The potential for evaporative cooling in Turkey

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ABSTRACT

The potential for evaporative cooling to meet Turkey’s growing cooling demand is investigated based on thermodynamics and human comfort. Weather and population data for 51 locations in Turkey were analyzed to estimate for each location the potential annual sensible cooling demand and how well evaporative cooling could meet this demand. In general, evaporative cooling is appropriate for all locations in Turkey except those located directly on a coast. Evaporative cooling appears particularly appropriate for the economically underdeveloped Southeast Anatolia region of Turkey.

1. INTRODUCTION

Turkey is experiencing a rapid increase in demand for air conditioning. Much of this cooling demand is being met with vapor-compression air conditioners that require electricity as their primary energy input. The increase in electricity usage associated with cooling can stress Turkey’s generating capacity and transmission and distribution infrastructure, increase pollution and global warming gas emissions, and have adverse economic impacts.

Alternative cooling technologies that do not rely on electricity or fossil fuels as their primary energy input and/or do not require large central electric generating stations and extensive transmission and distribution networks have the potential to reduce and possibly eliminate many, if not all, of the problems identified above. One such alternative cooling technology is evaporative cooling, which relies on the heat of evaporation of water as its primary energy input. Relative to a vapor-compression cooling system, both capital and operating costs for an evaporative cooling system can be significantly lower. However, these systems do require a consistent supply of water to operate. Additionally, they will only work effectively in drier climates, and in humid climates may not work at all. Bom et al., (1999) indicate that based on climatic considerations evaporative cooling can be implemented throughout all of Turkey. However, this generalization fails to account for the broad range of climates found within Turkey.

Turkey is generally defined as having the following seven regions based on differences in climate and geography: Aegean, Black Sea, Central Analotia, East Anatolia, Marmara, Mediterranean, and Southeast Anatolia. The mountains found throughout Turkey typically run parallel to the coasts and effectively separate these regions climatically from one another. The Mediterranean and Aegean regions have wet and mild winters and hot and dry summers. Most of Turkey’s tourism economy is in these two regions. The Black Sea region has a maritime climate with moderate temperatures and regular precipitation throughout the year. The Marmara region straddles the Aegean and Black Sea regions and is affected climatically by both. Much of Turkey’s industry, commerce and population are concentrated in this region, which includes Istanbul. The Central, East and Southeast Anatolia regions are semi-arid continental with large daily and seasonal temperature variations and dry summers. Temperatures become more extreme as one moves east. The mountainous East Anatolia region is known for its cold snowy winters and has a relatively small population. The Southeast Anatolia region is known for its extremely hot and dry summers and tends to be one of the most underdeveloped economic areas in Turkey.

The primary goal of this research is to determine whether Turkey’s large water resources can be used to displace electricity for cooling through evaporative cooling. The potential cooling demand for 51 locations in Turkey based on climate and population is estimated. Based on thermodynamic and human comfort, the potential for evaporative cooling to meet this cooling demand is estimated.

2. MODEL

Basic thermodynamic principles limit the amount of cooling that can be achieved using evaporative cooling. These thermodynamic limitations can be modeled based on an air’s dry-bulb temperature (T_{DB}), pressure (P), relative humidity (ϕ), humidity ratio (ω) and wet-bulb temperature (T_{WB}). If an air stream has a relative humidity less than 100%, liquid water can be evaporated into the air stream causing its relative humidity and humidity ratio to increase. When liquid water is evaporated into air, the water absorbs approximately 2500 kJ of thermal energy per kg of water from the surrounding air, causing the surrounding air to cool. An air stream can be cooled through this evaporative cooling process until the air becomes completely saturated with water vapor; i.e., ϕ = 100%. The final dry-bulb temperature of an air that undergoes an evaporative cooling process until the air is completely saturated is termed the air’s wet-bulb temperature.

Any air with a relative humidity less than 100% has a dry-bulb temperature greater than its wet-bulb temperature and can undergo an evaporative cooling process. During an evaporative cooling process, the dry-bulb temperature decreases while the wet-bulb temperature remains constant. For a fixed air pressure, once any two of the variables T_{DB}, T_{WB}, ϕ and ω are known, standard thermodynamic relations can be used to calculate the remaining two unknown variables (Schmidt et al., 2005; ASHRAE 1999).

In this analysis two types of evaporative cooling systems are considered. The first is a direct evaporative cooling system, where outside air undergoes an evaporative cooling process and is delivered directly to the space to be cooled. For human comfort reasons this air has a relative humidity less than 100%, and therefore this air stream is not cooled to its wet-bulb temperature. The second type of evaporative cooling system considered is an indirect evaporative cooling system, where an outside air stream (*stream 1*) undergoes an evaporative cooling process and then is passed through a heat exchanger where it cools a second outside air stream (*stream 2*). Stream 1 is exhausted to the surroundings while stream 2 is delivered to the space to be cooled. The relative humidities for both streams 1 and 2 increase, but the increase for stream 1 is greater than that for stream 2. In this analysis the limiting case of a thermodynamically ideal indirect system is assumed, where stream 2 exits the heat exchanger at the ambient air’s wet-bulb temperature but with a relative humidity less than 100%. The advantages of a direct system relative to an indirect system are simple design and operation, and low capital costs. The disadvantage of a direct system relative to an indirect system is that for a fixed outlet dry-bulb temperature the air delivered to the conditioned space has a higher relative humidity, and therefore can be more uncomfortable.

In this model, the ambient air’s dry-bulb temperature data are used to determine the magnitude of the potential sensible cooling demand while wet-bulb temperature and humidity ratio data are used to determine how well evaporative cooling can be used to meet this cooling load. Dry- and wet-bulb temperature data for the year 2004 for 51 locations in Turkey were taken from the Turkish State Meteorological Service. The data are daily at hours 7, 14 and 21. As a first approximation, the daily dry-bulb and wet-bulb temperature profiles are modeled by assuming that for the hour intervals 0-8, 8-16, and 16- 24 the dry-bulb and wet-bulb temperatures are equal to that at 7:00, 14:00 and 21:00.

Sensible cooling is only assumed to be required if the dry-bulb temperature is greater than 25^0C, which is termed the cooling threshold temperature (T_{CLG}). The cooling degree days (CDD) for each 8 hour interval i is calculated as:

$$CDD_i = \frac{x_i}{3}\left(T_{DB,i} - T_{CLG}\right) \tag{1}$$

where x_i is 1 if $T_{DB,i} > T_{CLG}$ and is 0 if $T_{DB,i} \leq T_{CLG}$. By calculating cooling degree days using three data points for each day rather than an average daily temperature, hourly variations in the ability of evaporative cooling to meet this cooling load can be better quantified as described below. Monthly cooling degree days (CDD_j) and annual cooling degree days (CDD) are calculated by summing CDD_i over the required time period.

While the number of cooling degree days quantifies the potential cooling demand based on climate, it does not account for population and therefore is not indicative of the total potential cooling demand for a location. To better quantify the total potential cooling demand for a location, an annual people cooling degree days ($PCDD$) is defined as:

$$PCDD = Population \times CDD \qquad (2)$$

Human comfort based on climatic considerations is primarily a function of dry-bulb temperature, relative humidity, air speed and activity level. Generally the appropriateness of evaporative cooling for a certain location is determined by whether a sufficiently cool dry-bulb temperature can be achieved through evaporative cooling and, if so, whether the relative humidity of the air being delivered to the conditioned space is acceptable. In this analysis the possibility of having air that is too dry for human comfort being delivered to the conditioned space is not considered.

As described above, in a direct evaporative cooling system the air undergoes a constant wet-bulb temperature cooling process, and therefore the ambient air’s wet-bulb temperature data are sufficient to determine how well a direct system will work. For an indirect evaporative cooling system, the air stream delivered to the conditioned space undergoes a constant humidity ratio process and the coldest possible dry-bulb temperature is the ambient air’s wet-bulb temperature. Therefore, wet-bulb temperature and humidity ratio data are sufficient to determine how well an indirect system will work. Wet-bulb temperature and humidity ratio data are combined to make an evaporative cooling index (*ECI*) to rate how well evaporative cooling will work for a given set of ambient conditions. This index is similar to an index proposed by Bom, et al., 1999. The *ECI* is based on two human comfort zones. The first comfort zone is derived from the ASHRAE standards for summer time comfort for light activity and is defined as $T_{WB} < 20^0$C and $22.5 < T_{DB} < 26^0$C, which corresponds to $T_{DB} = 22.5^0$C and $\phi \leq 80\%$ or $T_{DB} = 26^0$C and $\phi \leq 60\%$ (McQuiston et al., 2000). This comfort zone is termed the ASHRAE Comfort Zone herein. Evaporative air conditioners typically result in greater air flows than vapor-compression air-conditioning systems and therefore many people feel comfortable with a higher relative humidity when evaporative air-conditioning systems are used. An expanded comfort zone for evaporative cooling has been proposed that increases the comfortable relative humidity at 25^0C from the 65% defined by the ASHRAE Comfort Zone to 80% (Bom et al., 1999). This comfort zone is termed the Expanded Comfort Zone herein. The *ECI* is presented in Table 1.

The weather data supplied by the Turkish State Meteorological Service consists of dry- and wet-bulb temperatures data but not air pressure data, which are required to calculate the humidity ratio from dry- and wet-bulb temperature data. However, a separate analysis of hourly air pressure data from a different source (Wunderground, 2004) for several locations in Turkey that differed in terms of region and elevation showed that typically the air pressure deviated less than 2% from standard atmospheric pressure (101.325 kPa), which is negligible relative to the other uncertainties in this model. Therefore, an air pressure of 101.325 kPa is assumed for all calculations.

For each dry-bulb temperature greater than 25^0C, the dry- and wet-bulb temperature data are used to calculate the humidity ratio and the *ECI* is determined. For each month, an average *ECI* is calculated weighted by the cooling degree days as:

$$ECI_j = \frac{\sum_{Month} \left(ECI_i \times CDD_i \right)}{CDD_j} \qquad (3)$$

A similar calculation is performed to calculate an average annual *ECI* weighted by the cooling degree days.

The results from the analysis are summarized in Table 2. For each location, the population, annual cooling degree days, people cooling de-

Table 1: Evaporative Cooling Index (*ECI*)

ECI	T_{WB} (^{0}C)	ω (kg_{WV}/kg_{DA})	Description
4	< 20	Any	Direct: Can reach ASHRAE Comfort Zone Indirect: Can reach ASHRAE Comfort Zone
3	20-22.5	Any	Direct: Can reach Expanded Comfort Zone. Indirect: Can reach ASHRAE Comfort Zone.
2	22.5-25	< 0.0164	Direct: Moderately effective; e.g. with $T_{WB} = 25^0C$, $T_{DB} > 28^0C$ and any ω, cooling to $T_{DB} = 28^0C$ and $\phi = 80\%$ is possible. Indirect: Can reach Expanded Comfort Zone.
1	25-27.5	< 0.0184	Direct: Marginally effective; e.g. with $T_{WB} = 27.5^0C$, $T_{DB} > 31^0C$ and any ω, cooling to $T_{DB} = 30.5^0C$ and $\phi = 80\%$ is possible. Indirect: Moderately effective; e.g., with $T_{WB} = 27.5^0C$ and $\omega = 0.0184$ kg_{WV}/kg_{DA} cooling to $T_{DB} = 27.5^0C$ and $\phi = 80\%$ is possible.
0	> 27.5	Any	Evaporative cooling is not appropriate.

gree days and average *ECI* are given along with their ranking, denoted as (R), from largest to smallest. The percent of the annual CDD that fall into each *ECI* category are also presented. For the primary cooling months of June through September, the monthly average *ECI's* are presented. The following locations have fewer than 50 annual CDD and are not included in Table 2 for brevity: Ardahan, Artvin, Erzurum, Erzurum Bolge, Giresun, Kars, Samsun, Trabzon, Van, and Zonguldak. All of these excluded locations are located in the Black Sea or East Anatolia regions.

The data for each region and for all of Turkey are summarized in Table 3. The average annual *ECI* and the percent of the degree days that fall into each *ECI* category are calculated using the cooling degree days and the people cooling degree days as weights.

3. DISCUSSION AND CONCLUSIONS

From Table 2, the best general predictor of whether a location has a low or high *ECI* is whether it is located directly on a coast, and not to which region in Turkey it belongs. For example, all cities listed in the Mediterranean region in Table 2 are located on the coast except for Isparta and Burdur, which are located high in the mountains. Both Isparta and Burdur have significantly higher annual average *ECI*'s than the coastal cities. Although the Black Sea region is typically described as being humid, from Table 3 this region has the second highest average annual *ECI*. However, none of the cities listed in the Black Sea region in Table 2 are on the coast, as all of the coastal cities are not included in Tables 2 and 3 as they had fewer than 50 annual CDD (i.e., Artvin, Giresun, Samsun, Trabzon, and Zonguldak). Consequently, the results summarized in Table 3 should not be extended to these Black Sea coastal cities.

Adana and Antakya are the only two locations with relatively large variations in average monthly *ECI'*s, and neither of these locations is an ideal location for evaporative cooling for any month. The remaining locations exhibited little variation in average monthly *ECI*'s.

Evaporative cooling does not appear appropriate to displace the large cooling demand at resorts along the Mediterranean and Aegean coasts or in the urban centers of Istanbul and Kocaeli in the Marmara region, due to the high level of comfort and reliability commonly expected. However, evaporative cooling can be used to provide some relief from the heat at a low cost in these regions.

Evaporative cooling appears to be a very appropriate throughout all of Central Anatolia.

The Southeast Anatolia region is perhaps the most appropriate region for evaporative cooling. This region has both the highest cooling degree days and people cooling degree days. With the exception of Batman, all locations analyzed have an annual average *ECI* greater than 3.5. Additionally, due to climatic conditioning, people in this region will likely feel very comfortable at temperatures well above the ASHRAE

Table 2: Potential Cooling Demand and Evaporative Cooling Index Values for 41 Locations in Turkey

	Population		CDD		PCDD		Annual ECI							Monthly ECI Averages			
Region			(^{0}C·Day)		(People·^{0}C·Day)				% of Annual CDD								
City	x 10^3	(R)		(R)	x 10^6	(R)	Avg	(R)	0	1	2	3	4	Jun	Jul	Aug	Sep
Aegean																	
Afyon	372	(19)	106	(33)	39	(25)	3.76	(21)	0	0	0	24	76	4.00	3.72	3.58	4.00
Denizli	414	(18)	396	(8)	164	(14)	3.08	(32)	0	1	23	43	33	3.16	3.02	2.75	3.19
Izmir	2,733	(3)	347	(10)	949	(1)	2.50	(38)	2	6	42	40	10	2.62	2.45	2.17	2.39
Mugla	268	(24)	297	(14)	80	(20)	3.66	(24)	0	0	1	32	67	3.80	3.57	3.51	3.82
Black Sea																	
Amasya	197	(28)	194	(18)	38	(27)	3.98	(8)	0	0	0	2	98	4.00	4.00	3.93	4.00
Bartin	48	(40)	75	(37)	4	(40)	3.10	(31)	0	0	18	55	28	3.32	3.04	2.94	2.52
Bayburt	41	(41)	63	(40)	3	(41)	4.00	(1)	0	0	0	0	100	4.00	4.00	4.00	4.00
Bolu	143	(31)	70	(38)	10	(39)	3.71	(23)	0	0	6	16	77	4.00	3.44	3.76	3.92
Central Anatolia																	
Ankara	3,541	(2)	126	(29)	446	(6)	3.83	(17)	0	0	0	17	83	4.00	3.79	3.74	3.95
Cankiri	141	(32)	140	(24)	20	(33)	3.90	(12)	0	0	0	10	90	4.00	3.93	3.74	4.00
Eskisehir	557	(16)	103	(35)	57	(22)	4.00	(1)	0	0	0	0	100	4.00	4.00	4.00	4.00
Karaman	140	(33)	186	(21)	26	(31)	3.88	(14)	0	0	2	9	90	4.00	4.00	3.62	4.00
Kayseri[3]	732	(12)	142	(23)	104	(17)	3.98	(8)	0	0	0	2	98	4.00	4.00	3.95	4.00
Konya	1,295	(6)	136	(26)	176	(13)	4.00	(1)	0	0	0	0	100	4.00	4.00	4.00	4.00
Nevsehir	137	(36)	92	(36)	13	(38)	3.97	(10)	0	0	0	3	97	3.89	4.00	3.95	4.00
Nigde	127	(37)	120	(31)	15	(36)	4.00	(1)	0	0	0	0	100	4.00	4.00	4.00	4.00
Yozgat	315	(21)	52	(41)	16	(35)	4.00	(1)	0	0	0	0	100	4.00	4.00	4.00	4.00
East Anatolia																	
Bingol	123	(39)	310	(11)	38	(26)	3.46	(26)	0	0	6	41	52	3.82	3.26	3.33	3.70
Elazig	364	(20)	279	(15)	102	(18)	3.91	(11)	0	0	0	9	91	4.00	3.85	3.88	4.00
Hakkari	139	(35)	136	(27)	19	(34)	4.00	(1)	0	0	0	0	100	4.00	4.00	4.00	4.00
Malatya	500	(17)	306	(13)	153	(15)	3.84	(16)	0	0	1	15	85	4.00	3.94	3.61	3.92
Mus	160	(30)	193	(19)	31	(28)	3.77	(20)	0	0	0	22	78	3.85	3.78	3.70	3.91
Marmara																	
Balikesir	578	(15)	224	(16)	130	(16)	3.35	(27)	0	0	4	56	40	3.24	3.22	3.21	3.58
Bilecik	124	(38)	106	(34)	13	(37)	3.74	(22)	0	0	0	26	74	4.00	3.57	3.73	3.83
Bursa	1,631	(4)	182	(22)	297	(10)	3.23	(28)	0	0	10	58	33	3.40	3.05	2.99	3.38
Canakkale	216	(26)	123	(30)	27	(30)	3.03	(33)	7	0	7	57	29	3.58	3.05	2.74	3.21
Edirne	231	(25)	188	(20)	44	(23)	3.15	(30)	0	0	13	59	28	3.16	3.07	3.01	3.32
Istanbul	9,086	(1)	68	(39)	621	(4)	2.97	(34)	1	2	15	62	19	3.37	2.75	3.02	3.16
Kirklareli	189	(29)	115	(32)	22	(32)	3.22	(29)	0	0	11	56	33	3.37	3.21	3.03	3.49
Kocaeli	723	(13)	137	(25)	99	(19)	2.88	(36)	1	0	26	57	16	3.03	2.74	2.69	2.70
Mediterranean																	
Adana[3]	1,398	(5)	484	(4)	676	(2)	2.06	(39)	24	13	22	13	28	2.48	1.26	0.79	2.63
Antakya	581	(14)	354	(9)	206	(11)	1.87	(40)	29	11	22	19	18	2.95	1.19	0.86	2.07
Antalya	936	(9)	450	(5)	421	(7)	2.89	(35)	11	4	16	23	47	3.29	2.89	2.21	3.11
Burdur	140	(34)	211	(17)	30	(29)	3.88	(14)	0	0	0	12	88	4.00	3.92	3.80	3.81
Isparta	302	(23)	135	(28)	41	(24)	3.78	(19)	0	0	0	22	78	4.00	3.73	3.71	3.85
Mersin	999	(8)	406	(6)	406	(8)	0.84	(41)	65	7	9	15	4	0.80	0.49	0.36	0.99
Southeast Anatolia																	
Batman[1]	304	(22)	582	(3)	177	(12)	2.75	(37)	2	11	25	33	28	2.52	2.32	2.89	3.02
Diyarbakir	818	(11)	604	(2)	494	(5)	4.00	(1)	0	0	0	0	100	4.00	4.00	4.00	4.00
Gaziantep	1,009	(7)	399	(7)	403	(9)	3.79	(18)	0	0	1	18	81	4.00	3.98	3.48	3.72
Sanliurfa	842	(10)	777	(1)	655	(3)	3.52	(25)	0	0	8	31	61	3.79	3.53	3.06	3.66
Sirnak[2]	211	(27)	306	(12)	65	(21)	3.90	(12)	0	0	0	9	90	4.00	3.85	3.87	4.00

[1] Data from January 1 to March 13 are missing; [2] December 31 data are missing; [3] December data are missing

Table 3: Potential Cooling Demand and Evaporative Cooling Index Values for 7 Regions in Turkey

Region	**Population**		**CDD**		**ECI weighted by CDD**							**PCDD**		**ECI weighted by PCDD**						
			(^{0}C·Day)		**Avg**	**(R)**	**% of Annual CDD**					(People·^{0}C·Day)		**Avg**	**(R)**	**% of Annual PCDD**				
	x 10^3	(R)		(R)			**0**	**1**	**2**	**3**	**4**	x 10^6	(R)			**0**	**1**	**2**	**3**	**4**
Aegean	3,787	(4)	1,147	(4)	3.12	(6)	1	2	21	38	39	1,232	(4)	2.69	(6)	2	5	36	39	19
Black Sea	429	(7)	402	(7)	3.77	(2)	0	0	4	14	81	54	(7)	3.87	(2)	0	0	2	8	89
Central Anatolia	6,985	(2)	1,097	(6)	3.94	(1)	0	0	0	5	95	873	(5)	3.90	(1)	0	0	0	10	90
East Anatolia	1,286	(6)	1,224	(3)	3.77	(3)	0	0	2	20	78	343	(6)	3.82	(3)	0	0	1	16	83
Marmara	12,778	(1)	1,144	(5)	3.21	(5)	1	0	11	54	34	1,251	(3)	3.08	(5)	1	1	13	59	26
Mediterranean	4,356	(3)	2,041	(2)	2.27	(7)	26	7	14	17	35	1,780	(2)	2.62	(7)	30	9	17	16	28
SE Anatolia	3,184	(5)	2,669	(1)	3.54	(4)	1	2	8	20	69	1,794	(1)	3.65	(4)	0	1	6	19	74
TURKEY	**32,805**		**9,723**		**3.27**		**6**	**2**	**9**	**24**	**59**	**7,327**		**3.18**		**8**	**3**	**14**	**27**	**48**

Comfort Zone. Although this region has dry summers, it has large water resources due to the reservoirs constructed on the Tigris and Euphrates rivers that flow through this region. This region is economically underdeveloped relative to the more western regions in Turkey and therefore could benefit from low cost evaporative cooling. Finally, the current actual cooling demand in this region should be a small fraction of its potential cooling demand, and therefore, there is a potential for a rapidly growing evaporative cooling market.

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