* **2022**, *16*, 1–13.
11. Badiei, A.; Jadowski, E.; Sadati, S.; Beizaee, A.; Li, J.; Khajenoori, L.; Xiao, X. The energy-saving potential of air-side economizers in modular data centers: Analysis of opportunities and risks in different climates. *Sustainability* **2023**, *15*, 10777. [CrossRef]
12. Kim, J.H.; Shin, D.U.; Kim, H. Data center energy evaluation tool development and analysis of power usage effectiveness with different economizer types in various climate zones. *Buildings* **2024**, *14*, 299. [CrossRef]
13. Park, M.K.; Chang, H.J. A study on the regional energy conservation effects of a multi-stage OA enabled cooling system in a data center. *J. Korean Sol. Energy Soc.* **2017**, *37*, 71–80. [CrossRef]
14. Lan, J.; Zhang, Z.; Liang, X.; Wu, H.; Wang, G.; Mao, R. Experimental and numerical investigation on thermal performance of data center via fan-wall free cooling technology. *Appl. Therm. Eng.* **2023**, *228*, 120467. [CrossRef]
15. Fan, C.; Zhou, X. Model-based predictive control optimization of chiller plants with water-side economizer system. *Energy Build.* **2023**, *278*, 112633. [CrossRef]
16. Jin, Y.; Bai, X.; Xu, X.; Mi, R.; Li, Z. Climate zones for the application of water-side economizer in a data center cooling system. *Appl. Therm. Eng.* **2024**, *250*, 123450. [CrossRef]
17. Park, S.; Seo, J. Analysis of air-side economizers in terms of cooling-energy performance in a data center considering exhaust air recirculation. *Energies* **2018**, *11*, 444. [CrossRef]
18. *ANSI/ASHRAE 169-2020*; Climatic Data for Building Design Standards. ASHRAE: Peachtree Corners, GA, USA, 2021.
19. Jang, A.; Jung, D.E.; San, J.; Do, S.L. Development of a data center model for evaluating cooling energy consumption according to IT equipment heat generation. *KIEAE J.* **2023**, *23*, 23–28. [CrossRef]
20. *ANSI/ASHRAE TC 9.9-2019*; Energy Standard for Data Centers. ASHRAE: Atlanta, GA, USA, 2019.
21. U.S. Department of Energy. *EnergyPlus*, version 24.1.0; U.S. DOE: Washington, DC, USA, 2024.
22. *ANSI/ASHRAE/IES Standard 90.1-2022*; Energy Standard for Buildings Except Low-Rise Residential Buildings. ASHRAE: Atlanta, GA, USA, 2022.
23. Pacific Northwest National Laboratory. *Building Re-Tuning Training Guide: Air-Side Economizer Operation (PNNL-SA-86706)*; U.S. Department of Energy: Richland, WA, USA, 2014.

24. ASHRAE. *International Weather for Energy Calculations (IWEC2) Weather Data Files*; ASHRAE: Atlanta, GA, USA, 2012.
25. U.S. Department of Energy. *EnergyPlus Engineering Reference: The Reference to EnergyPlus Calculations*; U.S. Department of Energy: Washington, DC, USA, 2024.
26. Qu, S.; Yang, D.; Zhang, J.; Wang, Y. Real-time optimization of the liquid-cooled data center based on cold plates under different ambient temperatures and thermal loads. *Appl. Energy* **2024**, *363*, 123101. [CrossRef]
27. Chaudhry, M.T.; Chong, C.Y.; Ling, T.C.; Rasheed, S.; Kim, J. Thermal prediction models for virtualized data center servers by using thermal-profiles. *Malays. J. Comput. Sci.* **2016**, *29*, 1–14. [CrossRef]
28. Cho, J. Optimal supply air temperature with respect to data center operational stability and energy efficiency in a row-based cooling system under fault conditions. *Energy* **2024**, *288*, 129797. [CrossRef]
29. Wang, S.; Kang, Y.; Xu, Y.; Ma, C.; Wang, H.; Wu, W. Data center temperature prediction and management based on a two-stage self-healing model. *Simul. Model. Pract. Theory* **2024**, *132*, 102883.