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Determination of free cooling potential: A case study for İstanbul, Turkey

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ABSTRACT

A significant portion of energy consumed in buildings is attributed to energy usage by heating, ventilating and air conditioning (HVAC) systems. Free cooling is a good opportunity for energy savings in air conditioning systems. With free cooling, commonly is known economizer cycle, the benefits of lower ambient temperatures are utilized for a significant proportion of the year in many climates. The detailed analysis of local weather data is required to assess the benefits of economizer. In this study, free cooling potential of İstanbul, Turkey was determined by using hourly dry-bulb temperatures measurements during a period of 16 years. It is found that the free cooling potential varies with supply air temperature and months. It is determined that although there are substantial energy savings during a significant portion of the year especially in transition months (April, May, September and October), the high outdoor air temperatures from June to August, made the system not beneficial for free cooling except at high supply air temperature.

1. Introduction

The higher living and working standards, the adverse outdoor conditions in urban environments and reduced prices of air-conditioning units, have caused a significant increase in demand for air conditioning in buildings. On the other hand, heating, cooling, ventilating and air conditioning (HVAC) systems are major responsible for energy consumption in buildings. As reported in the literature, air-conditioning energy consumption shows an increasing trend [1,2]. In recent years, many solutions have been suggested for reducing energy consumption in buildings. Solutions are mainly about initial stage of architectural design related to thermal performance of building and the correct selection of HVAC system. Reducing energy use for space cooling in buildings is a key measure to energy conservation and environmental protection. The yearly cooling load and the peak cooling demand of building can be reduced significantly in the thermally insulated buildings [3,4]. At the same time, there has been a rapid change in the technology of air conditioning. Energy conservative building design has triggered greater interests in developing flexible and sophisticated air conditioning systems capable of achieving enhanced energy-savings potential without sacrificing the desired thermal comfort and indoor air quality (IAQ) [5]. Various types of variable air volume (VAV) systems, air and water economizer, heat recovery, thermal storage, desiccant dehumidification, variable-speed drives, and direct digital control (DDC) devices have become more effective and more advanced for energy efficiency [6]. A considerable amount of energy can be saved if the HVAC system is properly designed, operated and controlled. In all-air HVAC systems using an economizer cycle can result in considerable energy savings [7]. Although economizer systems have existed for many years, in recent years, many packaged unit manufacturers more extensively offer air economizers to provide free cooling for energy savings as well as to improve indoor air quality.

Free cooling application, commonly is known economizer cycle, is used when outside conditions are suitable, that is, when outside air is cool enough to be used as a cooling medium [8]. Two types of economizers are in use today. Those are water-side economizer and air-side economizer. The air-side economizer takes advantage of cool outdoor air to either assist mechanical cooling or, if the outdoor air is cool enough, provide total cooling. In an all air conditioning system, outdoor air is used as supply air. The water-side economizer consists of a water coil located in the self-contained unit upstream of the direct-expansion cooling coil. ASHRAE Standard 90.1 addresses the application of water-side economizer [8].

One method of improving the indoor air quality (IAQ) is to increase the ventilation. Due to the fact that the outdoor air is used directly in free cooling applications; a high indoor air quality can be achieved. Providing high indoor air quality, compared with the mediocre air that is present in many existing office building worldwide, may increase productivity by an estimated 5–10%. An annual loss of this magnitude caused by mediocre indoor air quality will often be much higher than energy costs, capital costs, and the cost of operating the building [9].

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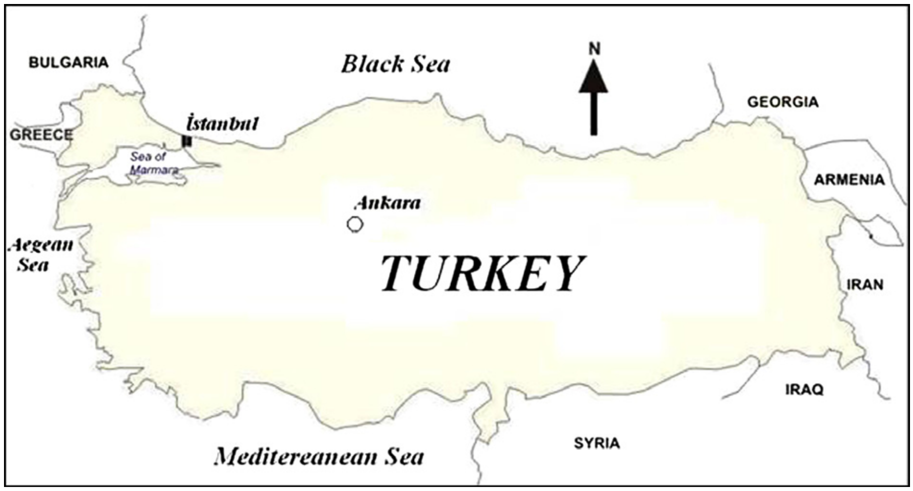

Fig. 1. The location of İstanbul on the map of Turkey.

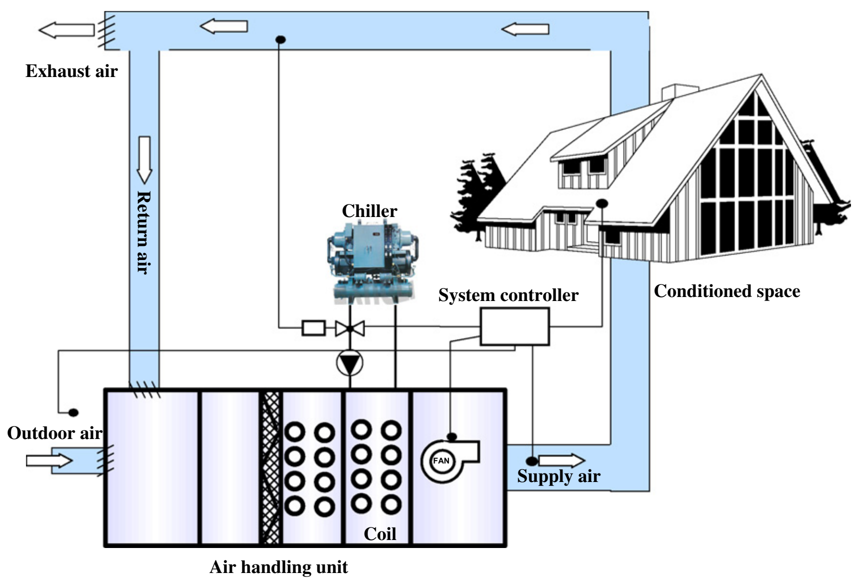

Fig. 2. Schematic of a typical all air conditioning system.

The potential of free cooling represents a measure of the capability of ventilation to ensure indoor comfort without using mechanical cooling systems [10]. Free cooling is not alternative of mechanical cooling, it must be thought as complementary and supportive application for air conditioning system. Available studies revealed that considerable energy savings could be achieved using the free cooling under different climatic conditions. Olsen et al. [11] showed that low-energy cooling systems that maximize free cooling from outside air have the best energy performance under mild UK climate conditions. Budaiwi [7] investigated energy performance of the economizer cycle under three climatic conditions in Saudi Arabia and presented significant results for HVAC designers and operators seeking energy efficiency in buildings through the economizer cycle. Wacker [12] investigated the energy-savings potential and indoor comfort implications of economizer controls for packaged rooftop HVAC equipment under weather conditions in Asheville, North Carolina, USA. Karunakaran et al. [5] proposed a combined variable refrigerant volume (VRV) and variable air volume (VAV) air conditioning system that was controlled by the intelli-

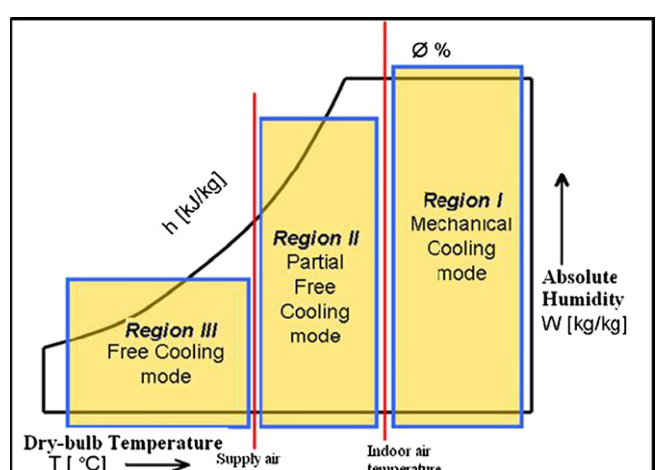

Fig. 3. The control regions of a fixed dry-bulb temperature economizer on psychrometric chart.

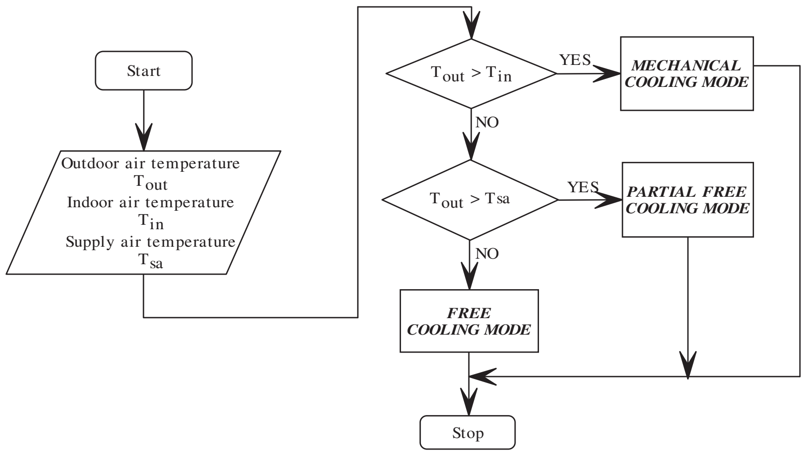

Fig. 4. The flow chart of a fixed dry-bulb temperature economizer.

gent fuzzy controller. They analyzed and tested the VRV–VAV air conditioning system for the summer and winter conditions of Chennai, India under fixed ventilation, demand controlled ventilation (DCV) and combined DCV–economizer cycle ventilation. The proposed system experimentally analyzed under fixed ventilation, demand controlled ventilation (DCV) and combined DCV and economizer cycle ventilation techniques effectively conserved 44% and 63% of per day average energy savings in summer and winter design conditions respectively, while compared to the conventional constant air volume (CAV) air conditioning system.

Cooling energy requirements can be also reduced by using low-energy technologies. Of the available technologies, night ventilation, which is one of free cooling applications, is particularly suited to office buildings because these are usually not occupied during the night. Night ventilation works by using natural or mechanical ventilation to cool the surfaces of the building fabric at night and is more effective where a building includes a reasonably high thermal mass, so that heat can be absorbed during the day [13]. The effectiveness of night ventilation technique for residential buildings in hot-humid climate of Malaysia was investigated by Kubato et al. [14].

The most important and characteristic parameter for free cooling is local climatic features. Because free cooling potential is a function of outdoor climate. So, only detailed analysis of weather data reveals the free cooling potential of a region. Aktacir and Bulut [15–17] carried out some useful studies on the free cooling potential of different regions of Turkey. The free cooling potential of Kayseri, one of the main provinces of Central Anatolia, was determined by using hourly outdoor temperatures by Aktacir and Bulut [15]. The result of their study showed that the free cooling potential is high during cooling season (from 15 May to 30 September) and especially in transit months (April and October) for Kayseri. The free cooling potential of Antalya, located in Mediterranean region of Turkey, was analyzed by Aktacir and Bulut [16]. It was determined that while the region has low free cooling potential during cooling season (from June to August), the transitions months (April, May, September and October) have the highest potential. Aktacir and Bulut [17] also investigated the free cooling potential of İzmir, one of the biggest cities of Turkey and located in Aegean region. They found that the free cooling potential significantly varies with supply air temperature and months in Aegean region. Their study showed that the Aegean region has low free cooling potential during cooling season (from June to August) and the transitions months (April, May, September and October) have significant potential.

The main purpose of this study is to determine and analyse the free cooling potential in İstanbul (latitude: 40°58′N, longitude: 29°05′E and elevation: 39 m). The location of İstanbul is shown on the map of Turkey in Fig. 1. İstanbul is the largest city of Turkey and the third largest city in the world. İstanbul is located in the north-west Marmara region of Turkey. İstanbul is the only city in

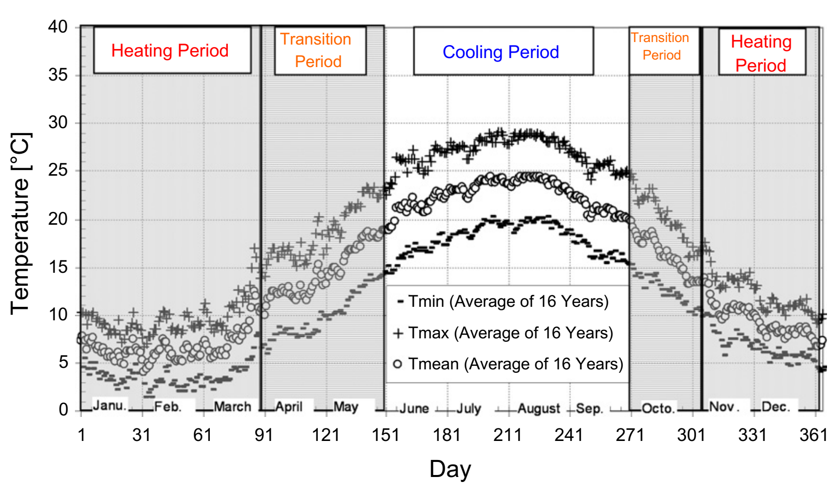

Fig. 5. Variation of extreme and mean temperatures throughout the year and heating, cooling and transition periods for İstanbul.

Table 1
Monthly total N_{bin} values (h/month) for İstanbul.

Month	Time	Temperature bin (°C)															
		−9/−6	−6/−3	−3/0	0/3	3/6	6/9	9/12	12/15	15/18	18/21	21/24	24/27	27/30	30/33	33/36	36/39
January	1–4	0	0	4	26	43	29	17	4	1	0	0	0	0	0	0	0
	5–8	0	0	4	29	40	31	16	4	0	0	0	0	0	0	0	0
	9–12	0	0	1	16	37	36	21	11	2	0	0	0	0	0	0	0
	13–16	0	0	1	11	34	36	23	15	4	0	0	0	0	0	0	0
	17–20	0	0	2	17	42	34	20	8	1	0	0	0	0	0	0	0
	21–24	0	1	2	22	44	30	18	6	1	0	0	0	0	0	0	0
	Total	0	1	14	121	240	196	115	48	9	0	0	0	0	0	0	0
February	1–4	0	2	11	23	39	22	12	3	0	0	0	0	0	0	0	0
	5–8	0	2	11	25	39	20	12	3	0	0	0	0	0	0	0	0
	9–12	0	2	6	15	26	32	17	11	3	0	0	0	0	0	0	0
	13–16	0	1	6	13	21	30	19	15	6	1	0	0	0	0	0	0
	17–20	0	2	8	15	33	27	15	10	2	0	0	0	0	0	0	0
	21–24	0	2	10	17	39	24	14	5	1	0	0	0	0	0	0	0
	Total	0	11	52	108	197	155	89	47	12	1	0	0	0	0	0	0
March	1–4	0	1	4	20	45	30	18	5	1	0	0	0	0	0	0	0
	5–8	0	1	4	20	44	30	18	6	1	0	0	0	0	0	0	0
	9–12	0	0	3	7	27	38	24	15	8	2	0	0	0	0	0	0
	13–16	0	0	2	6	21	35	26	14	13	6	1	0	0	0	0	0
	17–20	0	1	2	9	36	33	20	14	7	2	0	0	0	0	0	0
	21–24	0	0	3	14	46	30	19	10	2	0	0	0	0	0	0	0
	Total	0	3	18	76	219	196	125	64	32	10	1	0	0	0	0	0
April	1–4	0	0	0	1	14	37	39	22	6	1	0	0	0	0	0	0
	5–8	0	0	0	1	11	34	41	22	8	3	0	0	0	0	0	0
	9–12	0	0	0	0	3	16	29	28	25	14	4	1	0	0	0	0
	13–16	0	0	0	0	2	12	22	24	27	20	9	3	1	0	0	0
	17–20	0	0	0	0	4	19	32	26	22	11	5	1	0	0	0	0
	21–24	0	0	0	0	7	31	38	27	11	5	1	0	0	0	0	0
	Total	0	0	0	2	41	149	201	149	99	54	19	5	1	0	0	0
May	1–4	0	0	0	0	0	7	26	47	32	10	2	0	0	0	0	0
	5–8	0	0	0	0	0	4	21	42	35	16	5	1	0	0	0	0
	9–12	0	0	0	0	0	0	4	20	32	36	21	9	2	0	0	0
	13–16	0	0	0	0	0	0	3	13	25	34	29	14	5	1	0	0
	17–20	0	0	0	0	0	1	8	24	33	31	18	7	2	0	0	0
	21–24	0	0	0	0	0	3	17	40	38	21	4	1	0	0	0	0
	Total	0	0	0	0	0	15	79	186	195	148	79	32	9	1	0	0
June	1–4	0	0	0	0	0	0	1	9	48	50	11	1	0	0	0	0
	5–8	0	0	0	0	0	0	1	6	28	54	26	5	0	0	0	0
	9–12	0	0	0	0	0	0	0	1	4	24	46	34	10	1	0	0
	13–16	0	0	0	0	0	0	0	1	2	12	38	39	23	5	0	0
	17–20	0	0	0	0	0	0	0	1	5	31	45	27	10	1	0	0
	21–24	0	0	0	0	0	0	1	2	26	57	29	5	0	0	0	0
	Total	0	0	0	0	0	0	3	20	113	228	195	111	43	7	0	0
July	1–4	0	0	0	0	0	0	0	1	13	57	49	4	0	0	0	0
	5–8	0	0	0	0	0	0	0	0	8	39	57	19	1	0	0	0
	9–12	0	0	0	0	0	0	0	0	1	5	24	57	32	5	0	0
	13–16	0	0	0	0	0	0	0	0	0	4	12	44	48	14	2	0
	17–20	0	0	0	0	0	0	0	0	1	8	42	50	18	4	1	0
	21–24	0	0	0	0	0	0	0	0	5	33	71	14	1	0	0	0
	Total	0	0	0	0	0	0	0	1	28	146	255	188	100	23	3	0
August	1–4	0	0	0	0	0	0	0	1	13	50	55	5	0	0	0	0
	5–8	0	0	0	0	0	0	0	0	10	38	56	19	1	0	0	0
	9–12	0	0	0	0	0	0	0	0	1	5	21	58	34	5	0	0
	13–16	0	0	0	0	0	0	0	0	0	4	10	42	54	13	1	0
	17–20	0	0	0	0	0	0	0	0	1	9	42	54	16	2	0	0
	21–24	0	0	0	0	0	0	0	0	4	31	73	15	1	0	0	0
	Total	0	0	0	0	0	0	0	1	29	137	257	193	106	20	1	0
September	1–4	0	0	0	0	0	0	3	19	46	42	9	1	0	0	0	0
	5–8	0	0	0	0	0	0	3	17	41	43	15	1	0	0	0	0
	9–12	0	0	0	0	0	0	0	1	8	26	45	31	8	1	0	0
	13–16	0	0	0	0	0	0	0	1	5	19	38	35	19	3	0	0
	17–20	0	0	0	0	0	0	0	5	17	43	37	15	3	0	0	0

(*continued on next page*)

Table 1 (*continued*)

Month	Time	Temperature bin (°C)															
		−9/−6	−6/−3	−3/0	0/3	3/6	6/9	9/12	12/15	15/18	18/21	21/24	24/27	27/30	30/33	33/36	36/39
	21–24	0	0	0	0	0	0	0	12	35	51	20	2	0	0	0	0
	Total	0	0	0	0	0	0	6	55	152	224	164	85	30	4	0	0
October	1–4	0	0	0	0	0	7	30	44	30	12	1	0	0	0	0	0
	5–8	0	0	0	0	1	6	29	43	31	11	3	0	0	0	0	0
	9–12	0	0	0	0	0	2	11	20	36	36	13	5	1	0	0	0
	13–16	0	0	0	0	0	2	8	18	30	37	18	8	3	0	0	0
	17–20	0	0	0	0	0	3	14	33	41	22	9	2	0	0	0	0
	21–24	0	0	0	0	0	6	23	42	37	13	3	0	0	0	0	0
	Total	0	0	0	0	1	26	115	200	205	131	47	15	4	0	0	0
November	1–4	0	0	0	4	15	31	34	27	8	1	0	0	0	0	0	0
	5–8	0	0	0	4	15	30	34	28	8	1	0	0	0	0	0	0
	9–12	0	0	0	1	7	21	30	29	24	7	1	0	0	0	0	0
	13–16	0	0	0	1	5	17	28	30	25	12	2	0	0	0	0	0
	17–20	0	0	0	1	10	26	34	29	17	3	0	0	0	0	0	0
	21–24	0	0	0	2	14	28	35	29	10	2	0	0	0	0	0	0
	Total	0	0	0	13	66	153	195	172	92	26	3	0	0	0	0	0
December	1–4	0	0	3	14	30	42	23	10	2	0	0	0	0	0	0	0
	5–8	0	0	3	16	29	43	23	9	1	0	0	0	0	0	0	0
	9–12	0	0	1	9	20	44	29	18	3	0	0	0	0	0	0	0
	13–16	0	0	1	7	19	38	33	19	7	0	0	0	0	0	0	0
	17–20	0	0	1	10	24	45	28	14	2	0	0	0	0	0	0	0
	21–24	0	0	2	13	27	42	26	12	2	0	0	0	0	0	0	0
	Total	0	0	11	69	149	254	162	82	17	0	0	0	0	0	0	0

the world that spans over two continents. It encloses the southern Bosphorus which places the city on two continents – the western portion of İstanbul is in Europe, while the eastern portion is in Asia. İstanbul has always been the center of the country's economic life and industry because of its location as an international junction of land and sea trade routes. The city has a temperate climate with hot and humid summers; and cold, wet winters. The city has a population of 12,573,836 residents according to the latest count as of 2007 [18].

2. Economizer cycle and economizers in HVAC systems

An economizer cycle is an air conditioning cycle that utilizes the free cooling capacity of outdoor air either directly or to cool the condenser water in a cooling tower (or an evaporative cooler), and then to cool the air indirectly, instead of using refrigeration to provide cooling/dehumidification so as to maintain a required space temperature. The component and devices used in the operation of an economizer cycle are collectively called an economizer, and the type of control used to operate the economizer cycle effectively and energy-efficiently is called economizer control. There are two types of economizers, typically referred to as air-side and water-side economizers. An air economizer consists of outdoor, exhaust, relief, and recirculating ducts and dampers in the air handling unit or packaged unit, as well as a control system to operate them. Air economizer control can be subdivided into enthalpy-based differential enthalpy, fixed enthalpy, and electronic enthalpy economizer controls and also temperature-based fixed dry-bulb and differential dry-bulb economizer controls. Water-side economizers use the outdoor air to cool the condenser water or cooling water in the cooling tower or evaporative cooler first, and then to cool the mixture of outdoor and recirculating air through a precooling coil. A water economizer consists mainly of a cooling tower (or an evaporative cooler), a water precooling coil in the air handling unit or packaged unit, a circulating pump to circulate cooling water, and the associated control system [6]. This article discuses the use of free cooling potential in air-side economizers for an all-air HVAC system.

Fig. 2 shows a schematic of a typical all-air HVAC system which consists of an air handling unit, a refrigeration (chiller) system, dampers, fans and air ducts. A significant energy saving is possible when the system is properly switched over to an economizer cycle. At the onset of economizer operation, return dampers are closed, outside dampers are opened, and the maximum possible outside air is supplied to cooling coils. The control algorithms for switchov-

Table 2
Yearly total N_{bin} values (h/year) for six separate time periods of day for İstanbul.

Time	Temperature bin (°C)															
	−9/−6	−6/−3	−3/0	0/3	3/6	6/9	9/12	12/15	15/18	18/21	21/24	24/27	27/30	30/33	33/36	36/39
1–4	0	3	22	88	186	205	203	192	200	223	127	11	0	0	0	0
5–8	0	3	22	95	179	198	198	180	171	205	162	45	2	0	0	0
9–12	0	2	11	48	120	189	165	154	147	155	175	195	87	12	0	0
13–16	0	1	10	38	102	170	162	150	144	149	157	185	153	36	3	0
17–20	0	3	13	52	149	188	171	164	149	160	198	156	49	7	1	0
21–24	0	3	17	68	177	194	191	185	172	213	201	37	2	0	0	0
Total	0	15	95	389	913	1144	1090	1025	983	1105	1020	629	293	55	4	0

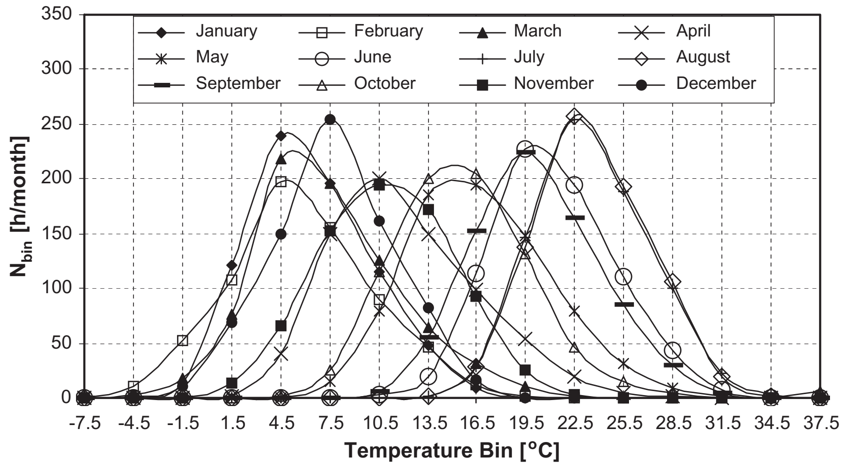

Fig. 6. Variation of monthly total N_{bin} values for İstanbul.

er are typically classified into dry-bulb temperature based and enthalpy based [8]. With the economizer cycle, the need for mechanical cooling can be eliminated completely (free cooling) or reduced partially (partial free cooling) whenever outdoor air conditions allow. The energy cost savings can be very significant, depending on the economizer load and the hours of operation.

Many control methods and applications which determine set points and the control strategy for an economizer are recommended to maximize energy saving [8]. The enthalpy economizer control yields lower overall energy consumption. Simulation results by Wacker [12] show that enthalpy economizer saves 5–50% more compressor energy compared to dry-bulb economizer with switchover set point of 24 °C in the six different cities of USA. Comparing the enthalpy of outdoor air with that of recirculating air requires wet-bulb temperature or dry-bulb temperature and relative humidity measurement. In actual practice, humidity sensors may demonstrate considerable errors (sometimes up to 10%) and have extensive maintenance requirements. Dew point sensors are delicate and expensive and cause maintenance difficulties. In spite of the superiority of enthalpy economizer, its application is greatly impeded by the so-far notoriously unreliable humidity measurement of outdoor air [19]. Therefore, it is simpler and more convenient to use only temperature sensors and to compare the outdoor air temperature to with the recirculating temperature (or a predetermined set point) instead of sensing and comparing enthalpies. This method of control is called temperature economizer control [6]. Outside weather zones using temperature-based economizer control are shown in Fig. 3. As shown in Fig. 3, in fixed dry-bulb temperature economizer, the psychrometric chart can be broken down into three regions by selecting an appropriate supply air temperature (typically between 13 and 18 °C) and indoor temperature (typically set point is 24 °C). When outdoor air temperature is greater than indoor air temperature (region 1: mechanical cooling mode), the outdoor and exhaust air dampers will be at their minimum opening and the mechanical cooling is needed. When outdoor air temperature is located in region 2 (partial free cooling mode), bounded by the indoor and supply air dry-bulb temperature, 100% outdoor air is used since the outdoor air dry-bulb temperature is less than the room temperature and the mechanical cooling can be required. But, the operation hours of the refrigeration system are less than that of region 1. In region 3 (free cooling mode) , since the outdoor air temperature is less than supply air temperature, no need for mechanical cooling and the free cooling capacity of outdoor air is utilized directly. In free cooling mode, the outdoor air

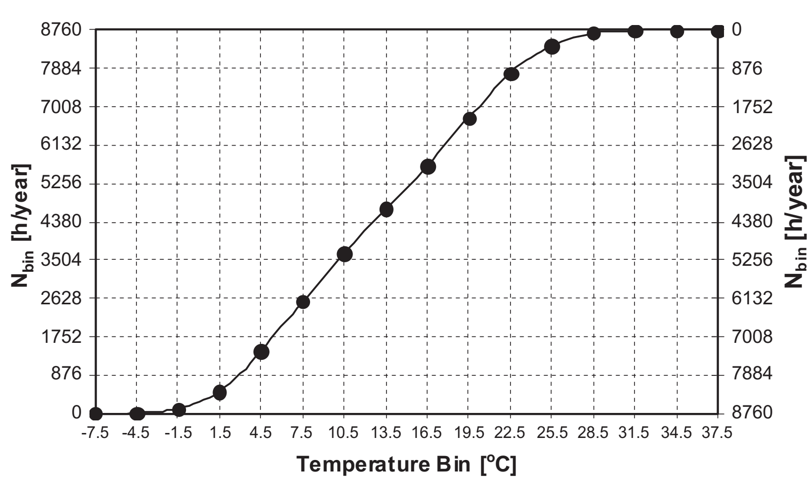

Fig. 7. Cumulative distribution of yearly total bin data for İstanbul.

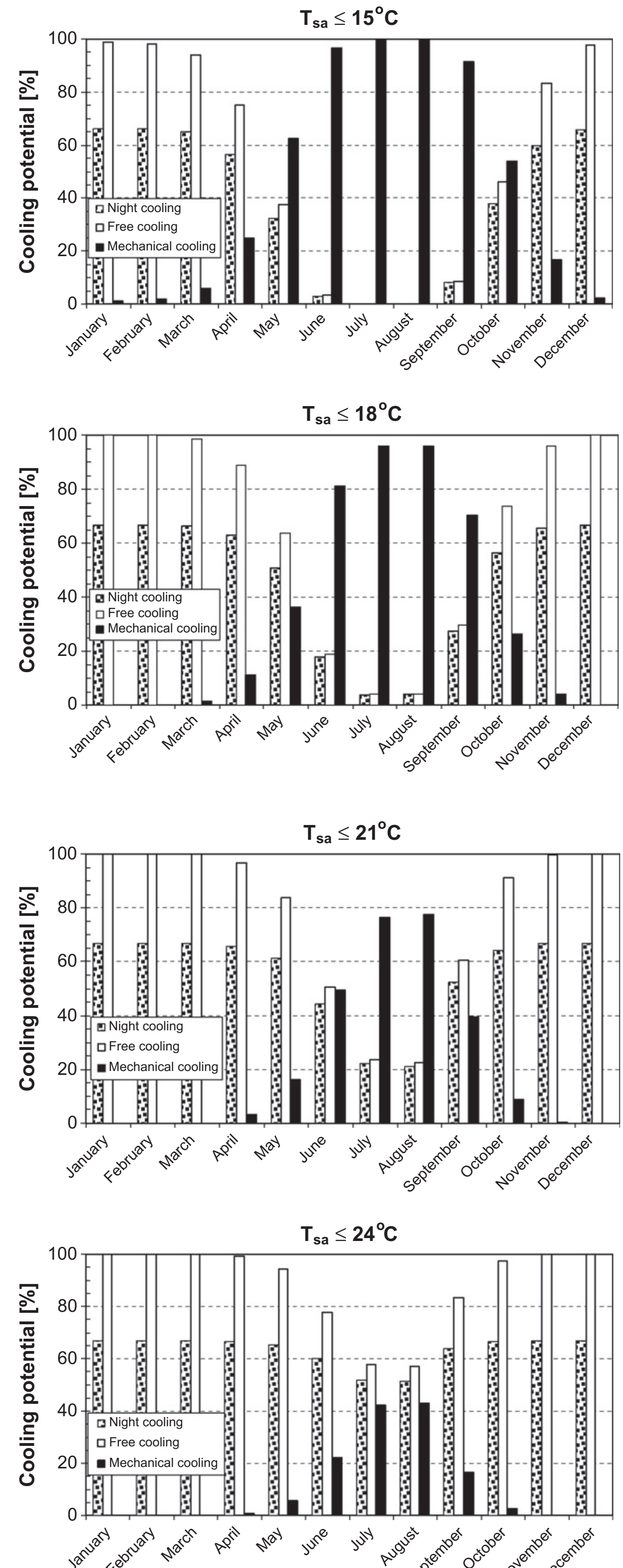

Fig. 8. Variation of monthly free cooling, night cooling and mechanical cooling potential for İstanbul throughout year.

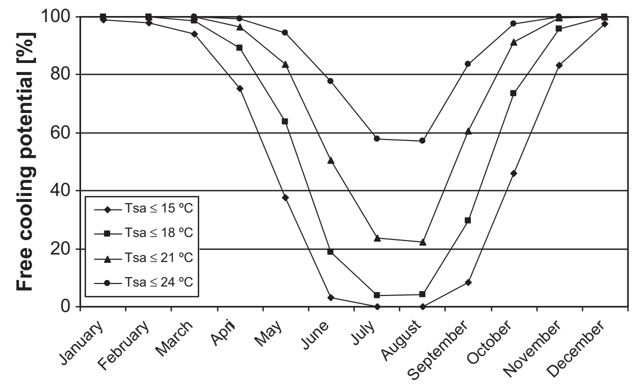

Fig. 9. Variation of monthly free cooling potential at different supply air temperatures.

and return air are blended to achieve a desired supply air temperature and the refrigeration system is shut off. The flow chart of a fixed dry-bulb temperature economizer is depicted in Fig. 4.

3. Analysis of outdoor air temperature

Detailed analysis of outdoor climatic conditions is required in order to assess free cooling potential. In this study, the cooling season for İstanbul was determined by using long term daily mean dry-bulb temperature. Fig. 5 shows the variation of daily minimum, maximum and mean dry-bulb temperature data throughout the year for İstanbul. These dry-bulb temperature data is obtained from the means of 16 years (1981–1996) the long-term measured data. As seen from Fig. 5, by choosing daily mean temperature 20 °C (mean of maximum temperatures is about 24 °C) as base temperature, cooling season starts at the month of June (152nd day), and ends at the month of September (273rd day). If the daily mean temperatures are between 13 °C and 20 °C, this period is accepted as transition period. Thus, April, May and October can be handled as the transition months for İstanbul.

In this study, the bin data for the dry-bulb temperature is used to determine the potential of free cooling. The bin method requires the bin weather data. Bin method is based on the concept that all the hours of a month, season or year, when a particular temperature interval (bin) occurs, can be grouped together and the energy calculations can be performed for those hours with the equipment operating under those particular conditions. The instantaneous energy requirements are calculated at different values of the outdoor dry-bulb temperature ($T_{o,i}$) and then are multiplied by the corresponding number of hours ($N_{bin,i}$) in the temperature interval (bin) centered on that temperature [20,21]. The result is the energy consumption $Q_{bin,i}$ at the corresponding bin:

$$Q_{bin,i} = N_{bin,i}\frac{K_{tot}}{\eta}(T_b - T_{o,i})^{\pm} \quad (1)$$

where K_{tot} and η are, respectively, total heat loss coefficient of the building, and the efficiency of the HVAC system. The balance point temperature T_b is the value of outdoor temperature below or above which heating or cooling is needed. The bin method can be used for estimating both heating and cooling energy requirements. The plus subscript on the parenthesis of Eq. (1) is for heating and indicates that only positive values are to be counted. For cooling, only negative values should be considered. Eq. (1) gives only the sensible energy requirements. The latent energy requirements can also be calculated if the mean coincident wet-bulb temperature at each temperature bin is known. $Q_{bin,i}$ values, which are calculated separately for each temperature interval (bin), are summed to obtain total energy consumption:

$$Q_{tot} = \sum_{i=1}^{m} Q_{bin,i} = \sum_{i=1}^{m} N_{bin,i} \frac{K_{tot}}{\eta} (T_b - T_{o,i})^{\pm} \quad (2)$$

where m is the total number of the temperature intervals (bins). This procedure can be performed either with monthly or with yearly data. It can account for the part-load performance of heating, ventilating and air-conditioning equipment as well as for the varying performance of heat pump systems and primary HVAC equipment. Since the ambient temperature effect on equipment efficiency is taken into account, the accuracy of the energy calculations is significantly improved as compared to that of the degree-day methods. The bin method can account for the part-load performance of HVAC equipment and has been specially used for analysis of heat pump systems. Additionally, by performing separate calculations for different time periods, variations of indoor loads with time, occupancy patterns and operating schedules of HVAC systems can be considered [20].

In this study, the bin data for dry-bulb temperature from −9 °C to 39 °C with 3 °C increments were calculated in six daily 4-h shifts (1–4, 5–8, 9–12, 13–16, 17–20 and 21–24 h) for İstanbul. Bin data were determined using hourly dry-bulb temperatures measured by The State Meteorological Affairs General Directorate (Turkish initials DMİ) in İstanbul (Göztepe) during a period of 16 years (between 1983 and 1998). Monthly bin data for cooling and transition period are given in Table 1 in 4-h periods. The smallest temperature bin observed in İstanbul is −4.5 °C (−6 °C/−3 °C) with 11 h in February, whilst the maximum bin observed is 34.5 °C (33 °C/36 °C) with 3 h in July. Annual N_{bin} values for six separate time periods of the day are presented in Table 2. As can be seen from the table, the maximum yearly total N_{bin} value is 1144 h in 7.5 °C (6 °C/9 °C) temperature interval.

Fig. 6 shows distribution of monthly total N_{bin} values for İstanbul. Heating and cooling periods can also be estimated from Fig. 6. As seen from Fig. 6, while winter months lay the left side of the graph, the summer months are at the right side of graphs. The transitions season remains in the middle of the graph. Cumulative distribution of yearly bin data for İstanbul is shown in Fig. 7. From Fig. 7, one can get approximately the number of hours for heating season or cooling season by choosing a base temperature. For example, it can be easily determined that the heating season is 6200 h for base temperature of 18 °C and cooling season is 980 h for 22 °C base temperature.

4. Analysis of free cooling potential

4.1. Monthly potential of free cooling

Free cooling potential for an all-air HVAC system in İstanbul, Turkey were determined for different outdoor air temperature values (15 °C, 18 °C, 21 °C and 24 °C). It is accepted that the supply air temperature (T_{sa}) equals or less than the outside temperature and a temperature raise due to fan dissipation is neglected. In Fig. 8, monthly distribution of free cooling, night cooling and mechanical cooling for İstanbul are shown when outdoor air temperature equal or less than the supply air temperature, i.e. when $T_{sa} \leqslant 15$ °C, $T_{sa} \leqslant 18$ °C, $T_{sa} \leqslant 21$ °C and $T_{sa} \leqslant 24$ °C. For night cooling, 17:00–08:00 time period was taken out in the analysis. The impact of supply air temperature on free cooling potential is obvious as indicated by Fig. 8. Variations of monthly free cooling at different supply air temperatures are shown in Fig. 9. As shown in Figs. 8 and 9, free cooling potential is high in April and October but the significant portion of this potential is appearing in night period. From June to August, the high outdoor air temperature made the system not beneficial for free cooling except at high supply air temperature. The free cooling potential goes up with increase of supply air temperature. The higher the supply air temperature, the greater is the cooling potential of the outdoor air. The increase of free cooling potential for T_{sa} = 24 °C is very significant. Almost more than half of the air-conditioned time from June to August was favorable for free cooling to save coil energy consumption

Table 3
Hourly free cooling potential at different supply air temperatures.

Time	Free cooling potential (%)				Free cooling potential (%)			
	T_{sa} = 15 °C	T_{sa} = 18 °C	T_{sa} = 21 °C	T_{sa} = 24 °C	T_{sa} = 15 °C	T_{sa} = 18 °C	T_{sa} = 21 °C	T_{sa} = 24 °C
	April				*May*			
01–04	94	99	100	100	65	90	98	100
05–08	91	98	100	100	54	82	95	99
09–12	63	84	96	99	19	45	74	91
13–16	50	73	89	97	13	33	60	84
17–20	68	86	95	99	27	53	78	93
21–24	86	95	99	100	48	79	96	99
	June				*July*			
01–04	8	48	90	99	1	11	57	97
05–08	6	29	74	96	0	6	38	84
09–12	1	4	24	63	0	1	5	24
13–16	1	3	13	44	0	0	3	13
17–20	1	5	31	68	0	1	7	41
21–24	3	24	72	96	0	4	31	88
	August				*September*			
01–04	1	11	52	96	18	57	92	99
05–08	0	8	39	84	17	51	87	99
09–12	0	1	5	22	1	8	29	67
13–16	0	0	3	11	1	5	21	53
17–20	0	1	8	42	4	18	54	85
21–24	0	3	28	87	10	39	82	98
	October				*November*			
01–04	65	90	99	100	93	99	100	100
05–08	64	89	98	100	93	99	100	100
09–12	27	56	85	95	73	93	99	100
13–16	23	47	77	91	68	88	98	100
17–20	40	73	91	98	83	98	100	100
21–24	57	87	98	100	90	98	100	100

for T_{sa} = 24 °C. The values of free cooling potential in the period of April to October are relatively high and should not be neglected.

4.2. Daily potential of free cooling

Hourly variation of free cooling potential when outdoor temperature equal or less than the supply air temperature of 15 °C, 18 °C, 21 °C and 24 °C is given in Table 3. As indicated by Table 3, the free cooling potential is high in April, May, and October as months of the transition period. As the supply air temperature increases, this potential increases parallelly. The free cooling potential remains relatively low in June, July, August and September as month of cooling season. The months of July and August which are the hottest month in the year has the lowest free cooling potential. As expected, while free cooling potential is low during daytime period especially during midday hours when the outdoor air temperature is high, the potential is high during nighttime period which has relatively low outdoor air temperature. It is evident that there is no significant potential during nighttime period of cooling season (especially July and August). But, at high value of supply air temperature (i.e. $T_{sa24} \leqslant 24$ °C), the potential is up to 100%.

As a case study, the operation hours of an all-air HVAC system (indoor set temperature is 24 °C) with economizer (free cooling mode or partially free cooling mode) and without economizer (mechanical cooling mode) is given in Table 4. As shown in Table 4, for $T_{sa} \leqslant 15$ °C at period of 09:00–12:00 in April, 76 h of total running hours of 120 is free cooling mode and the remaining time is mechanical cooling mode. For $T_{sa} \leqslant 24$ °C at the same period, there are 76 h for free cooling, 43 h for partially free cooling, and only 1 h for mechanical cooling.

The amount of the saving energy in a chiller system for yearly operation of an all-air HVAC system with economizer is given in Table 5. In this case, for $T_{sa} \leqslant 24$ °C, cooling unit installed in İstanbul will achieve 100% free cooling for 4671 h which represents 54% of the year. While, cooling unit will achieve partial free cooling for 3108 h, which is 35% of the year. Therefore, total free cooling is available for 89% of the year, which represents major potential energy and cost savings. If the installed compressor power is 500 kW in the refrigeration unit, the average part-load ratio is 0.5 and the average energy cost in İstanbul is 11 c/kWh, then the saving operating cost for $T_{sa} \leqslant 24$ °C will be 342.375 $ per annum as shown in Table 5.

5. Conclusion and recommendations

The determination and analysis of free cooling potential for an all-air HVAC system is carried out under outdoor conditions of İstanbul, Turkey. It is found that there is an energy saving potential during a significant portion of the year especially in transition months. The free cooling potential varies with supply air temperature and months. It is determined that the transitions months (April, May, September and October) have the highest potential. From June to August, the high outdoor air temperature made the system not beneficial for free cooling except at the high supply air temperature. As increase in supply air temperature, the greater potential for energy savings by the economizer cycle can be achieved.

The economizer cycle is a proven method for allowing many hours of free cooling in many applications at lower operating cost. Parallel to the economic growth of Turkey, package air-condition-

Table 4
The hours of operation of an all-air HVAC system with economizer and without economizer during transition months.

Month	Time	Classical operation hours (h)	The operation hours of temperature-based economizer (h)					
			T_{sa} = 15 °C			T_{sa} = 24 °C		
			Free cooling	Partial free cooling	Mechanical cooling	Free cooling	Partial free cooling	Mechanical cooling
April	01–04	120	113	0	7	113	7	0
	05–08	120	109	0	11	109	11	0
	09–12	120	76	0	44	76	43	1
	13–16	120	60	0	60	60	56	4
	17–20	120	81	0	39	81	38	1
	21–24	120	103	0	17	103	17	0
	Total	720	542	0	178	542	172	6
May	01–04	124	80	0	44	80	44	0
	05–08	124	67	0	57	67	56	1
	09–12	124	24	0	100	24	89	11
	13–16	124	16	0	108	16	88	20
	17–20	124	33	0	91	33	82	9
	21–24	124	60	0	64	60	63	1
	Total	744	280	0	464	280	422	42
September	01–04	120	22	0	98	22	97	1
	05–08	120	20	0	100	20	99	1
	09–12	120	1	0	119	1	79	40
	13–16	120	1	0	119	1	62	57
	17–20	120	5	0	115	5	97	18
	21–24	120	12	0	108	12	106	2
	Total	720	61	0	659	61	540	119
October	01–04	124	81	0	43	81	43	0
	05–08	124	79	0	45	79	45	0
	09–12	124	33	0	91	33	85	6
	13–16	124	28	0	96	28	85	11
	17–20	124	50	0	74	50	72	2
	21–24	124	71	0	53	71	53	0
	Total	744	342	0	402	342	383	19

Table 5
Yearly operation of an all-air HVAC system with economizer and the amount of the saving energy for chiller system.

Supply air temperature (°C)	Operation hours (h)			Total saving operation cost per annum
	Free cooling	Partial cooling	Mechanical cooling	
T_{sa} = 15	4671	0	4089	$256.905
T_{sa} = 18	4671	983	3106	$283.938
T_{sa} = 21	4671	2088	2001	$314.325
T_{sa} = 24	4671	3108	981	$342.375

ers are used more and more frequently for thermal comfort. Therefore, the HVAC systems which have a free cooling option should be preferred, if the climate is favorable. In order to find the exact benefit of economizer cycle, an economic assessment including cost analysis and detailed weather data analysis should be carried out. The free cooling potential of the other locations should be also determined.

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