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Energy and economic assessment of major free cooling retrofits for data centers in Turkey

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Abstract: Mechanical cooling is responsible for a significant fraction of the energy consumption of data centers (DCs). Free cooling systems take advantage of ambient conditions to reduce the need for compressor-based cooling. This study utilizes thermodynamic models of major free cooling systems such as the direct air-side economizer (ASE), indirect air-side economizer (IASE), indirect evaporative cooler (IEC), and indirect water-side economizer (WSE) integrated with the existing cooling infrastructure of a typical 1 MW IT load DC. Proposed models utilize hourly weather data of various cities in Turkey to compute annual energy consumption and cost-saving potentials of each free cooling method with respect to the baseline DC with both open aisle (OA) and enclosed aisle (EA). Results confirm the energy-saving potential by IEC leading to less than 10% of annual chiller hours across Turkey and less than 1% in half of the ten cities studied, especially in EA DCs. However, despite greater energy-saving potential, IEC has more extended payback periods of 1.5 to 3.7 years due to the high capital investment compared with those of ASE and WSE with less than 1.4 years.

Key words: Data centers, Turkey, free cooling, economizer, thermodynamic modeling, cooling infrastructure

1. Introduction

Data centers (DCs) are indispensable in today's world, where information technology (IT) is at the center of people's lives. Power usage effectiveness (PUE) is the most common energy efficiency metric for DCs, which is the ratio of the annual energy consumption of the DC facility (P_{DC}) to that of the IT equipment (P_{IT}).[1] Recent reports indicate a shift towards hyperscale cloud DCs with high-efficiency infrastructure and an average PUE of about 1.2 [1]. However, smaller DCs are responsible for almost 80% of DC energy use with average PUE values ranging from 1.7 to 2.5 [1]. Reports on in-house DCs constituting close to 80% of the installed capacity[2] roughly confirm the validity of these numbers for Turkey. Since the cooling energy used can be as much as 50% of that of IT equipment, there is a significant potential for energy savings through more efficient cooling, which is relevant for the Turkish DC sector with an annual growth rate higher than 30%.[2] [3]

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[1]Belady C, Rawson A, Pfleuger D, Cader T. Green Grid Data Center Power Efficiency Metrics: PUE and DCiE, White Paper 6, The Green Grid, 2008.
[2]Data Center Dynamics (2011). DCD Industry Census 2011 [online]. Website http://archive.datacenterdynamics.com/white-papers/2011/11/dcd-global-census-market-growth-figures
[3]Data Center Dynamics (2013). DCD Intelligence: 2013 Census Report, Global Data Center Power 2013 [online]. Website https://www.datacenterdynamics.com/news/dcd-industry-census-2013-data-center-power/

Free cooling/economization methods are becoming an essential component of the DC cooling infrastructure since they reduce or eliminate the need for mechanical cooling. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) publish thermal guidelines for IT equipment [2]. The maximum and minimum recommended temperatures for IT equipment are 27 °C and 18 °C [2]. The upper limit for humidity is 60% relative humidity and 15 °C dew point (DP) temperature, and the lower limit is –9 °C DP temperature.

Figure 1a provides a schematic view of a conventional baseline (BL) DC coupled with a cooling plant that consists of a water-cooled chiller with a cooling tower (CT) on the condenser side. Server racks form hot and cold aisles in conventional DCs. Perforated tiles in the cold aisle allow cold air from the plenum into the cold aisle, where cold air mixes with some hot air recirculated from the hot aisle before entering various servers. The cold air heats up flowing through servers and ends up in the hot aisle. Computer room air handling (CRAH) units have filters to reduce the particles in the room air, cross-flow heat exchangers to cool the warm room air by rejecting its heat to the chilled water supplied by the chiller plant, and fans to feed cold air into the plenum.

Figures 1b–1d include the schematics of four free cooling methods retrofitted into the BL DC. The most widely used method for free cooling in DCs is the direct air-side economizer (ASE)[4] (Figure 1b), which supplies the ambient air into DC when ambient conditions permit. However, there is a risk of exposing the IT equipment to contaminants and a need for advanced filtering [3], which translates into an increase in fan energy consumption. Intake of cold and dry ambient air in winter creates the need for humidification.

An indirect air-side economizer (IASE) consists of an air-to-air heat exchanger (HX) to reject heat from the DC return air to ambient when outside conditions permit (Figure 1c), which is limited by the thermal effectiveness of the HX. The IASE HX sets a physical barrier between the inside and outside air and eliminates the risk of contamination due to outside air conditions. Meanwhile, the IASE system fans should overcome the pressure drop due to the HX and additional filters to keep the HX clean on both sides. Air-side economizers can benefit from integrated evaporative cooling.[5] This study focuses on the indirect evaporative cooler (IEC), which has advantages of enhanced heat transfer compared to the IASE through a wetted-surface HX (Figure 1c).

Another method of evaporative cooling for DCs is the indirect water-side economizer (WSE), which uses CT water in plate-frame HXs to reject heat from the chilled water into the condenser water when ambient conditions permit. This study focuses on the WSE in the series mode allowing part-load operation in the case where the condenser water temperature is insufficient to handle the entire cooling load.

Techniques used for the energy assessment of ASEs typically overlook the off-design performance of cooling equipment [4, 5]. Based on the count of favorable hours, Siriwardana et al. [4] studied the energy-saving potential of ASEs in various cities of Australia, concluding with mostly favorable results except in humid and tropical regions. Similarly, Sorell [5] focused on four big cities across the United States and the United Kingdom to identify the potential of wasting energy using inaccurate sensors in ASEs. Another study utilized a more advanced method using simulation software [6], where the authors investigated ASEs for DCs in 17 climate zones specified by the ASHRAE [7] to meet the previous thermal guidelines of the ASHRAE [8].

Off-design performance modeling of major cooling equipment was part of a few studies, where authors compared a few of the free cooling methods. Shehabi et al. [9] compared ASEs and WSEs for five locations

[4]Kaiser J, Bean J, Harvey T, Patterson M, Winiecki J. Survey Results: Data Center Economizer Use, White Paper No. 41, The Green Grid, 2011.

[5]Niemann J, Bean J, Avelar V, Economizer Modes of Data Center Cooling Systems, Schneider Electric, 2011 [online]. Website http://www.apc.com/salestools/VAVR-5UDTU5/VAVR-5UDTU5_R2_EN.pdf

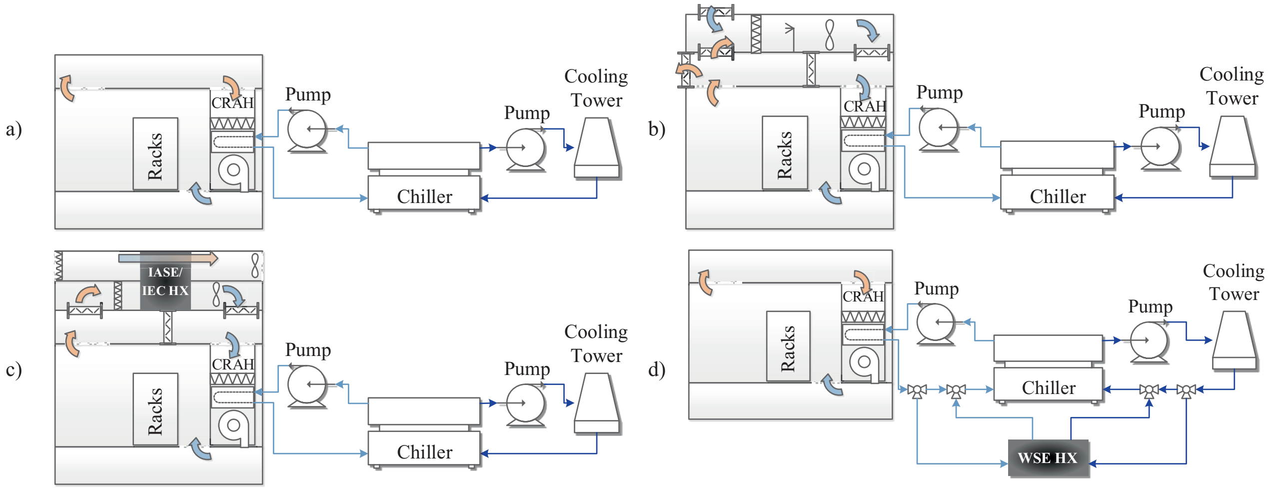

Figure 1. Representative drawings for various DC cases studied: (a) BL, (b) ASE, (c) IASE or IEC, and (d) WSE.

in California, identifying humidity constraints as the bottleneck of the ASE performance. Ham et al. [10] focused on the optimization of ASE and IASE in South Korea. Durand-Estebe et al. [11] also utilized energy simulation software to minimize the energy consumption of WSEs through adaptive control for a small DC in France. Agrawal et al. [12] compared WSEs and IECs based on annual energy simulations for 17 climate zones, indicating better performance of IECs overall. Gözcü et al. [13] also reported superior performance by IECs compared to ASEs, IASEs, and WSEs at high-temperature operation based on their analysis in 19 climate zones specified by the most recent ASHRAE Standard 169 [14] and updated thermal guidelines [2]. Gözcü and Erden [15] extended their work to several cities in Turkey to evaluate the energy performance of various free cooling methods. Güğül presented the only other study for data centers in Turkey assessing the free cooling potential of six cities based on a simplistic model without considering off-design performance [16].

In one of the few studies assessing the economics of free cooling methods, Spangler and Jeffers [17] computed the total cost of ownership (TCO) of various DC configurations including ASEs and WSEs for three cities of the United States. They identified the economic advantage of using WSE applications because of increased energy costs for ASEs due to humidification and dehumidification requirements and higher initial cost. Cho et al. [18] compared ASEs, WSEs, and combinations of them for a DC that operates at relatively low temperatures (5 °C chilled water temperature (T_{chw})). They concluded that an ASE with additional mechanical cooling is the most economical option. Khalaj et al. [19] studied energy, exergy, environment, and economic impact of various air-side economizers for DCs in Australia. They concluded with a gradual increase in energy-saving potential as they moved south in the country and a strong correlation between the capital cost and payback period.

This study utilizes hour-by-hour annual energy simulations considering the off-design performance of DCs with ASE, IASE, IEC, and WSE retrofits using energy simulation software, TRNSYS [20], and provides the economic value of each method in ten cities of Turkey. The existing literature does not address the energy and economic assessment of major free cooling methods in Turkey to the best knowledge of the authors. The following sections introduce the methodology followed by the results and conclusions.

2. Methodology

2.1. Modeling

This study considers the 1 MW IT load BL DC as well as each of four free cooling retrofit solutions. Hence, BL DC components (i.e. Room and Rack, CRAH fan and HX, water cooled chiller, pumps, and CT) are common in each free cooling method. Table 1 provides a summary of the design information of each item as well as the associated TRNSYS types used for modeling. The fluid flow paths in Figure 1 set the basis for the connections between various components linked on the software user interface.

Table 1. DC configurations and design parameters.

Cases	Components	Type	Parameters
BL	Room and Rack	88	1000 kW IT; 120 kW misc. load; adiabatic walls 66.1 m^3/s rack air flow
	CRAH fan	642	87.9 m^3/s air flow rate; 114.4 kW power
	CRAH HX	508	17.5% BP fraction
	Water-cooled chiller	53	3 × 500 kW capacity; 4.0 COP
	Chilled water pump	114	15.6 kW power; 44.6 kg/s water flow rate
	Cooling water pump	114	13.8 kW power; 44.4 kg/s water flow rate
	Cooling tower	51	18.6 kW power; 40.7 m^3/s air flow rate
ASE	ASE	684	
	Economizer fan	744	1 × 39 kW power; 87.9 m^3/s air flow rate
	Humidifier	641	165 kg/h moisture rate; 124 kW power
IASE	Air-Air HX	760	0.69 effectiveness
	Economizer fans	744	2 × 55 kW power; 87.9 m^3/s air flow rate
IEC	IEC	757	0.70 WB effectiveness
	Economizer fans	744	2 × 55 kW power; 87.9 m^3/s air flow rate
WSE	Water-water HX	699	0.80 effectiveness
	WSE pumps	743	3.6 kW power (CW); 3.5 kW power (CHW)

Enclosing aisles reduce the mixing of hot and cold air and lead to more uniform temperatures at the rack inlet. More uniform temperatures allow the DCs to operate at higher temperatures, which not only increases the efficiency of the cooling system but also increases the number of free cooling hours. This study investigates the impact of enclosing the aisle by simulating open (OA) and enclosed (EA) aisle configurations for each free cooling method. BL-H and BL-L represent baseline EA and OA configurations, where -H and -L stand for high- and low-temperature operation, respectively. T_{chw} for EA is 20 °C, maintaining a CRAH exit air temperature of 25 °C, whereas OA needs 10 °C T_{chw} to keep the CRAH exit air temperature at 15 °C, which are in line with the temperatures based on computational fluid dynamics modeling of a typical air-cooled data center by Ahmadi and Erden [21]. These assumptions help the server inlet air temperatures remain below the 27 °C maximum recommended limit considering fluctuations during free cooling operation.

The cooling load contribution of the IT equipment is 1 MW. Other electrical sources (e.g., electrical losses and lighting) dissipate 120 kW of heat at room level. The heat dissipated by racks leads to a 12.5 °C temperature rise in the airflow rate across the racks. CRAH units supply 33% more than rack airflow to compensate for a representative leakage airflow [22, 23] from the plenum into the room. Internal loads dominate the cooling load of DCs leading to the assumption that DC walls are adiabatic [23, 24].

CRAH fan power is constant assuming that economizers are retrofit with their own fans handling the increased flow resistance. The CRAH fan power depends on the representative information in the literature for typical system resistance [25], fan, and efficiency curves [26]. The CRAH HX thermal model utilizes the bypass (BP) method. Accordingly, the airflow through the HX consists of two parts, one bypassing the HX and the other one exiting the coil saturated at the average temperature of the chilled water in the coil, before they mix at the exit. The representative value for the BP fraction relies on the thermal performance for a CRAH unit [27].

The water-cooled chiller model [28] runs on the normalized performance map experimentally validated by Demetriou et al. [29] to compute the off-design chiller power as a function of part-load ratio and the normalized temperature difference between the condenser and evaporator water exit temperatures. Three parallel chillers each with 500 kW design cooling capacity and a design COP of 4.0 enhance the part-load performance.

The chilled and condenser water flow rates are constant. The chilled water experiences a 6.6 °C temperature rise across the CRAH unit based on the typical unit specifications [27]. Temperature rise across the condenser at full load is 8.3 °C as recommended by Taylor as a life-cycle optimum value [30]. When operational, pumping power is constant, and it depends on the baseline design pump power by the ASHRAE [31].

The coefficients of mass transfer correlations [32] govern the effectiveness of the CT model [33], for which a commercially available unit sets the basis for the rated power and airflow rate.[6] CT fan power varies with the cube of the fan speed. The control signal governing the CT fan speed is a high-order polynomial of ambient wet-bulb (WB) temperature, which keeps the condenser inlet temperature above 21 °C at low WB temperatures to avoid freezing. It also leads to linearly varying approach temperature as recommended by the ASHRAE [31] at higher temperatures to prevent significant variations in chiller performance.

2.1.1. Air-side economizer (ASE)

The ASE model computes the fraction of outdoor air needed based on the ambient conditions, DC return air temperature, and set-point temperature of the supply air. The model prevents outside air intake above 15 °C DP to avoid the need for the energy-intensive process of dehumidification. In cold and dry climates, the humidifier adds moisture to the air stream to keep the air temperature above –9 °C DP, where the capacity and power depend on the selection of a humidifier that can meet the maximum humidification requirements in the coldest ASHRAE climate zone.[7] ASE fans overcome the pressure drop due to the additional components such as humidifiers and MERV 8 and 11 filters based on catalog data.[8] ASE fan power depends on the catalog data for a typical fan along with the efficiency curves by the manufacturers.[9]

2.1.2. Indirect air-side economizer (IASE)

The IASE includes an air-to-air cross-flow HX model and two additional fans for both streams to overcome the pressure drop due to the HX and MERV 8 filters[8] as shown in Figure 1c. The sensible heat transferred between

[6]BAC (2017). PT2 Cooling Tower Performance at Standard Conditions [online]. Website www.baltimoreaircoil.com/english/wp-content/uploads/2017/02/PT2_CTI_Tables_20170220.pdf

[7]Nordmann ES4 [online]. Website www.nordmann-engineering.com/en/pdf/brochure-es4-en/?wpdmdl=1109

[8]Trane (2015). Performance Climate Changer™ Air Handlers [online]. Website https://www.trane.com/content/dam/Trane/Commercial/global/products-systems/equipment/air-handling/cataloged-air-handlers/performance/CLCH-PRC022B-EN_092015_Performance{%}20CSAA{%}20catalog.pdf

[9]Ebm-papst (2016). EC centrifugal fans - RadiPac [online]. Website http://www.ebmpapst.se/sv/dat/site_common/upload/EC_centrifugal_fans_-_RadiPac_2016.pdf

the DC return air and the ambient across the HX is

$$\dot{Q}_{iase} = \varepsilon_{iase}\dot{C}_{min}(T_{r,db} - T_{o,db}), \quad (1)$$

where ε_{iase} is a constant effectiveness value based on vendor data for a typical unit,[8] $\dot{C}_{min}$ is the smaller of the two heat capacity rates, and $T_{r,db}$ and $T_{o,db}$ are dry-bulb (DB) temperatures of DC return and the ambient air, respectively. When the ambient temperature is colder than needed for the IASE to meet the cooling demand of the DC, a fraction of the air returned from the room bypasses the IASE HX, and the other fraction passes through the HX to maintain the supply air temperature set-point and avoid freezing temperatures inside the DC. Representative pressure drop for commercially available HX and MERV 8 filters leads to the system pressure for the IASE fans.[8] The rated fan power for each fan depends on the fan efficiency at the design airflow rate.[9] Both IASE fans operate at the same speed, and their power varies with the cube of the fan speed.

2.1.3. Indirect evaporative cooler (IEC)

The only difference between the IEC and IASE is the type of HX and the supporting equipment for the IEC such as a water circulation pump (Figure 1c). The HX model for IEC relies on WB effectiveness,

$$\varepsilon_{iec} = \frac{T_{r,db} - T_{s,db}}{T_{r,db} - T_{o,wb}}, \quad (2)$$

to compute the DB temperature of the supply air $T_{s,db}$, where $T_{r,db}$ is the DB temperature of the return air and $T_{o,wb}$ is the WB temperature of the outdoor air. The effectiveness of 70% is determined based on typical values in the literature [34, 35]. In order to avoid the risk of freezing, the IEC system operates dry in IASE mode.

2.1.4. Indirect water-side economizer (WSE)

The thermodynamic model of the WSE consists of a plate-frame HX with constant effectiveness based on the manufacturer's data[10] (Figure 1d). A fraction of the condenser water bypasses the WSE HX to prevent the chilled water from overcooling in case the CT provides condenser water at a lower temperature than needed. The WSE includes two additional pumps on the chilled water and condenser side to overcome the additional pressure drop across the HX. The guidelines in the ASHRAE Standard 90.1-2013 [31] set the basis for the rated power of these pumps according to the recommended values per unit flow. Overall, CT fans operate at higher speeds and lower approach temperatures in the WSE compared to other configurations to increase the utilization of ambient conditions.

2.2. Climate data

The Meteonorm database is the source of hour-by-hour climate data of cities of Turkey in this study.[11] Adana (ADA), Ankara (ANK), Antalya (ANT), Bolu (BOL), Diyarbakır (DIY), Erzurum (ERZ), İstanbul (IST), İzmir (IZM), Konya (KON), and Van (VAN) are ten relatively populous cities studied in detail and their acronyms are used in this study. This study also presents an excerpt of results for 30 additional sites in Turkey to cover a range of locations sufficient to create a map of annual chiller hours during economizer operation, presented in Section 3.

[10] Bell & Gossett, Plate and Frame Heat Exchanger Specification Sheet, 2009.

[11] Remund J, Müller S, Kunz S, Huguenin-Landl B, Studer C, et al., Meteonorm Handbook Part 1: Software. Meteotest, 2015 [online]. Website: http://www.meteonorm.com/images/uploads/downloads/mn71_software.pdf

2.3. Economic assessment

The objective of the assessment is to compute the TCO of each retrofit free cooling application with respect to BL DC for each city. TCO analysis utilizes three metrics, the net present value (NPV), internal rate of return (IRR), and discounted payback period. Considering the time value of money based on a discount rate (r), NPV is the present value of cash flow over the economic life of the investment:

$$NPV = \sum_{n=m+1}^{t} \frac{F_n}{(1+r)^n} - \sum_{n=0}^{m} \frac{M_n}{(1+r)^n}, \quad (3)$$

where F_n is the present value of the cost savings at the nth year, M_n is the present value of expenditures at the nth year, m is the duration of the investment period, and $t-m$ is the economic life of the investment [36]. The investment period is zero and cost savings start at the end of the first year. For a favorable investment, NPV is expected to be positive. The discount rate that leads to NPV of zero is the IRR [36]. The IRR assumes reinvestment of any income (i.e. cost savings in this analysis) at the rate of IRR, which is rarely practical [37]. The modified internal rate of return (MIRR) addresses this issue by assuming a separate reinvestment rate on income [37]. The discounted payback period is the time until the discounted cash flow becomes positive [38].

2.3.1. Capital costs

The Turkish Ministry of Environment and Urbanization publishes capital cost estimates of construction items including mechanical infrastructure equipment including systems and components of various free cooling systems [39]. Table 2 lists the initial costs of components in each free cooling application. Personal communication with vendors is the basis for maintenance costs (Table 2).[12] [13]

Table 2. Initial capital and annual maintenance costs of components in various free cooling methods (Turkish lira (TL)).

Component name	ASE	IASE	IEC	WSE
Air handling unit	253,760	318,886	318,886	-
Fans	48,400	96,800	96,800	-
Filters	31,627	23,276	23,276	-
Humidifier	76,340	-	-	-
Water-to-water HX	-	-	-	25,440
Air-to-air HX	-	452,870	452,870	-
Pumps	-	-	483	6,040
Total capital cost	410,128	891,832	892,315	31,480
Annual maintenance cost	7,280	7,580	11,195	2,000

2.3.2. Labor costs

This study assumes that labor costs change at the rate of change in the minimum wage in Turkey. Based on the change in the minimum wage in Turkey between 2005 and 2017, the annual average rate of increase in labor rate is assumed to be 11.5%.[14] The resultant assumption is that maintenance costs increase at this rate annually.

[12] T. Aynacı, Interviewee, Personal Communication at Flaktgroup [interview]. 2017.
[13] Y. Evrim, Interviewee, Personal Communication at Ecoserv [interview]. 2017.
[14] KPMG Vergi (2017). Yıllar itibarıyla günlük ve aylık asgari ücretler [online]. Website https://www.kpmgvergi.com/PratikBilgiler

2.4. Operational costs (energy and water)

This study uses a constant annual electricity cost of 0.3166 TL/kWh as published by the Turkish Electricity Distribution Company (TEDAŞ) for medium voltage user commercial customers.[15] Historical data lead to an average rate of increase in the associated cost (6.1%) to project future electricity costs. Water unit costs are from public data of the associated municipalities or based on personal communication[16] (Table 3).

Table 3. Water unit costs for 10 cities (TL/m^3).

ADA [a]	ANK [b]	ANT [c]	BOL [16]	DIY [d]	ERZ [e]	IST [f]	IZM [g]	KON [h]	VAN [16]
7.20	13.70	3.85	8.80	6.45	5.34	9.70	8.28	7.20	3.60

[a]Adana Su ve Kanalizasyon İdaresi. http://www.adana-aski.gov.tr/web/tarifelistesi.aspx
[b]Ankara Su ve Kanalizasyon İdaresi. http://www.aski.gov.tr/tr/ucretler.aspx
[c]Antalya Su ve Atık Su İdaresi. https://www.asat.gov.tr/tr/kurumsal/tarifeler-45.html
[d]Diyarbakır Su ve Kanalizasyon İdaresi. https://www.diski.gov.tr/icerik/detay.aspx?Id=1276
[e]Erzurum Su ve Kanalizasyon İdaresi. http://www.eski.gov.tr/tarife/
[f]İstanbul Su ve Kanalizasyon İdaresi. https://www.iski.gov.tr/web/tr-TR/musteri-hizmetleri/su-birim-fiyatlari
[g]İzmir Su ve Kanalizasyon İdaresi. http://www.izsu.gov.tr/Pages/standartPage.aspx?id=65
[h]Konya Su ve Kanalizasyon İdaresi. https://www.koski.gov.tr/abonehizmetleri/sufiyatlari

2.5. Economic parameters

2.5.1. Discount and inflation rates

The discount rate is the minimum internal rate of return expected by the investor. Spangler and Jeffers used an 8% discount rate for the 15-year economic assessment of ASE and WSE [17]. In another study investigating the impact of filters on energy consumption and air quality in DCs, the authors used an 8% discount rate for a 20-year TCO analysis [40]. Similarly, this study assumes an 8% discount rate for the economic assessment of free cooling retrofits. This study assumes that the finance and reinvestment rates to compute MIRR are also 8%. Based on the data of the Turkish Statistics Institute for years of 2004–2016, the annual average inflation rate is 8.3%.[17] The yearly replacement costs of equipment such as filters during maintenance and water costs are assumed to increase at this rate.

2.5.2. Economic life

Table 4 lists the economic lives of various equipment, which appear to be typically greater than 15 years.[18] Spangler and Jeffers assumed 15 years of economic life for the TCO analysis assessing the economic benefit of two economizer applications in DCs [17]. Hence, 15 years of life for economic assessment is a reasonable assumption for this study.

Table 4. Free cooling system components and economic lives.[18]

System components	Fans	Filters	Air-air HX	Humidifier	Water-water HX	Pumps
Economic life (years)	17	0.5	30	15	25	19

[15]TEDAŞ (2017). Elektrik Tarifeleri [online]. Website http://www.tedas.gov.tr/#!tedas_tarifeler
[16]F. Unkar, Interviewee, Personal Communication at Türk Telekomünikasyon A.Ş. [interview]. 2016.
[17]Türkiye İstatistik Kurumu (2016). Enflasyon ve fiyat [online]. Website http://www.tuik.gov.tr/UstMenu.do?metod=temelist
[18]ASHRAE (2017). Service life data query [online]. Website http://xp20.ashrae.org/publicdatabase/system_service_life.asp?selected_system_type=1

3. Results and discussion

Figure 2a presents proportions of annual energy consumption associated with the components of BL-L in IST. The proportions consist of the contribution of IT equipment (IT), electrical losses and lighting (MISC), chiller compressor (CHILLER), fans in the CRAH units (CRAHFAN), chilled and cooling water pumps (CHWPUMP and CWPUMP), and cooling tower fans (CT). The PUE value of the BL-L in IST is 1.54, which is relatively better than average [1]. Figure 2b presents PUE values for ten cities considering OA and EA configurations (i.e. BL-L and BL-H). Operating the DC at a higher temperature (BL-H) leads to roughly 15% energy savings.

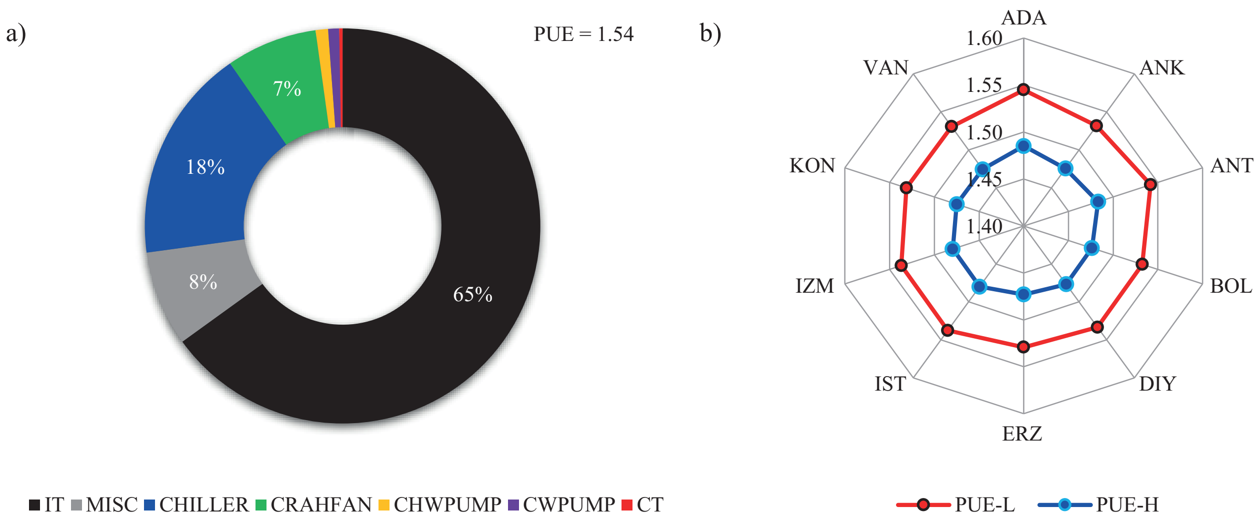

Figure 2. a) Proportions of annual energy for BL-L in IST, b) PUE for different climates and BL-L vs. BL-H.

Figure 3 presents the normalized cooling energy, which is the ratio of the annual cooling energy consumption for each configuration to that of the BL-L configuration in the climate conditions of IST. Among OA configurations, ASE-L leads to the highest energy savings, whereas IEC-H stands out as the best performer at higher temperatures with EA. Overall, higher temperature operation provides favorable results in all cases.

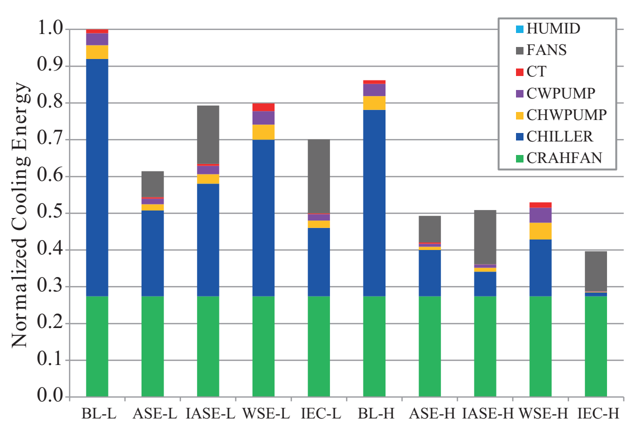

Figure 3. Annual energy consumption of various configurations in IST normalized by that of BL-L.

Figure 4 presents the normalized cooling energy for each free cooling configuration. In a previous study by Lee and Chen [6], the humidification requirement, especially in cold climates, was considerably high. Current results for ASE-L indicate the reduced need for humidification due to the relaxed lower limit of recommended humidity by the ASHRAE [2]. This modification increased the energy efficiency of the ASE in cold cities like ERZ (Figure 4a).

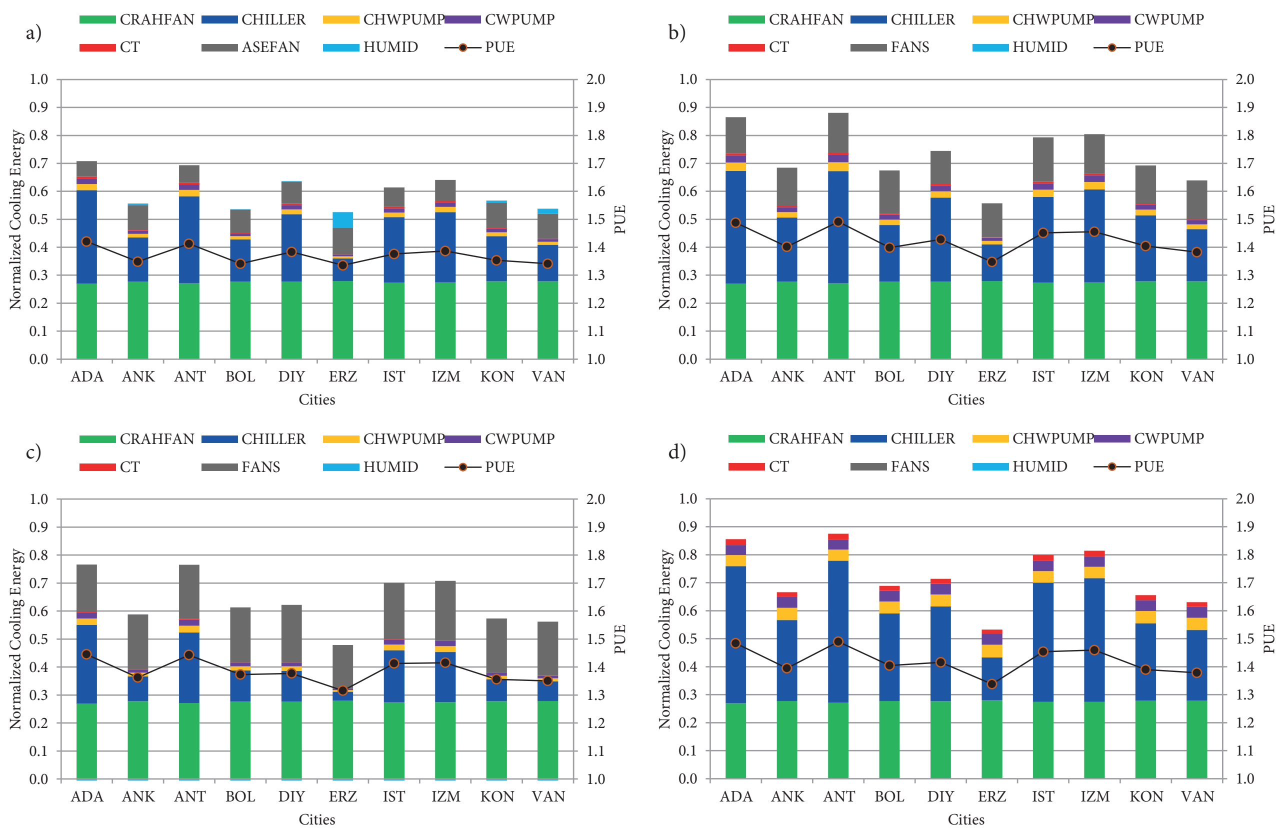

Figure 4. Energy consumption of a) ASE-L, b) IASE-L, c) IEC-L, and d) WSE-L with respect to BL-L and PUE values.

The variations in the ambient DB temperatures have a significant impact on the performance of IASE-L due to the sensible heat exchanging process. The additional fans to overcome the flow resistances of IASE HX and filters lead to a considerable amount of fan power beyond the existing CRAH fans (Figure 4b). Since DC and ambient are isolated, there is no humidification requirement in IASE. The IEC performs better than IASE due to the enhanced heat transfer via evaporative cooling (Figure 4c).

Unlike the IEC, where evaporative cooling removes heat directly from the DC air, the process in the WSE produces cold water at the CT that absorbs heat from the chilled water stream. Due to the indirect nature of the evaporative cooling process, results indicate relatively lower performance by the WSE compared to other methods for OA configurations, which is in line with the literature (Figure 4d)[12].

Figure 5 provides the cooling energy savings of all configurations with respect to the case of BL-L. ASE-L provides the highest energy savings in 9 out of 10 cities for the OA configuration. EA leads to better performance overall but ASE's improvement is relatively lower than that of other methods due to upper limits on humidity set by the ASHRAE [2]. IEC-H is the best performer among the ten cities. Even the warmest city, ADA, promises 50% reduction in annual cooling energy consumption with IEC-H.

The chiller is the primary electricity consumer in the DC cooling infrastructure. Hence, chiller-less

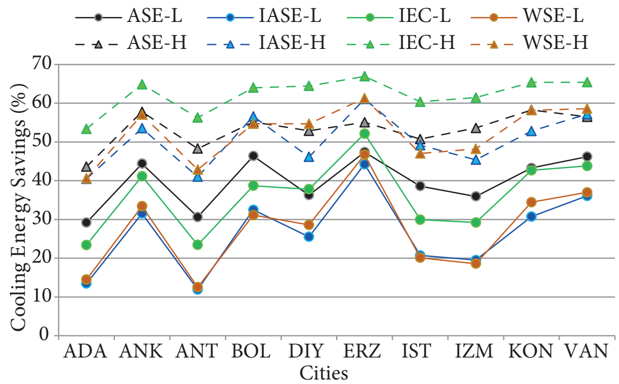

Figure 5. Energy savings of all free cooling configurations with respect to the case of BL-L.

operation is a trending objective. Figure 6 provides contours of annual percentage of the chiller operating hours (either partial or full load) based on annual energy simulation results of 40 sites in Turkey. Warmer locations in the southern coastal areas like ANT and ADA depend on the chiller operation for at least 60% of the time for all OA configurations. ERZ is the only city to achieve chiller operation of less than 10% of the time with ASE and OA configurations.

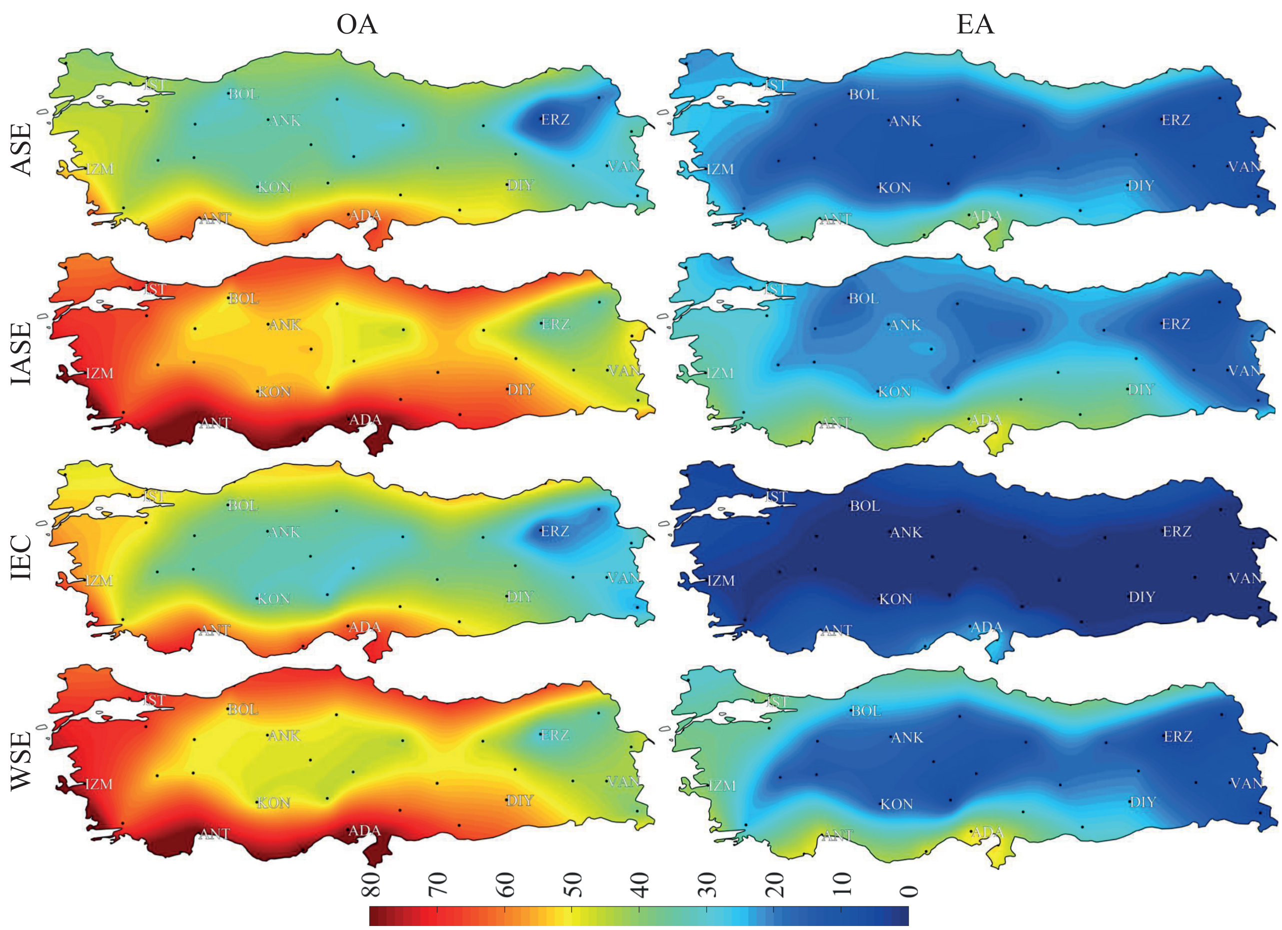

Figure 6. The annual percentage of chiller operating hours (partial and full).

On the other hand, higher temperature operation via EA configuration dramatically improves the potential of energy savings, leading to as much as 54% additional annual hours without the need for a chiller. Except cities in the warm regions in the southern coastal areas (e.g., ADA and ANT) and humid northern coastal areas, all cities resulted in less than 10% of annual chiller operating hours with the IEC method in the EA configuration. Other free cooling methods may still require mechanical cooling.

Water consumption can also be a significant cost factor. CTs, IEC HX, and humidifiers consume water. Figure 7 provides city-by-city annual water consumption of all free cooling methods normalized by that of the BL-L. The WSE method stands out as the most aggressive consumer of water due to the heavy use of CTs. Even though the IEC depends on an evaporative cooling process, the associated increase in water consumption is negligible because of the reduced number of chiller hours.

3.1. Economic assessment results

The previous section provided the operational cost-saving potential of each free cooling method. By combining operational, capital, and maintenance costs, Figure 8 presents the cumulative discounted cash flow diagram of free cooling applications in IST for OA (L) and EA (H) configurations with respect to the BL-L and BL-H, respectively. All cases in IST lead to payback periods of less than four years and NPVs greater than 2.5 million TL in 15 years of lifetime. WSE and ASE have payback periods of less than a year due to their lower initial cost.

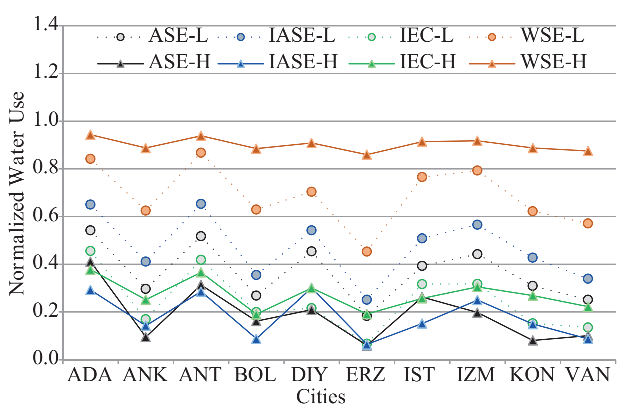

Figure 7. The annual water consumption of all free cooling methods normalized by that of the BL-L.

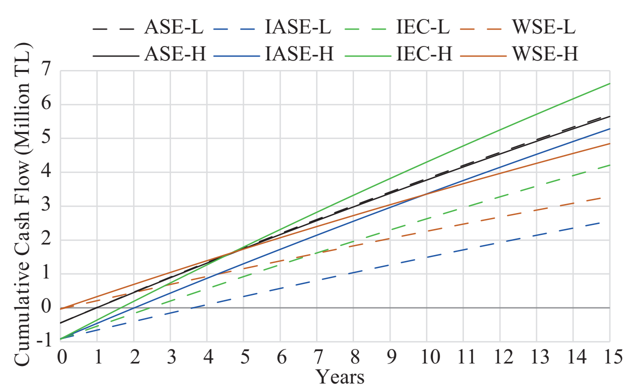

Figure 8. Cumulative discounted cash flow diagram for free cooling applications in IST.

The results indicate similar cash flows for ASE-L and ASE-H, which is due to the higher cost savings by ASE-L with respect to BL-L than that by ASE-H with respect to BL-H. It is important to note that the economic analysis of enclosing the aisle is not within the scope of this study. Figure 9 presents NPV (million TL), MIRR (percentage), and discounted payback period (years) for all cases with respect to the BL-L and BL-H, respectively. Color formatting highlights the worst case in red and best case in blue for each metric.

NPV values of IEC are the best in all cities for EA cases. For all cities except ERZ and VAN (where WSE-L is comparable to IEC-L), ASE-L and IEC-L present higher NPV values among OA configurations (L) (Figure 9a). However, WSE stands out economically considering MIRR (Figure 9b) and payback period (less than one year for all cases) (Figure 9c) due to its lower capital cost, in line with the literature [17]. ASE, IASE, and IEC require air handling units integrated with CRAH units. Contrarily, WSE requires modifications of the chilled and condenser water circuits and installation of the WSE HX in between, which allows for both a cost-

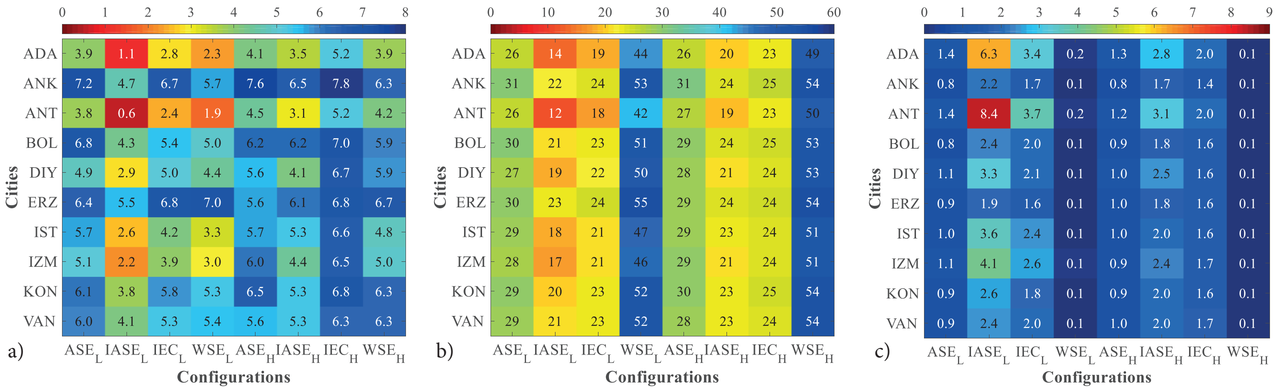

Figure 9. TCO of free cooling methods: (a) NPV (million TL), (b) MIRR (%), (c) discounted payback period (years).

effective and operationally less disruptive investment. If DC operators are reluctant to see higher temperature operation (EA), and they can take measures to mitigate contamination risks, ASE may be a decent free cooling approach. IEC is the better option among indirect air-side economizers (IASE and IEC), primarily due to more efficient HX with evaporative cooling. The operational cost reduction is far more significant than the slight increase in the capital and maintenance cost for the IEC configuration.

The impact of regional water consumption on the NPV can be seen especially in cities like ANK where water costs are high. To illustrate, even though ANK is not the best regarding energy consumption, NPV is better than that of ERZ in some cases, especially for EA, due to the high price of water in ANK. Depending on the company policies, discount rates may vary and lead to different NPVs. MIRR values give hints about the effect of the discount rates on the feasibility of applications. For instance, a slight increase of up to 10%–15% of discount rate may lead to unfavorable NPV for the retrofit applications of IASE in ANT and ADA. Similarly, IEC is an unfavorable option for companies seeking high rates of return with payback times of less than a year. Despite the high energy-saving potential, the IEC retrofit has a payback period between 1.5 and 3.7 years as opposed to ASE and WSE with less than 1.4 years due to the high capital investment.

4. Conclusions

The goal of this study was to investigate the energy-saving potential and economic advantages of four major free cooling methods in data centers located in Turkish climates. Thermodynamic models in this work utilize the off-design performance of key mechanical infrastructure and provide annual energy savings with respect to the baseline data center based on hour-by-hour simulations. The IEC method provided the highest annual energy savings, leading to less than 1% of annual hours of chiller operation in half of the cities. Based on the TCO analysis for 15 years, IEC and ASE stand out with the highest NPV values among other air-side economizer options. However, it is notable that IEC has a higher upfront cost than other methods, leading to lower rates of return and more extended payback periods (i.e. 1.5 to 3.7 years) compared to that of ASE and WSE (i.e. less than 1.4 years). WSE application provided the most cost-effective option regarding the MIRR metric and the payback period of less than a few months due to its lower capital cost. Future work may include the analysis of other free cooling methods applicable to legacy and other types of data centers as well as waste heat recovery methods for emerging liquid-cooled data centers.

Nomenclature

Abbreviations

ADA	Adana
ANK	Ankara
ANT	Antalya
ASE	Air-side economizer
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BL	Baseline
BOL	Bolu
BP	Bypass
CHW	Chilled water
CRAH	Computer room air handling
CT	Cooling tower
CW	Cooling tower water
DC	Data center
DIY	Diyarbakır
DP	Dew-point
EA	Enclosed aisle
ERZ	Erzurum
H	High temperature operation
HX	Heat exchanger
IASE	Indirect air-side economizer
IEC	Indirect evaporative cooler
IST	İstanbul
IT	Information technology
IZM	İzmir
KON	Konya
L	Low temperature operation
OA	Open aisle
TCO	Total cost of ownership
TEDAŞ	Turkish Electricity Distribution Company
TL	Turkish lira
WB	Wet-bulb
WSE	Water-side economizer

Latin and Greek letters

$\dot{C}$	Heat capacity rate
COP	Coefficient of performance
F	Present value of cost savings
IRR	Internal rate of return
M	Present value of expenditures
MIRR	Modified internal rate of return
NPV	Net present value
P	Energy consumption
PUE	Power usage effectiveness
$\dot{Q}$	Heat transfer rate
r	Discount rate
T	Temperature
ε	Effectiveness

Subscripts

chw	Chilled water
db	Dry-bulb
$iase$	Indirect air-side economizer
iec	Indirect evaporative cooler
m	Investment period
min	Minimum
n	nth year
o	Outside
r	Return
s	Supply
t	Time
wb	Wet-bulb

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