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The Energy-Saving Potential of Air-Side Economisers in Modular Data Centres: Analysis of Opportunities and Risks in Different Climates

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Abstract: This study examines the feasibility of utilising outside air for 'free cooling' in modular data centres through the implementation of an air-side economiser, as an alternative to traditional mechanical cooling systems. The objective is to offset the energy consumption associated with cooling by leveraging the natural cooling capacity of the ambient air. To investigate this potential, a 90-kW modular data centre is employed as the base case for model validation and analysis of energy reduction possibilities. The research employs dynamic thermal modelling techniques to assess the efficacy of the air-side economiser in four distinct climatic zones: Stockholm, Dubai, San Francisco, and Singapore, representing diverse worldwide climates. The model is meticulously calibrated and validated using power usage effectiveness (PUE) values obtained from the Open Compute Project. Simulation runs are conducted to evaluate the energy-reduction potential achievable with the air-side economiser compared to conventional mechanical air-conditioning systems. The results indicate significant energy reductions of up to 86% in moderate climates, while minimal reductions are observed in dry and hot climates. This comprehensive analysis offers valuable insights into the intricate relationship between modular data centres, their operational characteristics, and the viability of employing air-side economisers for free cooling and energy efficiency across different climatic conditions. The contribution of this publication to this field of science lies in its exploration of the practicality and energy-saving potential of air-side economisers in modular data centres. By utilising dynamic thermal modelling and empirical validation, this study provides evidence-based insights into the effectiveness of this cooling strategy, shedding light on its applicability in various climates. The findings contribute to the understanding of energy-efficient cooling solutions in data-centre design and operation, paving the way for more sustainable practices in the field.

Keywords: economiser; data centre; energy; model; PUE; simulation; free cooling

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Citation: Badiei, A.; Jadowski, E.; Sadati, S.; Beizaee, A.; Li, J.; Khajenoori, L.; Nasriani, H.R.; Li, G.; Xiao, X. The Energy-Saving Potential of Air-Side Economisers in Modular Data Centres: Analysis of Opportunities and Risks in Different Climates. *Sustainability* **2023**, *15*, 10777. https://doi.org/10.3390/su151410777

Academic Editors: Andrea Nicolini and Baojie He

Received: 2 April 2023
Revised: 21 June 2023
Accepted: 26 June 2023
Published: 10 July 2023

1. Introduction

1.1. Background

The increasing rate of worldwide energy consumption in recent history has encouraged many countries to revisit their supply and demand models [1]. Among the key contributors to this rising global energy consumption, the service sector plays a substantial role—covering all of the commercial and public buildings with a wide range of HVAC systems [2]. The global energy consumption of the service sector has increased by 295 Mtoe in 2018 compared to 2000 levels; with this trend, the sector would consume a further 323 Mtoe by 2040 [3]. The development of advanced, efficient, and low-energy HVAC solutions in recent years has offered a great solution for reducing the carbon emissions associated with the service sector. The growing energy use by HVAC systems is particularly significant in developed countries. In the U.S., HVAC energy use accounts for up to 50% of building energy consumption [4]; while in China, HVAC energy use represents between 50 and 70% of the total energy consumed in buildings [5]. Issac and Vuuren [6] estimated that the energy demand associated with air conditioning will rise rapidly in the 21st century, reaching a peak of 4000 TWh in 2050 and more than 10,000 TWh by 2100. Numerous studies have predicted a similar rise in the energy demand of air conditioning [7] under future weather conditions of the U.S. [8], Switzerland [9], and Australia [10].

1.2. Data Centres: Past, Present, and Future

The prevalence of data-centre facilities is on the rise in tandem with the exponential growth of the computer technology industry. As a consequence, the energy demand associated with operating these facilities is escalating, leading to a corresponding increase in energy costs. Historically, data-centre operational expenditure has followed an upward trajectory, and this trend is expected to persist in light of growing demands [11]. The electricity consumption attributed to data-centre processes is substantial, with data centres in the United States experiencing a 36% increase in energy consumption between 2005 and 2010, accounting for approximately two percent of the country's total energy consumption [12]. More recently, in 2014, data centres in the U.S. consumed an estimated 70 billion kWh, equivalent to 1.8% of the nation's total electricity consumption [13]. Projections based on current trends suggest that U.S. data centres will consume approximately 73 billion kWh by 2020 [13]. Moreover, alongside the escalating energy demand, the concept of scalability has emerged as a prominent trend in data-centre facilities. Modular data centres, which offer the ability to rapidly expand their size and accommodate varying IT workloads, have gained traction [14]. It was projected in a 2017 article that the number of modular data centres would increase from 259 at the end of 2015 to 485 by 2020, representing 47% of all installed data-centre servers in that year [15].

Conventional data centres rely on mechanical cooling systems such as computer room air conditioners (CRAC) or computer room air handlers (CRAH) equipped with direct expansion or chilled water refrigeration mechanisms. These mechanical cooling systems consume energy to generate the necessary work for achieving the low temperatures required for cooling purposes. The concept of 'free cooling' offers an advantage by utilising the natural outdoor environment to reduce or offset the energy consumption associated with traditional mechanical cooling. Free-cooling methods can be implemented through air-side economisers or water-side economisers. The effectiveness of using outside air for free cooling depends on the outdoor air conditions being within acceptable parameters for efficiently removing heat from the data centre's indoor environment. The geographical location of a data centre plays a crucial role in determining the practicality of implementing free-cooling techniques. Since data centres operate continuously, 24/7, air-side economisers can take advantage of cooler night-time temperatures, even in regions with hot climates [16]. In a study conducted by Hassan et al. [17], the air-side economiser free-cooling strategy was examined in an 84-kW data centre located in Islamabad. The researchers specifically focused on evaluating the energy offset during the months of December, January, and February. The results indicated that when the conditions were favourable for free cooling, there was a significant reduction of approximately 95% in energy consumption. Furthermore, both Facebook and Yahoo have demonstrated the viability of operating their data centres using air-side economisers for 99% of the year [18].

Air-side economisers employ different control strategies, including fixed dry-bulb temperature, differential dry-bulb temperature, fixed enthalpy, and differential enthalpy. Given the sensitivity of critical IT equipment in data centres to humidity levels, it is essential to meet the humidity requirements for their optimal operation. Consequently, the utilisation of enthalpy control or a combination of sensors such as dry bulb, wet bulb, or humidity sensors becomes necessary to assess the suitability of the outside air for cooling purposes. These control strategies and sensor combinations help ensure that the outdoor air meets the necessary conditions before being utilised within the data-centre environment [19]. Additionally, the subsequent use of enthalpy control is beneficial, as stated by Hydeman et al. [20]: "*Differential enthalpy controls are theoretically the most energy efficient*". Enthalpy control is better suited for achieving energy savings because it can accurately eliminate the need for humidification or dehumidification. Relying solely on sensible economiser control without considering humidity levels can result in the introduction of excessively dry or humid air into the data-centre environment. This can lead to increased energy consumption due to the subsequent need for additional humidification or dehumidification processes. Conversely, the adoption of enthalpy control, which considers both temperature and humidity, for air-side economisers is comparatively more costly. This is primarily due to the calibration and complexity involved in implementing and maintaining humidity sensors, which are required for accurate enthalpy control [21]. Therefore, the selection of a suitable control algorithm for air-side economisers depends on the specific requirements and limitations of data centres in different geographical locations and climates. While air-side economisers have already been implemented in 40% of data centres utilising free-cooling technology [18], comprehensive investigations to explore their full potential in various contexts and climates are still limited.

1.3. Modelling Data Centres: Advantages, Limits, and the Gap

Upon reviewing the available literature, it becomes apparent that the utilisation of energy-simulation methods is prevalent when evaluating the potential improvements in performance for data centre air-conditioning systems. Energy-simulation techniques have been employed since the 1960s and have experienced an increased adoption over the past decade. From a practical standpoint, energy simulation offers computational efficiencies for conducting HVAC load calculations, facilitating the selection of appropriate HVAC equipment, and enabling the comparison of various design scenarios. By employing energy simulation, researchers and practitioners can gain valuable insights into the energy performance of buildings, aiding in the optimisation of data-centre air-conditioning systems [22]. Data centres can undergo cooling-system redesign as often as every 12–18 months [23]. Consequently, energy simulation holds significant importance in assessing the energy consumption of data centres and facilitating informed decision-making regarding design modifications and operational strategies. An essential aspect of energy simulation is its ability to predict the energy usage of data centres under different scenarios. However, one of the challenges associated with modelling data centres is the uneven distribution and variability of the heat load, which is typically concentrated in specific areas rather than being evenly distributed throughout the facility.

There are many variations to energy-modelling software, each with their own benefits and limitations. The U.S. Department of Energy presents an extensive list of energy-simulation software; however, the department does not formally state which software should be applied to data centres. Energy-simulation software has traditionally been applied at the commercial, residential, multi-family, and district scales with an unclear specificity on data centres [24]. Current data-centre modelling programs focus on either data-centre room airflow management or cooling-system simulation, with models designed only for limited, specific applications [25]. More specifically, energy-modelling software has been developed for data-centre simulations such as Project CoolEmAll in March 2013 commissioned by the EU—designed to be the first data-centre simulation tool using a thermal airflow simulation and coupled workload [26].

Fu et al. [27] states that in the past, previous work for cooling systems using water-side and air-side economisers has been modelled with modelling software such as eQuest, EnergyPlus, TRNSYS, or a customised energy modelling protocol (EMP) [27]. The research suggests that many simulation software programs are capable of application to data centres in some form or another; however, the understanding of the level of detail required and resources applied, respectively, will vary. Hence, a robust validation and calibration regime is required to ensure that the energy software is capable of capturing the full scale of reality in the data centres.

Sujatha and Abimannan [28] completed energy simulation to compare the energy use of water-side and air-side economisers for cities in the United States, namely Chicago, Atlanta, and Phoenix. They utilised the TRACE energy-simulation program which analysed the heat load and building features and utilised weather data. Sujatha found that for these three locations, air-side economisers reduced the energy annual energy use by an average of 47% and water-side economisers reduced the energy use by an average of 58% [28].

Gozcu et al. [29] employed energy simulation to compare the energy use of free-cooling systems: a direct air-side economiser, an indirect air-side economiser, an indirect evaporative cooler, and an indirect water-side economiser integrated with the existing cooling infrastructure of a typical 1-MW IT load data centre using the TRNSYS energy-simulation program. The indirect air-side economiser with an evaporative cooler yielded the highest annual energy savings; however, it had an increased payback compared to the other technologies analysed. The water-side economiser provided the shortest payback due to its low capital cost [29]. Lee and Chen [30] analysed seventeen climate zones through eQuest energy-simulation software, applying an air-side economiser with enthalpy control to a five-storey data centre. The energy savings ranged from +40% to −50% depending on the influence from the climate. Air-side economisation also increased fan energy consumption. Conclusively, the results showed that for every 2 °C decline in the data centre's indoor environment temperature, a subsequent 2.8–8.5% increase in energy consumption occurred [30].

Other studies by Wang et al. [31], Balaras et al. [32], Badiei et al. [33], and Akhlaghi et al. [34,35] all performed a form of modelling exercise on data centres' systems and energy consumption and validated their findings through comparison with experimental data or other models. While all these studies were successful in recording minor or extraordinary improvements in the performance of the investigated systems, most of the improvements were recorded under controlled test conditions and for a single climate condition, neglecting the impact of diverse weather conditions on the performance and energy-saving potential of air-side economisers. This study, therefore, fills the existing gap in data-centre and air-side economiser research by investigating the performance of air-side economisers for energy saving in modular data centres under four different dominant climate conditions around the world. The outside air temperature, humidity, and enthalpy were investigated in the identified climates to discover whether free cooling is viable to supplement or substitute mechanical cooling, and what level of savings can be achieved in different climates. The study presented in this paper considered a 90-kW modular data centre as a base case scenario, and empirical model validation was carried out using power usage effectiveness (PUE) values at two different locations. This research adds value by building on the knowledge base for understanding the use of air-side economisers in data centres and specifically modular data-centre applications.

The existing literature reveals a significant increase in the energy consumption and operational expenditure of data-centre facilities. With the emergence of modular data centres, the need for scalable and energy-efficient cooling solutions becomes crucial. Although air-side economisers offer the potential for free cooling, there is a lack of comprehensive investigation regarding their full potential in diverse climates. Previous studies have focused on specific applications and limited climate conditions, neglecting the impact of weather variations on air-side economiser performance [27–35]. Therefore, this study aims to bridge this gap by evaluating the energy-saving potential of air-side economisers in modular data centres across four different dominant climate conditions. The research considers outside air temperature, humidity, and enthalpy to assess the viability of free cooling as an alternative or supplement to mechanical cooling. By utilising a 90-kW modular data centre as the base case scenario and validating the models using power usage effectiveness (PUE) values, this study contributes to the understanding and application of air-side economisers in data centres, particularly in the context of modular data-centre applications.

2. Methodology

The dataset used in the study was derived from the design specifications provided by the Open Compute Project [36]. The Open Compute Project is a collaborative initiative that promotes open-source standards and practices for the construction and advancement of modular data centres. The specifications outlined by this project encompass a comprehensive all-in-one design, specifically optimised for the application of prefabricated modular data centres. These specifications cover various technical aspects of modular data centres, including environmental considerations, power supply systems, cooling systems, structural systems, and generic cabling, as well as management and control systems. The dynamic thermal model of the data centre and its systems was developed using the EnergyPlus (*e*+) software package (version 8.9.0.1) [37], which is open source, widely used, and verified. Information from the specification was reviewed and screened for alignment and insertion into the model. The inferences used were influenced and similar to the ones used by Lee and Chen [30].

In this analysis, an air-side economiser system was employed, which utilises a control mechanism based on dry-bulb temperatures. This control approach was selected due to its broad applicability and ease of operation. The operational sequence of the system was simplified to introduce outside air into the modular data centre only when the temperature of the outside air is lower than the return air temperature within the facility. The HVAC system was responsible for regulating the internal temperatures of the modular data centre to maintain them within a specified range deemed safe for the operation of the IT equipment housed within the space.

2.1. Layout and Construction Materials

The modular data centre in the study had a compact rectangular layout, designed for easy deployment (see Figure 1). Its exterior consisted of a steel frame and insulated panels, with access doors and emergency egress doors located on each side of the building. Inside, the data centre was equipped with IT equipment, such as server racks, arranged in a layout that facilitated accessibility and promoted an even airflow distribution. The dimensions of the modelled facility were based on its external measurements, resulting in a floor area of 11.88 m^2. The building was oriented to face north, with the elevation varying depending on the specific location being modelled. It was constructed above ground level and had minimal unnecessary openings, with no windows present. There was a single primary entrance and two emergency exit doors; however, for modelling purposes, the emergency exit doors were assumed to be permanently closed and thus were not considered in the analysis.

The building materials were provided by the Open Compute Project Standalone 90-kW Modular Data Centre design specifications [36]. The modelled U-values were set up accordingly to match the specified U-values. Table 1 presents the U-values for each of the specified and modelled building components.

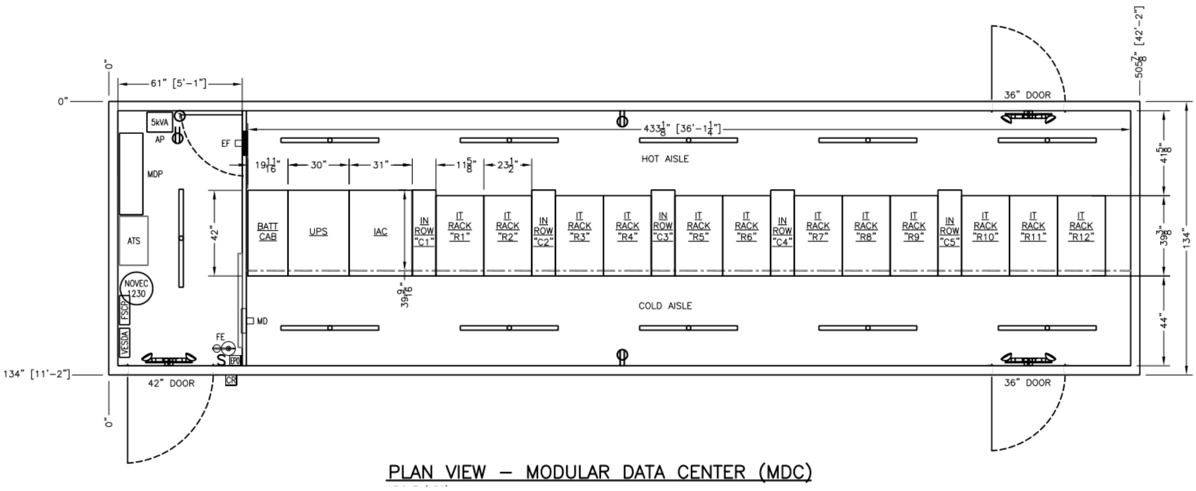

Figure 1. Geometrical layout of the modular data centre as modelled in EnergyPlus [36].

Table 1. Construction materials of the modular data centre as modelled in EnergyPlus [36].

Component	Source	Material	U-Value	Thickness
External Walls	Specified	Insulated Panel with Steel Frame 44 mm Stainless steel, R-33.6	0.470 W/m^{2}k	80–150 mm
	Modelled	Expanded Polystyrene Insulation, 40 mm Cement Plaster	0.471 W/m^{2}k	151 mm
External Door	Specified	Steel door 50 mm Stainless Steel, 6″ R-33.6	n/a	n/a
	Modelled	Expanded Polystyrene Insulation, 50 mm Stainless Steel	1.501 W/m^{2}k	117.4 mm
Flat Roof/Ceiling	Specified	Insulated Panel with Steel Frame 44 mm Stainless Steel, 6″ R-33.6	0.470 W/m^{2}k	145 mm
	Modelled	Expanded Polystyrene Insulation,40 mm Gypsum Plasterboard	0.470 W/m^{2}k	148 mm
Floor	Specified	Steel plate, with anti-static floor surface, insulating thermal barrier	n/a	n/a
	Modelled	70 mm Aerated Concrete Slab, 100 mm Cast Concrete, 100 mm Urea Formaldehyde foam	0.309 W/m^{2}k	270 mm

2.2. Modelled Locations and Weather Data

The Köppen climate classification system is widely recognised and utilised to categorise different climates based on seasonal precipitation and temperature patterns [38]. It divides climates into five main climate groups: A (tropical), B (dry), C (temporal), D (continental), and E (polar). Each group is further subdivided to designate specific subtypes based on precipitation and seasonal variations. In this study, energy simulations of the modular data centre were conducted for four distinct climatic regions, chosen based on the Köppen climate classification. The selected locations were Stockholm, Sweden (Dfb); Dubai, United Arab Emirates (BWh); San Francisco, California (Csb); and Singapore (Af). These regions were selected for two main reasons: (i) they provide a diverse representation of climate types found worldwide, and (ii) two of the chosen locations (Stockholm and Dubai) had available power usage effectiveness (PUE) values, which were used for model validation purposes. By considering these four regions, which differ in climate classification and geographical location, the study aimed to provide an unbiased and representative analysis of how energy consumption could vary across different climate zones.

The custom EnergyPlus weather files were employed based on typical weather year data from the International Weather for Energy Calculations (IWEC) [39]. Table 2 presents the average monthly dry-bulb and wet-bulb temperatures for the modelled locations. Each region additionally has its own characteristics regarding humidity, wind speed, precipitation, and daylight.

Table 2. Average monthly weather data for the modelled locations [39].

Dry Bulb (°C)	Dew Point (°C)	Relative Humidity (RH%)	Wind Speed (m/s)	Solar Radiation (kWh/m^2)	Dry Bulb (°C)	Dew Point (°C)	Relative Humidity (RH%)	Wind Speed (m/s)	Solar Radiation (kWh/m^2)
		Dubai					Stockholm		
18.0	11.9	67.5	3.0	207.0	−3.6	−4.9	90.7	4.4	17.8
19.9	11.9	59.9	3.5	222.8	−0.8	−4.0	78.9	3.5	40.8
22.2	15.5	65.8	3.9	223.6	0.3	−2.1	83.9	4.4	88.9
26.5	15.2	49.9	3.8	238.2	4.4	−2.0	63.1	3.2	167.5
30.8	17.5	45.0	4.2	285.3	11.7	4.3	60.4	3.0	223.7
32.8	20.3	47.8	4.2	278.5	14.5	8.0	65.0	3.4	199.2
34.4	22.3	49.4	3.6	268.8	17.0	11.6	70.5	3.1	198.4
34.8	22.1	47.7	3.7	267.2	16.0	10.4	69.4	3.0	148.3
32.6	23.0	57.0	3.7	249.0	11.3	8.0	80.1	2.8	98.1
28.6	18.8	55.4	3.5	244.6	6.7	4.3	84.7	3.4	65.8
24.4	18.1	67.9	3.0	212.9	1.6	−0.1	88.5	3.3	32.8
20.1	13.0	63.6	3.7	198.7	−1.9	−3.5	88.8	2.7	19.5
		Singapore					San Francisco		
26.7	23.5	82.6	3.9	155.3	9.6	6.4	80.4	3.3	113.0
27.2	23.8	81.7	3.1	152.6	11.3	6.6	72.8	3.5	142.5
27.6	24.5	83.2	1.7	164.1	12.7	8.1	73.6	4.5	192.8
28.1	24.7	81.8	1.3	162.5	13.7	8.2	69.4	5.5	222.8
28.2	25.0	82.8	1.7	159.8	15.0	9.4	69.2	5.8	248.2
28.5	24.7	79.9	2.3	148.8	15.3	10.0	70.6	5.9	269.4
27.8	24.4	81.8	2.1	160.7	15.9	10.7	71.2	5.9	278.5
27.8	24.0	79.8	2.5	149.9	16.6	11.5	71.8	5.4	257.4
27.2	24.0	82.7	1.8	150.8	16.7	12.5	76.2	5.4	229.2
27.5	24.4	83.2	1.7	150.2	15.1	9.4	68.7	4.4	178.5
26.7	24.5	87.7	1.4	136.0	12.8	8.3	74.1	3.2	128.9
26.3	23.8	86.1	2.7	141.0	10.7	6.1	73.2	3.2	129.5

2.3. Modelled Heat Loads and HVAC System

In order to simulate the heat load generated by the IT equipment within the modular data centre, a fixed radiative heat load was incorporated into the internal space of the facility. The heat load for the modular data centre was determined using the calculations outlined in Equation (1), as indicated below. The capacity and area utilised in the calculations were derived from the specifications provided by the Open Compute Project [36].

$$\begin{gathered} \text{Heat Load} = \text{Nominal Capacity}/\text{Internal Area} \\ \text{Heat Load} = 90\ \text{kW}/41.85\ \text{m}^2 \\ \text{Heat Load} = 2150\ \text{W}/\text{m}^2 \end{gathered} \tag{1}$$

The EnergyPlus model was augmented by incorporating a constant emitting radiative heat load to simulate a consistent IT load within the modular data centre. This heat load was classified as a process load and represented as a block generating heat at the centre of the data centre, as depicted in Figure 2. It is important to note that the model did not account for layout and rack configuration factors, such as the implementation of hot-aisle and cold-aisle distribution systems. Previous research has indicated that these details have a minimal influence on the outcomes of comparative studies and, therefore, they were not included in the current analysis [30].

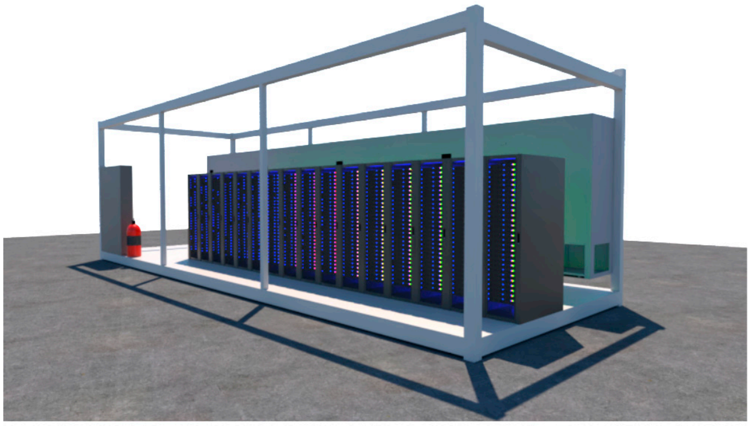

Figure 2. Block heat load representation as modelled in EnergyPlus.

It was assumed that the heat load of 2150 W/m^2 is constantly operating 24/7 and that the cooling system must always be able to meet this demand and maintain a specified operational temperature.

The HVAC system which was incorporated into the model to fulfil the cooling requirements of the data centre consisted of an air handling unit that includes a two-stage direct expansion cooling coil and a heating hot water coil supplied by a boiler. The air-distribution system incorporated a variable air volume unit with reheat coils. Furthermore, an air-side economiser configuration was included in the air handling unit to assess the impact of free cooling. The primary objective of the HVAC system within the model was to align the energy flows in a manner that effectively satisfied the cooling load demand, consistent with the specifications provided [36].

The HVAC system's operation is determined by a predefined sequence that governs its control. In this case, the sequence of operation for the HVAC system is as follows: The unit operates continuously, with a supply fan responsible for pushing air through the air handling unit and into the modular data-centre space via a variable air volume (VAV) distribution network. A return fan recirculates the air back to the supply fan. When the outside air's dry-bulb temperature falls below the return air temperature, the air-side economiser is modulated open to allow the introduction of outside air into the system. This reduces the need for mechanical cooling, thus lowering the energy consumption. A barometric relief damper is employed to release excess air pressure during the economisation mode. The cooling-temperature setpoint for the space is maintained at 24 °C dry-bulb temperature with a relative humidity range of 30–50%. It should be noted that the data-centre equipment remains the same across all climates, implying similar operational requirements, while the only variable is the climatic conditions. The space-cooling setpoint is variable and can be aligned with any of the ASHRAE TC.9.9 guidance for Thermal Guidelines within Processing Environments classes: A1, A2, A3, A4, B, and C [40,41]. The heating hot water boiler system was overridden, as heating was not required at the air handling unit's coils or VAV coils at any time. This was due to the constant process load within the space generating a substantial radiative heat.

The efficiency of the HVAC system is focused primarily on the effective use of electrical energy converting to mechanical energy used in the air handling unit fans and direct expansion cooling system. A default gross rated COP value of 3.0 is provided by the Open Compute Project specifications [36] for modelling the HVAC system. The COP is directly related to the power usage effectiveness (PUE) metric used in determining the overall efficiency of the data centre. The calculation of power usage effectiveness (PUE) involves considering the total energy usage of the facility, which is influenced by the coefficient of performance (COP) of the HVAC system. A higher COP will result in a higher PUE value. In order to focus specifically on the impact of the air-side economiser on the overall energy efficiency of the data-centre facility, the analysis can adopt a standard COP value for the HVAC system. This approach allows for the exclusion of variations arising from different HVAC systems. Furthermore, the energy consumption of the motorised actuators and sensors within the air-side economiser is accounted for as a percentage of the overall consumption (5%) in the analysis.

Given that the primary space of the modular data centre is not continuously occupied by individuals and is only temporarily utilised for purposes other than maintenance, it was assumed that there are no occupants present within the space. Consequently, the space was designated as unoccupied on a 24/7 schedule. With occupancy values set to zero, the necessity to introduce fresh outside air into the space was eliminated as well. This decision to exclude outdoor air for ventilation purposes presents a significant opportunity to decrease energy consumption that would otherwise be required to condition the incoming outside air, particularly during unfavourable conditions.

2.4. Model Validation

The model was validated through the comparison of PUE (Equation (2)) values provided through the Open Compute Project Modular Data Centre Specifications [36]. It was determined that the PUE values were derived from two companies: Swedish Modules and Schneider Electric which were involved in the development of the modular data-centre specification and established the PUE values and locations. These companies deployed and utilised modular data centres in two sites located in Stockholm and Dubai where metered energy-consumption data were used to derive real-life and empirical PUE values. Singapore and San Francisco were not provided with PUE values for validation; however, they were included in this study for a representation of different climate types. Hence, the model was validated and calibrated using PUE values for Stockholm and Dubai, and the validated model was utilised to derive realistic simulation results for the other two locations.

$$\mathrm{PUE} = \frac{\text{IT Load}}{\text{Total Data Facility Load}} \tag{2}$$

Dubai and Stockholm had PUE values of 1.5 and 1.54, respectively. Considering that variations of the cooling system were being explored, this study focused on validating the energy flows in and out of the modular data centre as accurately as possible to demonstrate the effects of an air-side economiser.

3. Simulation Results and Analysis

3.1. Empirical Model Validation: Comparison of the Dynamic Thermal Model Results with Real-Life Data

The models were validated through comparison with the real-time PUE values provided by the Open Compute Project [36]. The PUE values obtained for Dubai (1.5) and Stockholm (1.54) were sourced from the Open Compute Project, specifically from modular data-centre facilities that did not utilise air-side economisers in these locations. In order to evaluate the energy efficiency of the Singapore and San Francisco data centres, a reference PUE value of 1.5 was employed, ensuring that their PUE values fell within a 10% range of the suggested benchmark. The choice of reference PUE values was primarily based on their accessibility as comparative metrics for validating the model's performance in the context of Singapore and San Francisco. Table 3 summarises the key monthly parameters used to derive the simulated PUEs, including the process and overall electricity consumption of the modelled data centres in the identified locations.

As seen in Table 3, the average annual PUE values simulated for Dubai, Stockholm, Singapore, and San Francisco showed a divergence from reference values of 2%, 9%, 6.3%, and 6.3%, respectively. While all divergences were within the set margin of 10%, the difference between the two validated locations is greater in Stockholm than in Dubai. This observation can be attributed to the relatively stable PUE value maintained by Stockholm throughout the year, in contrast to the fluctuating PUE of Dubai during the summer and winter seasons. The difference in PUE patterns suggests a potential calibration error in the

Stockholm data, which, with further fine-tuning, could be adjusted to align more accurately with the reported PUE value of 1.54.

Table 3. Key monthly parameters to validate simulated PUE values in identified locations with empirical data from the Open Compute Project [36].

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Simulated Dubai PUE Validation												
Simulated Process Energy (kWh)	62,958	56,865	62,958	60,927	62,958	60,927	62,958	62,958	60,927	62,958	60,927	62,958
Simulated Electricity (kWh)	89,133	81,067	90,418	89,208	94,451	92,517	96,653	96,869	92,388	93,235	88,248	89,612
Simulated PUE (kWh)	1.42	1.43	1.44	1.46	1.50	1.52	1.54	1.54	1.52	1.48	1.45	1.42
Simulated Average PUE	1.48	-	-	-	-	-	-	-	-	-	-	-
% Divergence from Empirical PUE	2%	-	-	-	-	-	-	-	-	-	-	-
Simulated Stockholm PUE Validation												
Simulated Process Energy (kWh)	62,958	56,865	62,958	60,927	62,958	60,927	62,958	62,958	60,927	62,958	60,927	62,958
Simulated Electricity (kWh)	87,676	79,298	87,850	85,261	88,571	85,917	88,965	88,718	85,485	88,120	85,058	87,723
Simulated PUE (kWh)	1.39	1.39	1.40	1.40	1.41	1.41	1.41	1.41	1.40	1.40	1.40	1.39
Simulated Average PUE	1.40	-	-	-	-	-	-	-	-	-	-	-
% Divergence from Empirical PUE	9.0%	-	-	-	-	-	-	-	-	-	-	-
Simulated Singapore PUE Reference Validation												
Simulated Process Energy (kWh)	62,958	56,865	62,958	60,927	62,958	60,927	62,958	62,958	60,927	62,958	60,927	62,958
Simulated Electricity (kWh)	92,135	83,462	92,592	89,829	92,905	90,006	92,692	92,656	89,377	92,515	89,150	91,921
Simulated PUE (kWh)	1.46	1.47	1.47	1.47	1.48	1.48	1.47	1.47	1.47	1.47	1.46	1.46
Simulated Average PUE	1.41	-	-	-	-	-	-	-	-	-	-	-
% Divergence from Empirical PUE	6.3%	-	-	-	-	-	-	-	-	-	-	-
Simulated San Francisco PUE Reference Validation												
Simulated Process Energy (kWh)	62,958	56,865	62,958	60,927	62,958	60,927	62,958	62,958	60,927	62,958	60,927	62,958
Simulated Electricity (kWh)	88,215	79,756	88,376	85,596	88,595	85,828	88,613	88,786	85,896	88,555	85,515	88,247
Simulated PUE (kWh)	1.40	1.40	1.40	1.40	1.41	1.41	1.41	1.41	1.41	1.41	1.40	1.40
Simulated Average PUE	1.41	-	-	-	-	-	-	-	-	-	-	-
% Divergence from Empirical PUE	6.3%	-	-	-	-	-	-	-	-	-	-	-

3.2. Simulation Results for Each Location

The selected simulation locations consisted of Stockholm, Sweden (Dfb); Dubai, United Arab Emirates (BWh); San Francisco, California (Csb); and Singapore (Af), based on their respective climatic classifications. Each location's simulation model incorporated the same mechanical system and input parameters, with the sole variation being the climatic conditions. Figure 3 illustrates the average monthly dry-bulb temperature for the four locations throughout a one-year period.

The maximum and minimum design conditions of each location have a significant impact on the operation of the air-side economiser for free cooling, thereby influencing the outcomes of the simulation. Climates with outdoor air temperatures consistently below the activation threshold of 24 °C for free cooling are expected to achieve a greater energy reduction compared to those with ambient conditions above this temperature, as they can effectively leverage the benefits of free cooling. Figure 3 illustrates the variations in outdoor air temperature throughout the year for each location. It is evident from the graph that Singapore and San Francisco exhibit minimal temperature fluctuations, while Stockholm and Dubai display a curved pattern with peak temperatures in the summer and lower temperatures in the winter months.

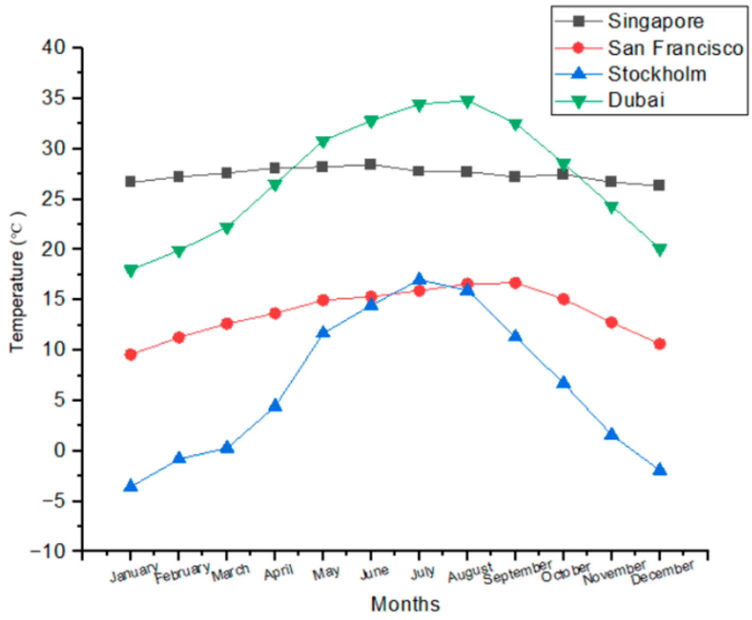

Figure 3. Outdoor air temperatures as modelled in DesignBuilder for different locations.

3.2.1. Singapore

The first location examined is Singapore (climate zone: Af). This location has a primarily tropical climate. Figure 4 displays the Singapore hourly ambient temperature, depicting the daily fluctuating temperatures for the climate zone. This provides a detailed visualisation of the minimum and maximum peak temperatures for Singapore.

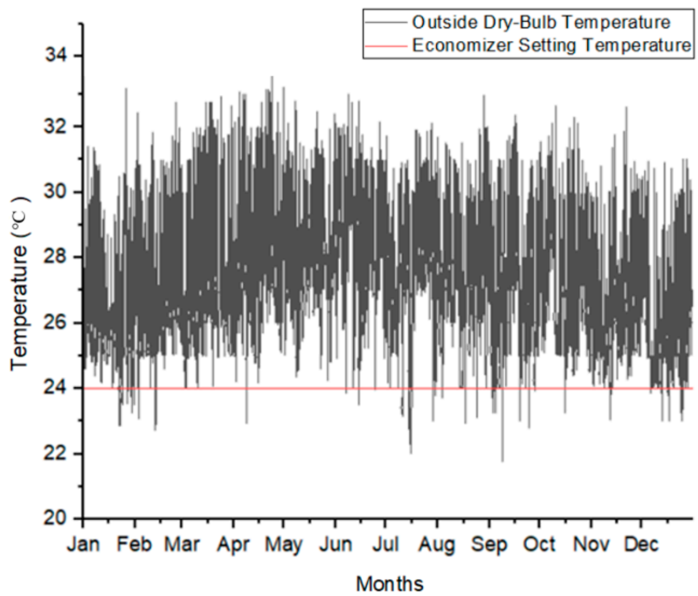

Figure 4. Singapore hourly ambient temperature.

Figure 5 presents the cumulative distribution of hours throughout the year in which the ambient temperature falls within a specific temperature range. It illustrates the percentage of the total 8760 h per year that the ambient temperature remains within each specified range. The graph reveals that the majority of the ambient temperature, throughout the year, resides within the range of 25 °C to 30 °C. This temperature range does not align effectively with the 24 °C threshold required for economiser operation, indicating limited opportunities for utilising the economiser during these hours.

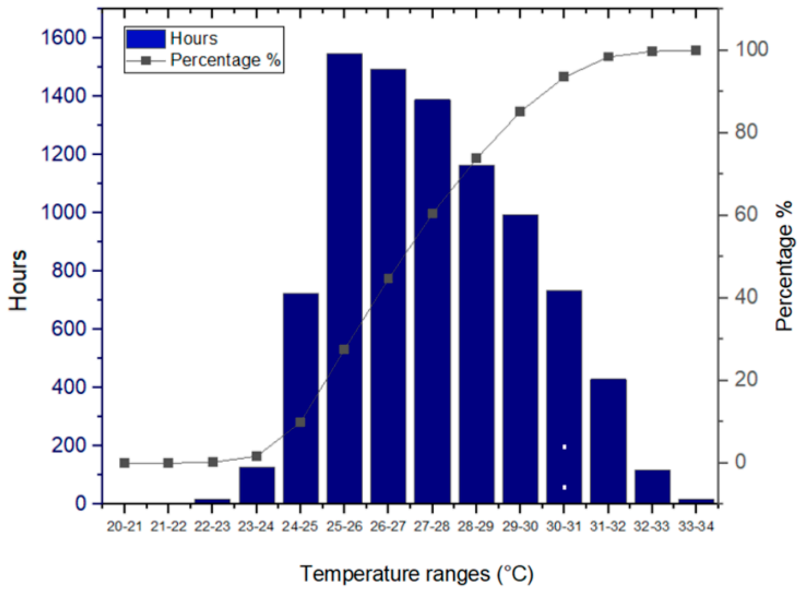

Figure 5. Singapore frequency of ambient air temperature.

The modelled data presented in Figure 6 depict the relationship between the fluctuating outdoor air temperature, the free-cooling setpoint, and the total cooling energy required for the facility under both scenarios with and without an economiser.

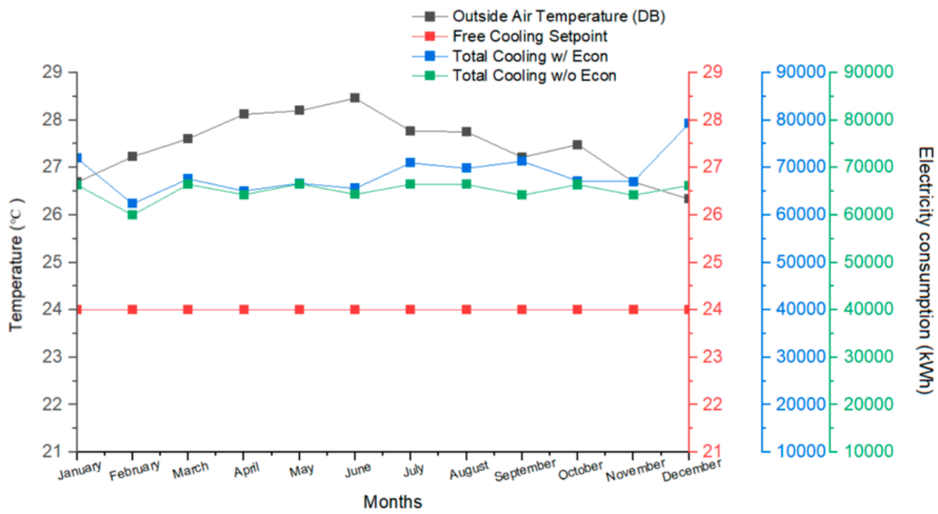

Figure 6. Singapore outdoor air temperature electricity impact (economiser vs. no economiser).

As depicted in Figures 4–6, the outdoor temperature in Singapore remains consistently above the threshold required for free cooling, preventing the economiser system from operating. Consequently, the facility continuously relies on mechanical cooling to meet its cooling demands. Since the economiser system is never engaged, the energy consumption with and without the economiser should theoretically be equal. However, it is important to note that the ventilation rate for the system without an economiser is slightly reduced, resulting in a slight reduction in the cooling energy required, as illustrated in Figure 6.

3.2.2. San Francisco

The second location analysed is San Francisco, California, classified as a Csb climate zone. This region is characterised by temperate temperatures. Figure 7 presents the hourly ambient temperature in San Francisco, illustrating the daily variations in temperature within the climate zone. This graph offers a comprehensive depiction of the lowest and highest temperatures experienced in San Francisco.

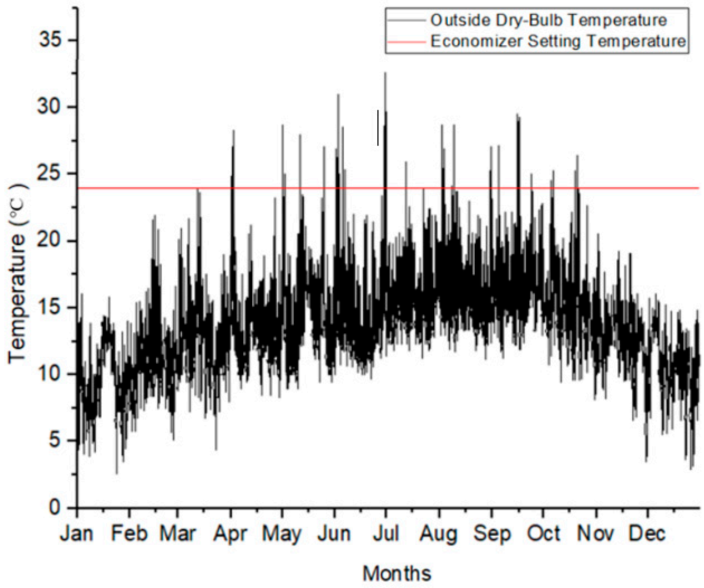

Figure 7. San Francisco hourly ambient temperature.

Figure 8 illustrates the cumulative hours throughout the year during which the ambient temperature falls within a specific temperature range. This graph provides insight into the distribution of the 8760 annual hours in relation to temperature ranges. It is evident that the majority of the ambient temperature in San Francisco lies within the 9 °C to 18 °C range throughout the year. This temperature range is conducive to the operation of an economiser system with a threshold set at 24 °C.

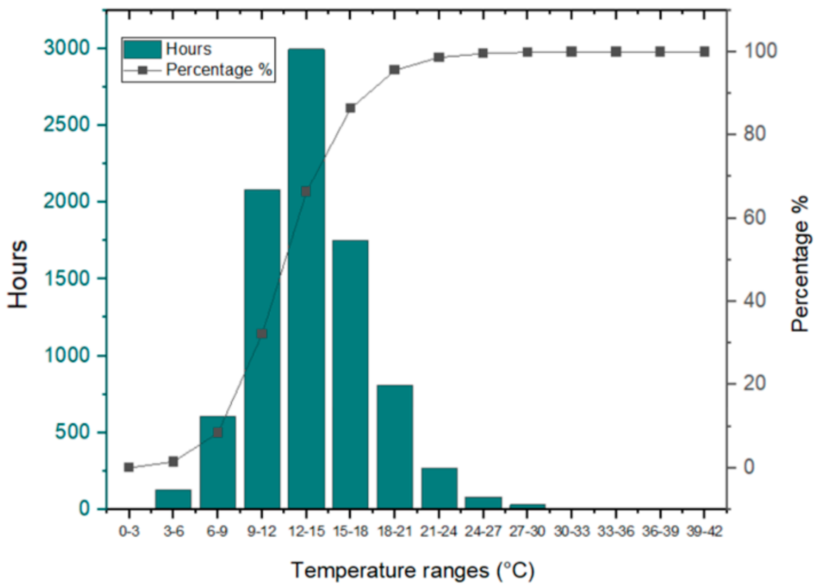

Figure 8. San Francisco frequency of ambient air temperature.

The modelled data presented in Figure 9 depict the relationship between the fluctuating outdoor air temperature, the free-cooling setpoint, and the total cooling energy required for the facility under both scenarios with and without an economiser.

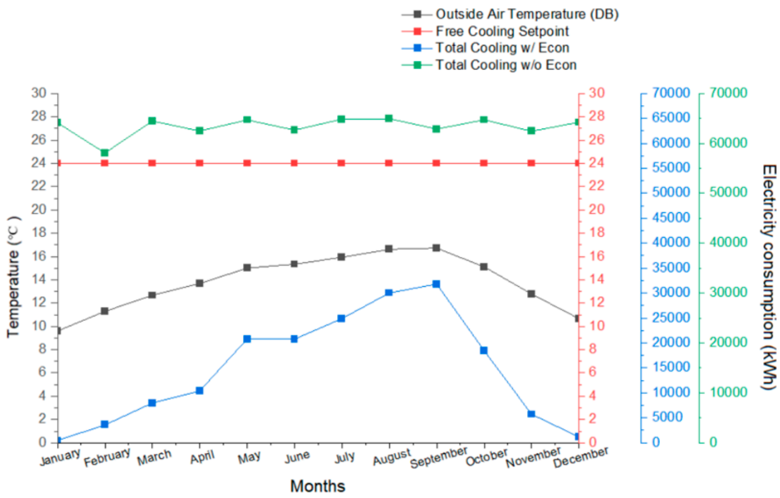

Figure 9. San Francisco outdoor air temperature electricity impact (economiser vs. no economiser).

As evidenced by Figures 7–9, the outdoor temperature in San Francisco remains consistently below the free-cooling setpoint throughout the entire year, allowing for continuous utilisation of the economiser system. Consequently, the economiser system can take advantage of 'free cooling' at all times. A comparison between the simulated system without the economiser and the system with the economiser reveals that energy consumption would be consistently higher in the former, as there is no opportunity to utilise any free cooling, despite its continuous availability. Mechanical cooling would be required throughout the year in the absence of the economiser system. Figure 9 clearly demonstrates that the total cooling energy with the economiser is significantly lower than that without the economiser. The total cooling energy with the economiser follows the trend of the outside air temperature, with increased energy use during the summer when less free cooling is available and decreased energy use during the winter when more free cooling is accessible.

3.2.3. Stockholm

The third location examined is Stockholm, Sweden (climate zone: Dfb). This location has a primarily continental climate. Figure 10 displays the Stockholm hourly ambient temperature, depicting the daily fluctuating temperatures for the climate zone. This provides a detailed visualisation of the minimum and maximum peak temperatures for Stockholm.

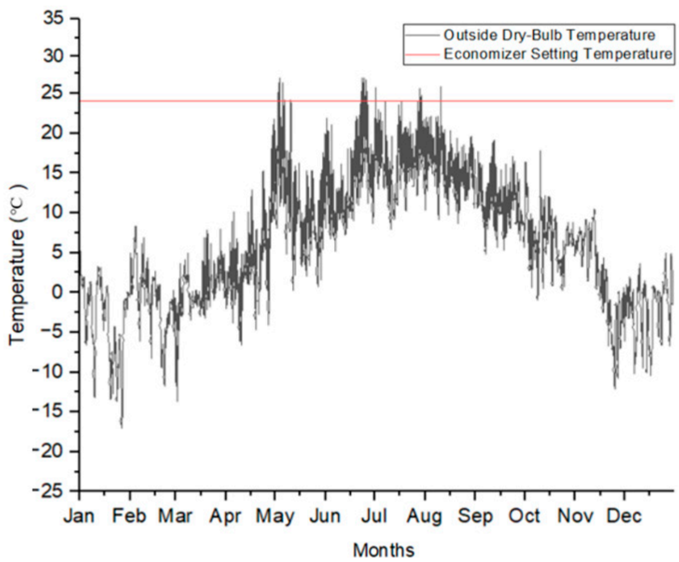

Figure 10. Stockholm hourly ambient temperature.

Figure 11 presents the cumulative hours throughout the year during which the ambient temperature falls within a specified temperature range. This graph provides insights into the distribution of the 8760 annual hours in relation to specific temperature intervals. It is evident that a significant portion of the ambient temperature in the examined location lies within the range of −4 °C to 16 °C throughout the year. This temperature range allows for the activation of an economiser system at a 24 °C threshold.

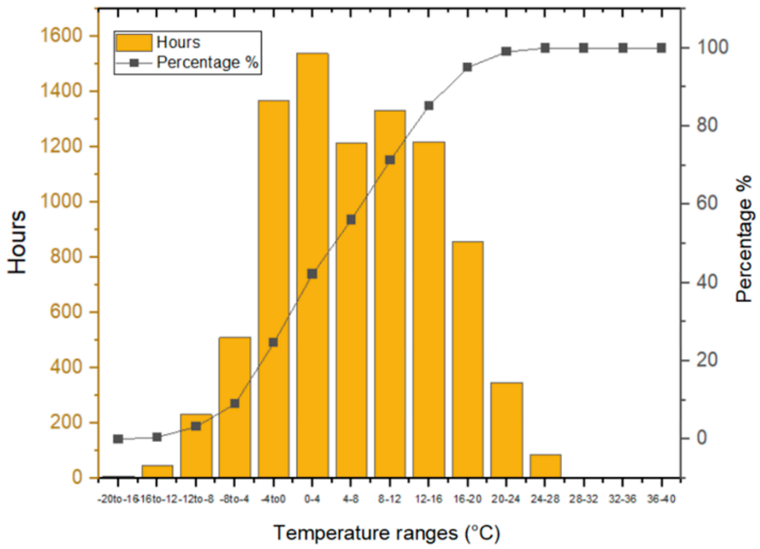

Figure 11. Stockholm frequency of ambient air temperature.

As depicted in Figures 10–12, the outdoor temperature in Stockholm remains consistently below the free-cooling setpoint throughout the entire year, allowing for continuous utilisation of the economiser system for 'free cooling'. Comparing the simulation results of the system with and without the economiser system reveals that the energy consumption would be consistently higher without the option to harness free cooling, as mechanical cooling would be constantly required. Consequently, the graph demonstrates that the total cooling energy with the economiser system is significantly lower than the total cooling energy without the economiser system. The trend of the total cooling energy with the economiser follows the pattern of the outside air temperature, with increased energy use during the summer when the availability of free cooling is reduced and decreased energy use during the winter when more free cooling is accessible.

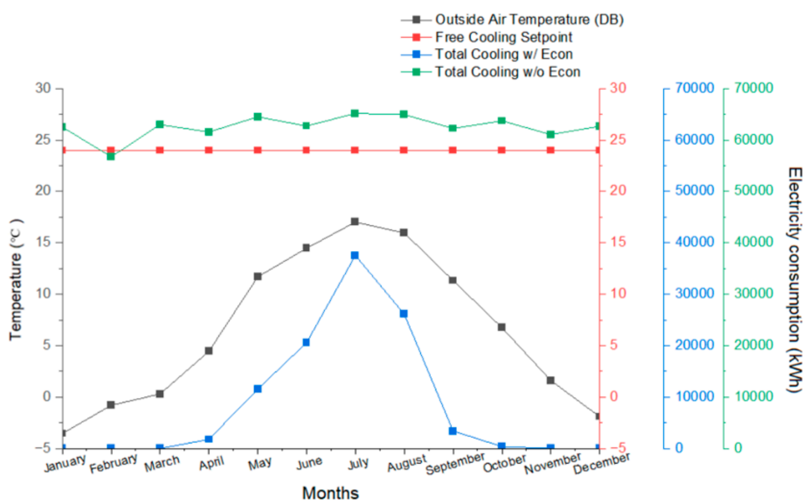

Figure 12. Stockholm outdoor air temperature electricity impact (economiser vs. no economiser).

The modelled data presented in Figure 12 depict the relationship between the fluctuating outdoor air temperature, the free-cooling setpoint, and the total cooling energy required for the facility under both scenarios with and without an economiser.

3.2.4. Dubai

The fourth location examined is Dubai, United Arab Emirates (climate zone: Bwh). This location has a primarily dry climate. Figure 13 displays the Dubai hourly ambient temperature, depicting the daily fluctuating temperatures for the climate zone. This provides a detailed visualisation of the minimum and maximum peak temperatures for Dubai.

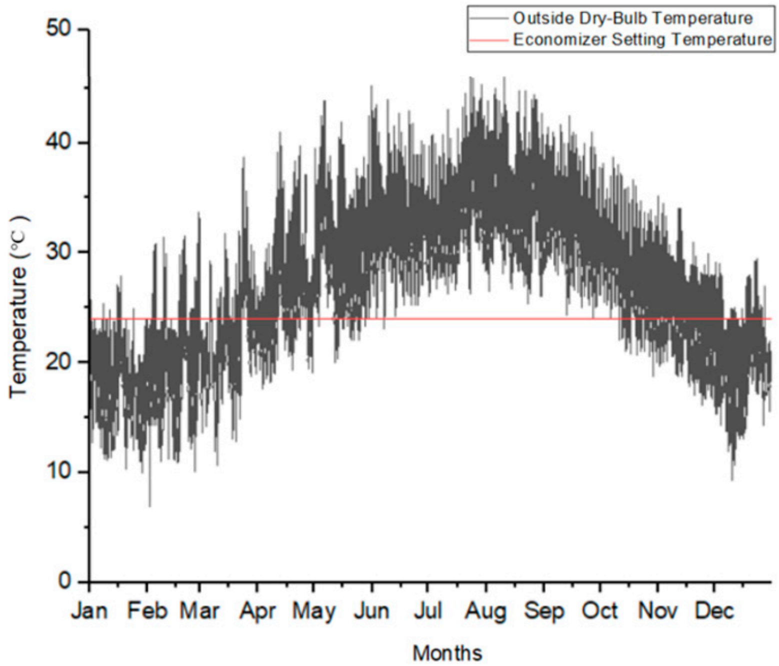

Figure 13. Dubai hourly ambient temperature.

The cumulative hours throughout the year during which the ambient temperature falls within a specific temperature range are presented in Figure 14. This graph illustrates the number of hours out of the total 8760 h per year in which the ambient temperature remains within a designated temperature range. It is evident that the majority of the ambient temperature fluctuates between 17 °C and 38 °C throughout the year, which renders the utilisation of an economiser at a 24 °C threshold ineffective for a significant portion of the time. Additionally, there is a daily variation of approximately 20 °C in the ambient temperature, indicating that an economiser system would continuously open and close, necessitating adaptive control to optimise its operation.

The modelled data presented in Figure 15 depict the relationship between the fluctuating outdoor air temperature, the free-cooling setpoint, and the total cooling energy required for the facility under both scenarios with and without an economiser.

As depicted in Figures 13–15, the average outdoor temperature in Dubai remains below the free-cooling setpoint during the months of November to March, while it exceeds the setpoint from April to October. The graph provides insight into the behaviour of the total cooling energy with the economiser system, particularly during the months of January to March, where it aligns with the curve of the outdoor air temperature until it begins to intersect the free-cooling setpoint. Notably, the outside air temperature reaches its peak in June, July, and August, during which the total cooling energy with an economiser decreases, likely due to the consistent elevation above the free-cooling setpoint. The reverse pattern occurs again when the outside air temperature falls below the free-cooling setpoint in November and December.

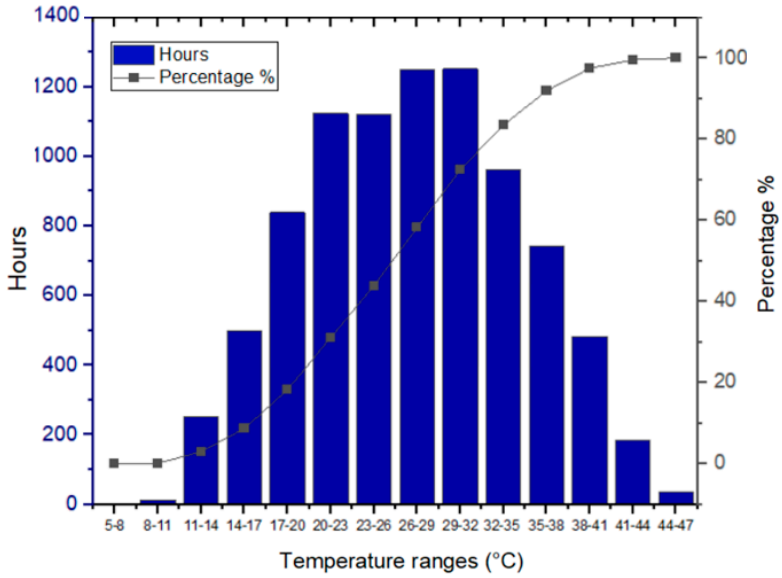

Figure 14. Dubai frequency of ambient air temperature.

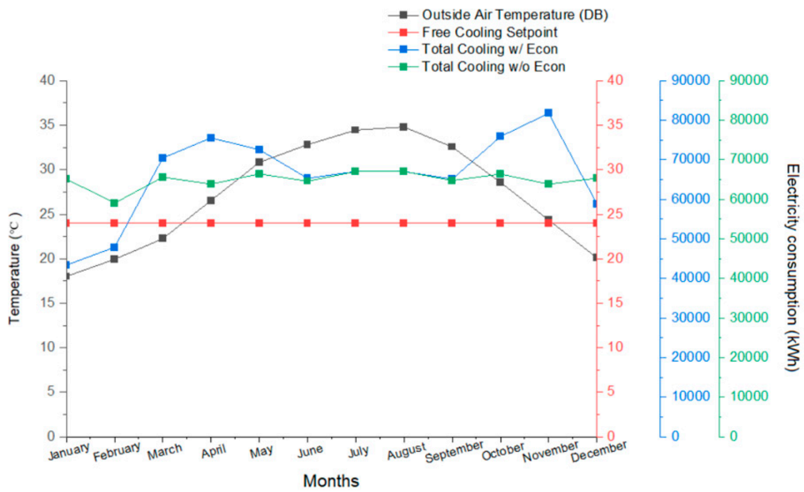

Figure 15. Dubai outdoor air temperature electricity impact (economiser vs. no economiser).

The system without an economiser exhibits a total cooling energy which maintains a relatively consistent flat line throughout the entire year, not being influenced by the energy savings provided from the economiser. An analysis of the total cooling energy with and without an economiser determines that the economiser system utilises 2% more cooling energy than the system without an economiser.

3.3. Analysis of Simulation Results Exploring Energy Saving Potentials for Each Location

The electricity consumption for cooling in the four modelled locations exhibited variations based on the specific climatic conditions they experienced. This metric accounts for the electricity utilised to satisfy the cooling load, encompassing fan energy. It is important to note that this measure differs from the cooling energy required to meet the actual cooling demand.

When comparing the electricity consumption of each location, as illustrated in Figure 16, it becomes evident that both San Francisco and Stockholm experienced significant reductions. San Francisco exhibited a reduction of 76%, while Stockholm achieved a remarkable reduction of 86%.

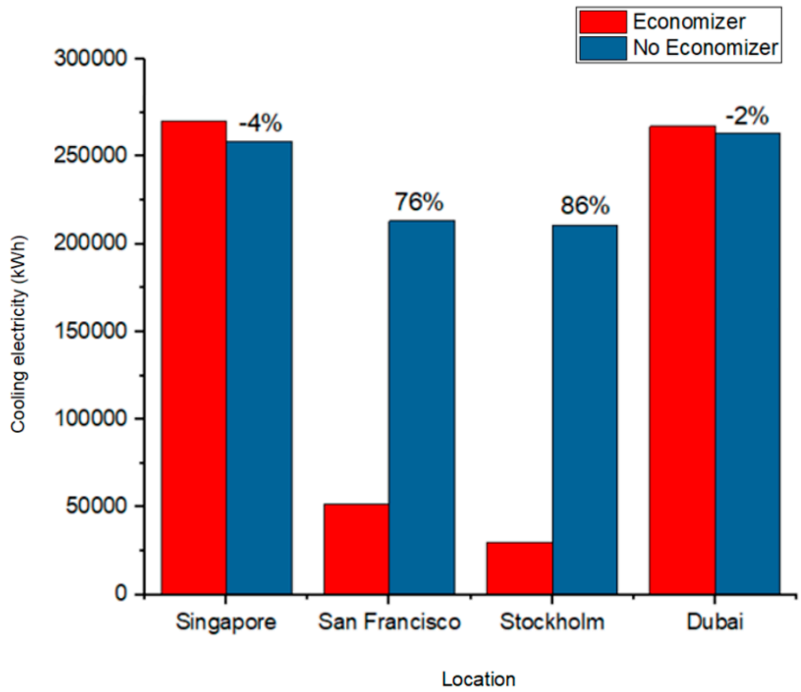

Figure 16. Total annual electricity use for modelled locations (economiser vs. no economiser).

Dubai and Singapore emerged as outlier locations, displaying nearly equal electricity consumption in both economiser and non-economiser scenarios. Surprisingly, the economiser system performed slightly worse in these locations, with a 2% increase in Dubai and a 4% increase in Singapore. The rise in energy consumption while using the economiser system can be attributed to the heightened fan energy demand of the mechanical system, along with an increased requirement for cooling energy.

4. Discussion

In the past, free cooling using economisers has been restricted because the environmental demands of the system were so stringent that the introduction of outside air was not acceptable to meet these conditions; however, in recent years, the ASHRAE TC.9.9 [41] released guidance allowing for the utilisation of the previously unacceptable air within data centres. This new guidance opens the window to air-side economisers being applied to data centres and achieving substantial energy savings.

The initial literature review encompassed a broad range of studies, revealing diverse values for energy reduction achieved through the utilisation of air-side economisers. This wide variation can be attributed to differences in methodology and climatic conditions among the reviewed studies. Consequently, predicting energy savings becomes challenging due to the distinctive dynamics of each facility. However, it is evident that the model used in this thesis, specifically for the 90-kW modular data centre, deviated from the literature review findings. While the literature review suggested energy savings in the range of 15−30% for moderate climates with free cooling below 24 °C, the modelled results demonstrated more substantial reductions. Specifically, the model predicted energy reductions of 86% for Stockholm and 76% for San Francisco when employing air-side economisers.

In similar research, Lee and Chen [30] presented the analysis of the energy potential of air-side free cooling for data centres in worldwide climate zones. The research analysed seventeen climate zones through eQuest energy-simulation software, applying an air-side economiser with enthalpy control to a five-storey data centre. The energy savings ranged from 40% to 50% depending on the influence from the climate. The energy savings in moderate climates were the most fruitful. Air-side economisation also increased fan energy consumption. Conclusively, the results showed that for every 2 °C decline in the data centre's indoor environment temperature, a subsequent 2.8–8.5% increase in energy consumption occurred [30]. In a comparison between the research conducted by Lee and Chen [30] and the research conducted in this study, there are alignments in that both of the results exhibited a significant impact from the local climatic conditions—with moderate climates being much more fruitful in energy reduction than dry or humid climates.

It was expected that the four locations examined in this study would yield different outcomes. The simulation model for Dubai and Singapore did not show significant energy savings, mainly due to the high outdoor ambient temperatures experienced in these regions. The chosen economiser control strategy in the model was based on differential dry-bulb control, as opposed to enthalpy control. Although enthalpy control could have been considered for analysis purposes, it was not included due to research suggesting that it may be less accurate and could potentially reduce energy savings further. Moreover, employing an enthalpy control system would introduce the need for humidification or dehumidification, which could have a significant impact on energy consumption [19].

The increased temperature and humidity operational zone for IT equipment provided within the ASHRAE TC.9.9 guidance [41] suggests that if the density of IT equipment was not a factor in heat generating equipment that through proper design the use of outside air for 100% of the cooling needs would become potentially possible through the entire year in almost all climates except for humid and tropical zones. A number of trade-off factors can improve the financial case for air-side economisers as well, such as local electricity prices for use and demand rates, allowing for the offset of high humidification and dehumidification costs. Furthermore, incentives on the use of specific cooling technologies or renewable energy systems integrated within a data centre can improve the financial case.

The influence of local climate on the power usage effectiveness (PUE) of data centres can have a significant impact and pose challenges when comparing data centres located in different climate zones. It is essential to consider how outdoor conditions affect energy consumption from a holistic systems perspective. The comparative analysis conducted among Dubai, San Francisco, Stockholm, and Singapore revealed that the hot climates of Dubai and Singapore exhibited a higher baseline energy consumption (without an economiser) compared to San Francisco and Stockholm. This disparity can be attributed to the impact of outdoor ambient temperatures on the building envelope and the associated radiative heat loss through the facility walls. Given the substantial energy savings achieved through the utilisation of free cooling, organisations are increasingly interested in constructing new data-centre facilities in climates that are conducive to air-side economisers and free-cooling conditions.

5. Conclusions

The most important conclusion is that the introduction of outside air through air-side economisers in data centres can lead to substantial energy savings. The ASHRAE TC.9.9 guidance has allowed for the utilisation of previously unacceptable air within data centres, thereby opening the possibility of applying air-side economisers and achieving significant reductions in energy consumption. The universal conclusion is that the impact of the local climate on data-centre energy consumption is significant. Different climate zones have varying effects on energy usage, with moderate climates being more conducive to energy reduction through the implementation of air-side economisers. However, hot and humid climates such as Dubai and Singapore may not demonstrate substantial energy savings due to high outdoor ambient temperature conditions. The choice of economiser control strategy, such as differential dry-bulb control versus enthalpy control, can also influence energy savings. Moreover, the ASHRAE TC.9.9 guidance suggests that, with proper design considerations and increased operational zones for IT equipment temperature and humidity, outside air could potentially fulfil 100% of the cooling needs throughout the year in most climates except for humid and tropical zones. Additional factors such as local electricity prices, demand rates, and incentives for specific cooling technologies or renewable energy systems can further enhance the financial case for air-side economisers.

Overall, companies are seeking to construct new data centres in climates that are conducive to air-side economisers and free cooling conditions, considering the substantial energy savings achieved through the utilization of outside air.

Similar to the majority of modelling works in this field, this study has a number of limitations which impacted the outcomes of the simulations; hence, it is important to understand their implications. The validation of the model was performed solely using empirical PUE values, which ensured the reliability of the simulated system operation. The availability of more billing data and further building physics-related details such as heat-loss parameters and the infiltration rate of the data-centre fabric would have enabled further tuning of the model and hence development of more accurate results on all fronts. In addition, the study could be further expanded to include a wider range of data centres based on the current and future climates of the regions which are the most likely to host the highest number of data centres in the future.

Author Contributions: Conceptualisation, A.B. (Ali Badiei) and E.J.; formal analysis, A.B. (Ali Badiei) and E.J.; investigation, A.B. (Ali Badiei), E.J. and J.L.; methodology, A.B. (Ali Badiei) and E.J.; project administration, S.S., A.B. (Arash Beizaee), J.L., L.K., H.R.N., G.L. and X.X.; resources, A.B. (Ali Badiei), S.S., J.L. and X.X.; software, A.B. (Ali Badiei) and E.J.; supervision, A.B. (Ali Badiei); validation, A.B. (Ali Badiei) and E.J.; visualisation, E.J. and S.S.; writing—original draft, A.B. (Ali Badiei) and E.J.; writing—review and editing, A.B. (Ali Badiei), S.S., A.B. (Arash Beizaee), J.L., L.K., H.R.N., G.L. and X.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: This research has received administrative support from the ECO-I North–West project which has been set up to deliver low-carbon innovation and skills development and boost green economic growth. Eco-I North–West has delivered low-carbon innovation to all sectors, focusing on the thematic areas of Environmental Industries; Technology and Services; Future Energy Systems; Advanced Manufacturing; and Materials and Chemistry.

Conflicts of Interest: The authors declare no conflict of interest.

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