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A Research on Environmental Rating Systems Considering Building Energy Performances in Different Climatic Regions of Turkey

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Abstract

Turkey's diverse regions lead to complex issues in sustainability. We studied to cities in different areas of the country to examine the effects of local climate on energy use in energy-efficient buildings. Erzurum is the coldest city; Antalya lies in the Mediterranean region and has the highest solar global horizontal radiation in Turkey. We used Heating Degree Days (HDD) and Cooling Degree Days (CDD) values for both cities to estimate the energy demand for heating and cooling the buildings. In Erzurum, CO_2 emissions are high, because fuel consumption to heat the same building is more than 4 times of that of Antalya in winter. CO_2 emission is significant as the key greenhouse gas. In Antalya, the electricity costs for cooling the same building are more than 42 times that of Erzurum; CO_2 emissions are also higher during summer. A building certified by the Leadership in Energy and Environmental Design (LEED) uses about 35% less energy for heating and cooling in both cities. The economic and environmental contributions of a LEED-certified building in Erzurum is higher during cold weather, while in Antalya, a LEED-certified building conserves comparatively more energy and retains more CO_2 during hot weather. The results show that the LEED Certification System can be a more international system if geographical and climatic differences are also taken into consideration.

Keywords: *cooling degree days, heating degree days, carbon dioxide emission, energy, leadership in energy and environmental design, sustainability, Turkey*

1. Introduction

Government leaders, meteorologists, architects, and engineers are among the most important actors shaping the country for a sustainable future. Economic and environmental concepts of sustainability can work together in a manner consistent with the emergence of national policies. Energy protection policy has become an important issue in developed and developing countries, following the global recognition in the building industry to create sustainable built environments. Therefore, implementing energy rating procedures to assess buildings is becoming more popular. A robust and credible building environmental assessment scheme will play a key role in assessing building energy performance.

Innovative environmental rating systems may influence development plans. However, generalized ideas may be less useful in specific applications. In this study, we examine whether environmental rating systems are feasible in terms of building energy performance in different atmospheric regions.

A popular example for these environmental rating systems is the Leadership in Energy and Environmental Design (LEED) certification developed by the U.S. Green Building Council (USGBC). It is in widespread use in the United States. It is also used in Turkey, because there is no universal green building certification.

A building must score 26 points to earn LEED certification. In the "energy & atmosphere" criteria of the LEED certification, a building can score 17 possible points; 8 of these come from the "optimize energy performance" sub-criteria (Kubba, 2010). These categories therefore represent significant opportunities to increase a building's LEED score.

Seasonal energy consumption calculations play an important role in calculating heating and cooling loads of any household (Duryamaz et al., 2000). Precipitation and temperature records provide important information about the weather conditions of a region. Nevertheless, the degree day method is one of the simplest and reliable energy estimation techniques for energy analysis in buildings (Buyukalaca *et al*., 2001).

Degree days are originally used to evaluate energy demand and energy consumption (Dombaycı, 2009; Moss, 1997). Heating Degree Days (HDD) are quantitative indices designed to reflect the demand for energy needed to heat a building. A similar index, Cooling Degree Days (CDD), reflects the amount of

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energy used to cool a building. Heating degree days and cooling degree days provide considerable ease in estimating the heating and cooling loads of buildings, in energy planning, and in determining the dimensions of HVAC systems (Satman and Yalcınkaya, 1999). Degree days can provide a simplified method for energy estimation (for heating and cooling) that requires less data input, and can help assess rapidly how energy consumption may be influenced by major design decisions (Hitchin and Hyde, 1979). The relation between degree days and energy consumption can also give prior approximate information before construction starts (Matzarakis and Balafoutis, 2004). Several studies have used degree day methods in the energy analysis of buildings (Matzarakis and Balafoutis, 2004; Christenson *et al.*, 2006; Newsham *et al.*, 2009).

However, different climates, like those found in Turkey, may affect the viability of rating systems. For instance, Erzurum is the coldest city in Turkey because of its geographical characteristics. On the other hand, Antalya lies in the Mediterranean region of Turkey and has the highest solar global horizontal radiation. While CDD values for Antalya are extremely high compared to Erzurum, HDD values for Erzurum are almost 7 times those of Antalya. The same percentage of energy conservation for heating and cooling will not cost the same in both cities. There are huge differences in the fuel and electric consumption and CO_2 emissions of buildings of the same size in each city. This casts some doubt on LEED certification's applicability to varied environments.

In this paper, we investigate the LEED credit system in terms of its suitability for international applications. We will determine whether LEED is feasible for the local geographic and climatic conditions of Turkey. Fig. 1 is a map of Turkey, including the cities of Antalya in the Mid-South and Erzurum in the Northeast. The values of longitude, latitude, and elevation for Erzurum and Antalya provinces of Turkey are in Table 1.

Fig. 1. Map of Turkey; Antalya and Erzurum Located in Southern and Eastern Part of Turkey, respectively (European Dialogue, 2011)

Table 1. Values of Longitude, Latitude, and Elevation for the Cities Considered in the Study

Provinces	Latitude	Longitude	Elevation(m)
Antalya	36.70	30.73	47.33
Erzurum	39.92	41.27	1,869.00

The locations of these both cities provide an interesting illustration of the influence of local climates and the influences on the built environment. Therefore we used these two cities and their local climatic circumstances as the basis for evaluating the use and feasibility of the LEED system, with the focus on the energy consumption of buildings. This study will have a potential impact on prejudices about the leading environmental rating systems. It should inspire the development of more local but more reliable certification systems to make countries more sustainable.

2. Energy Consumption of Buildings: Materials and Methods

The contributions of building to environmental problems are increasing significantly. For example, buildings use a considerable amount of energy for heating and cooling to maintain residents' thermal comfort. That amount of energy varies due to local circumstances.

For example, in Turkey, the need for cooling is much more evident than in The Netherlands, whereas Iceland the need for heating is much more evident than in Saudi Arabia. However, it is also related to different perceptions of "heat" and "cold," which are perceptions affected by background, including culture. To keep the comparisons and analyses in this paper as neutral as possible, we did not focus on this perception element, which might vary from group to group (see also e.g., Akiner and Tijhuis 2007).

We therefore generally focus on computational differences, using well-known mathematical formulas in the field of energy consumption. Nevertheless, the influence of perceptions will still play an influencing role in thermal comfort, instead of on the differences in energy consumption. The concept of degree days originates from the work of Lt-Gen. Sir Richard Strachey (1878). We calculated degree days following the work of Hitchin (1990), who described climate classification methods for ASHRAE standards (2001).

Hitchin (1983) proposed a relatively simple formula for heating degree days:

$$D_m = \frac{N_m(\theta_b - \bar{\theta}_{o,m})}{1 - e^{-k(\theta_b - \bar{\theta}_{o,m})}} \tag{1}$$

where, D_m is the monthly degree day value, θ_b is the base temperature, N_m is the number of days in the month, $\bar{\theta}_{o,m}$ is the mean monthly temperature, and k is a location-specific constant derived by the following formula:

$$k = \frac{2.5}{\sigma_\theta} \tag{2}$$

where, σ_θ is the standard deviation of the variation in temperature throughout the month. Unfortunately, σ_θ is rarely known by the typical user, and Hitchin suggested the mean k value of 0.71 for inland areas (Hitchin, 1981). The benefit of Hitchin's formula (1983) is that it is quick to use and requires only limited information.

Two classical equations for the cooling and heating of a structure follow.

For cooling:

$$-C\frac{d\theta_i}{dt} = U'(\theta_i - \theta_o) \tag{3}$$

and for heating:

$$C\frac{d\theta_i}{dt} = Q_p - U'(\theta_i - \theta_o) \tag{4}$$

where, Q_p is the heating system output (at full load), dθ/dt is the rate of change of the building temperature. C is the effective thermal capacitance of the building, derived from the following formula:

$$C = \sum_n c_p \rho V_f \tag{5}$$

where, V_f is the volume of the structural element that is thermally responsive (m^3), ρ is the density of the element (kg·m^{-3}), and c_p is the specific heat of the element (kJ·kg^{-1}·K^{-1}) for n active elements.

We present mathematical calculations regarding heating energy demand and cooling energy demand in Appendix 1 and Appendix 2, respectively. They are the basis for further comparisons of energy consumption of buildings. The resulting values are therefore free of perceptual influences regarding, for example, thermal comfort. They are calculations of the energy consumption of identical buildings in different geographical regions, these being the basis for comparing the use of energy by the built environments-in this paper, the building projects considered.

3. Comparing the Average Climates of Antalya and Erzurum: Results and Findings

Heating and cooling energy demands of selected cities are shown in Fig. 2 and Tables 2, 3, 4, and 5. We obtained meteorological data for these cities from both domestic and international resources (NOAA, 2011; TMS, 2011), revealing profound differences in regional climates. For instance, the heating degree days value for Erzurum was almost 5 times that of Antalya; on the other hand, the cooling degree days value for Antalya was almost 7 times that of Erzurum.

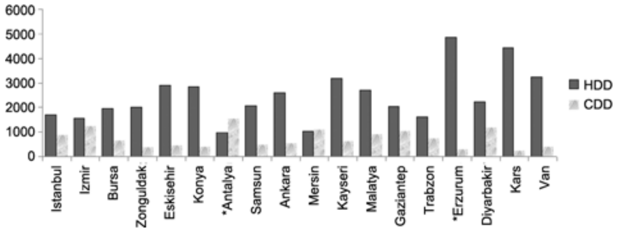

Fig. 2. Annual Heating Degree Days and Cooling Degree Days for Provinces of Turkey from all Geographical Regions of the Country at Base Temperature 18°C using Five Succesive Years' Temperature Data (2006 to 2010). (calculated by Hitchin's Formula (Hitchin, 1983)) (NOAA, 2011; TMS, 2011)

3.1 Case Study: Comparison of Two Building Projects

For this comparative case study, we developed the following building model. The theoretical constructions were five-story reinforced concrete university buildings, 60 meters × 60 meters, in Antalya and Erzurum. Glazing would constitute 30% of the external walls and would behave like a wall. Approximately 200 people would occupy each building. The floors would be cast in-situ concrete. The office space would be partitioned using plasterboard partition walls.

Table 6 below shows the areas of each component, together with typical values of density and specific heat. We set the effective depth of mass at 30 mm for the external walls and ground and internal floors, and 15 mm for the plasterboard partitions. The thermal capacitance, C, is the product of the four preceding columns of Table 6 below. This gives a value of C for

Table 2. 5 Year Average (2006 to 2010) Heating Degree Days / Cooling Degree Days at Distinct Base Temperatures in °C for Erzurum, Turkey (41.27E, 39.92N). (calculated by formulas from Section 2 (NOAA, 2011; TMS, 2011))

Base Temp.	12.5	13	13.5	14	14.5	15	15.5	16	16.5	17	17.5	18	18.5
Jan	755/0	771/0	786/0	802/0	817/0	833/0	848/0	864/0	879/0	895/0	910/0	926/0	941/0
Feb	568/0	582/0	596/0	610/0	624/0	638/0	653/0	667/0	681/0	695/0	709/0	723/0	737/0
Mar	387/2	403/1	418/1	433/1	448/1	464/0	479/0	495/0	510/0	525/0	541/0	556/0	572/0
Apr	238/11	251/9	265/8	279/7	293/6	307/5	321/4	336/4	350/3	365/3	380/2	394/2	409/2
May	118/44	129/39	140/34	151/30	163/27	175/23	188/21	202/18	215/16	228/14	242/12	255/11	269/9
Jun	48/114	54/104	59/95	66/87	73/79	80/72	89/65	98/58	107/53	117/48	128/43	138/40	149/35
Jul	22/202	25/190	29/178	33/167	36/155	41/144	46/133	50/123	56/112	62/103	68/94	75/85	82/77
Aug	20/226	23/214	26/201	30/189	33/177	37/166	41/154	46/143	50/132	56/122	61/112	67/103	74/94
Sep	68/117	74/109	80/100	87/92	95/84	103/77	111/71	121/65	131/60	141/55	151/51	161/46	172/42
Oct	154/32	166/29	179/26	191/23	204/20	217/17	230/15	244/13	257/11	271/10	285/8	299/6	313/5
Nov	346/2	361/1	375/1	390/0	405/0	420/0	435/0	450/0	465/0	480/0	495/0	510/0	525/0
Dec	580/0	596/0	611/0	627/0	642/0	658/0	673/0	689/0	704/0	720/0	735/0	751/0	766/0
Total	3304/750	3435/696	3564/644	3699/596	3833/549	3973/504	4114/463	4262/424	4405/387	4555/355	4705/322	4855/293	5009/264

Table 3. 5 Year Average (2006 to 2010) Heating Degree Days / Cooling Degree Days at Distinct Base Temperatures in °C for Antalya, Turkey (30.73E, 36.70N) (calculated by formulas from Section 2 (NOAA, 2011; TMS, 2011))

Base Temp.	12.5	13	13.5	14	14.5	15	15.5	16	16.5	17	17.5	18	18.5
Jan	97/25	108/20	120/17	132/13	145/10	158/8	171/6	185/4	199/3	214/2	229/2	244/1	259/1
Feb	74/31	83/26	92/22	102/18	113/15	124/12	136/9	148/7	161/6	173/5	186/3	199/2	213/2
Mar	36/74	42/65	50/56	57/49	66/42	76/36	86/31	97/26	108/22	120/19	131/14	144/11	157/9
Apr	12/143	15/131	18/120	22/108	26/97	30/87	36/77	42/68	49/60	56/52	64/45	73/39	82/34
May	1/262	2/247	3/232	3/218	5/203	6/189	8/176	10/163	14/151	17/139	21/127	25/116	30/105
Jun	0/409	0/394	0/379	0/364	0/349	0/334	0/319	0/304	0/289	1/275	1/260	2/246	3/232
Jul	0/517	0/502	0/486	0/471	0/455	0/440	0/424	0/409	0/393	0/378	0/362	0/347	0/331
Aug	0/530	0/515	0/499	0/484	0/468	0/453	0/437	0/422	0/406	0/391	0/375	0/360	0/344
Sep	0/399	0/384	0/369	0/354	0/339	0/324	0/309	0/294	0/280	1/265	1/251	2/236	3/222
Oct	0/281	1/266	1/251	1/236	2/221	3/206	4/192	6/179	8/165	11/153	14/140	17/128	21/116
Nov	19/129	22/117	26/106	31/96	36/86	41/76	48/68	55/60	63/53	71/47	81/41	90/35	100/31
Dec	59/55	68/48	77/42	86/35	96/30	107/26	119/21	131/18	158/15	163/13	169/10	182/7	196/6
Total	298/2855	341/2715	387/2579	434/2446	489/2315	545/2191	608/2069	674/1954	760/1843	827/1739	897/1630	978/1528	1064/1433

Table 4. Mean Daily Temperatures for each Month (average of 5 years from 2006 to 2010) for Antalya and Erzurum in °C (NOAA, 2011; TMS, 2011)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Antalya	9.7	10.1	12.4	16.0	20.4	25.4	28.5	28.0	24.5	19.8	14.5	11.0
Erzurum	-10.0	-8.6	-2.6	5.4	10.4	14.9	19.3	19.3	14.3	7.6	0.2	-6.5

Table 5. Monthly Solar Potential for Antalya and Erzurum in W/m^2 (NOAA, 2011; TMS, 2011)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Antalya	190	225	300	330	380	395	385	450	350	290	220	170
Erzurum	190	230	250	290	320	350	330	330	230	225	190	150

Table 6. Calculation of Thermal Capacitance for Proposed University Building

	Component area / m^2	Fabric density / (kg/m^3)	Fabric specific heat / (J/kg·K)	Effective depth of mass / m	C / (J/K)
External walls	6,000	1,400	1,000	0.03	252,000,000
Ground floor	3,600	2,100	840	0.03	190,512,000
Roof	3,600	2,100	840	0.03	190,512,000
Internal partitions	40,000	950	840	0.015	478,800,000
Internal floors	18,000	2,100	840	0.03	952,560,000
				Σ:	2,064,384,000

the building of 2.06×10^6 kJ·K^{-1}. In Table 7 and 8 we show the comparative calculations based on the specific mathematical values in each situation.

The highlighted parameters in Table 7 and 8 are most significant parameters of the heating and cooling calculations. Analyzing the above tables with the calculated values of CO_2 emission and also heating and cooling energy consumption in terms of fuel and electricity gives interesting food for thought, especially in considering the usefulness of the LEED certification system in different climates.

4. Conclusions

Sustainable building construction has an important role to play in socio-economic development. In Turkey and in many other developing countries, governments promote the application of new construction practices. Some energy and environmental problems may be solved if new development plans consist of environmentally friendly low-emission and low-energy buildings. Therefore, building designers, engineers, and architects must consider the role climate plays in successful sustainable building design.

A popular way of assessing the sustainability of buildings is to apply the LEED rating system. However, it is important that the system be reliable in varying distinct local geographic and climatic conditions. In this study, we address this issue.

The aim of our study was to examine the LEED credit system in terms of its suitability for international applications. For this reason, we used identical hypothetical model buildings in Antalya and Erzurum. The analysis revealed the effects of distinct

Table 7. Heating Calculated for Antalya and Erzurum in Winter Month (December)

	C (kJ K^{-1})	Σ(UA) (W/K)	V (m^3)	N (h^{-1})	Occupancy (h)	Unoccupied hours (t_3-t_1)	Ventilation loss (W/K)	U' (kW/K)	θ_{sp} (°C)	θ_o (°C)
Antalya December	2.06 × 106	20,000	90,000	0.5	10	14	15,000	35	20	11
Erzurum December	2.06 × 106	20,000	90,000	0.5	10	14	15,000	35	20	-6.5
	Q_P (kW)	Q_G (kW)	Days in week	η efficiency	C_g (\$/kw.h)	C_f (kg/kw.h)	k	τ (h)	θ_{so} (°C)	t_3-t_2 preheat time (h)
Antalya December	1,460	70	5	0.75	0.1	0.194	0.81	16.35	15.36	1.73
Erzurum December	1,230	55	5	0.75	0.1	0.194	0.71	16.35	13.38	9.29
	t_2-t_1 plant off time (h)	Σ_i Overnight internal temp. (°C)	$\bar{\theta}_i$ Mean 24-h temp. (°C)	θ_b Base temp. (°C)	D_m Monthly degree days (K.day)	F (kW.h)	$\Psi_{E(95\%)}$ Uncertainty of energy estimates (%)		C_g Cost of fuel (\$)	CO_2 emission (tonnes)
Antalya December	12.27	244.14	18.51	16.51	158.67	177,598	17.23		17,759.8	3.45
Erzurum December	4.71	214.66	17.23	15.66	664.80	744,576	2.78		74,457.6	14.45

Table 8. Cooling Calculated for Antalya and Erzurum in Summer Month (June)

	C (kJ K^{-1})	U' (kW/K)	Occupancy (h)	Unoccupied hours (t_3-t_1)	$\dot{m}c_p$ (kW/K)	N Days in the month	k; k_m	g_S supply moisture content	θ_{ai} (°C)	θ_{ao} (°C)
Antalya June	2.06 × 10^6	35	10	14	25	30	0.81; 1,800	0.009	22	25.4
Erzurum June	2.06 × 10^6	35	10	14	25	30	0.71; 1,600	0.008	22	14.9
	g_r; g_o room; outside moisture (kg/kg)	Δ_P fan pressure (Pa)	$\theta'_{ao(night)}$ (°C)	$\theta'_{ao(night)}$ (°C)	η_{fan} efficiency	C_e (\$/kw.h)	C_f (kg/kw.h)	Chiller CoP	τ (h)	Q_s (kW)
Antalya June	0.01; 0.012	1500	32	21	0.6	0.14	0.422	3	16.35	120
Erzurum June	0.007; 0.008	1500	18	10	0.6	0.14	0.422	3	16.35	100
	$\frac{Q_s}{\dot{m}c_p}$ (K)	$\frac{U'}{\dot{m}c_p}(\theta'_{ao(day)} - \theta_{ai})$ (K)	$\overline{\Delta\theta'_L}$ (K)	$\frac{Q_C}{\dot{m}c_p}$ (K)	θ_b (°C)	D_m (K.day)	F (kW.h)		C_e Cost of electric (\$)	CO_2 emission (tonnes)
Antalya June	4.8	4.76	2.34	-0.04	7.86	453.85	90,770		12,707.8	38.31
Erzurum June	4	-9.94	2.49	-0.08	22.53	10.57	2,114		295.96	0.89

Table 9. CO_2 Factors for various Fuels (BR, 2006)

Fuel	CO_2 factor - Cf (kg/kW·h)
Natural gas	0.194
Oil (average)	0.265
Coal (typical)	0.291
Electricity	0.422

geographic and climatic conditions of Turkey on both energy consumption and CO_2 emissions.

We calculated the heating estimates for the two buildings in the winter month of December, and found a huge difference in the fuel consumption and CO_2 emissions of the two buildings. The results showed that in Erzurum, fuel costs to heat the building would be more than 4 times those of the same model building in Antalya in winter. Accordingly CO_2 emissions were high compared to Antalya. A LEED-certified building uses about 35% less energy for cooling and heating in both cities. Hence, during cold sessions, the LEED-certified building in Erzurum would contribute more benefits to the economy and environment.

However, we also estimated the electricity consumption and CO_2 emissions from cooling the buildings in the summer month of June in Antalya and Erzurum. The electrical costs for cooling the model building in Antalya were more than 42 times those of the building in Erzurum in June. Hence during hot sessions, the LEED-certified building in Antalya would contribute more benefits to the economy and environment.

This study proves that sustainable building design is not possible if the climate is not taken into consideration. Electrical costs to the society and individual consist not only of money but also the loss of environmental resources. Also, reducing CO_2 emission is a highly important issue because it is the key greenhouse gas.

Academicians and entrepreneurs should make reducing the energy consumption of buildings a leading goal. For this aim, especially for international applications, designers must consider the distinct local conditions in developing environmental credit systems. In other words, the LEED Certification System can become a more useful international system if it takes geographic and climatic differences into consideration, instead of just using straightforward percentage-based evaluations when giving credits for a building.

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Appendix 1. Heating Energy Estimation

The following equations are based on accurate and well-defined input values; for their derivation see Day and Karayiannis (1998; 1999a; 1999b), Day (2005), Day *et al.* (2000; 2003).

$$U' = (\mathrm{AU} + 1/3\mathrm{NV})/1000 \tag{6}$$

where, U is the fabric U-value ($\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}$), average U was selected as 0.3 for this study (average for outdoor brick, concrete out and inner layers, plasterboards, glazings etc.), A is the component area ($\mathrm{m^2}$), N is the air infiltration rate in air changes per hour ($\mathrm{h^{-1}}$) and V is the volume of the space ($\mathrm{m^3}$).

Subtracting this gain-related temperature rise from the internal temperature gives rise to the concept of a base temperature, thus:

$$\theta_o = \theta_{sp} - Q_G/U' \tag{7}$$

where, $\bar{\theta}_{o,m}$ is mean monthly outdoor temperature (K), Q_G is average casual gains to the space (kW), θ_{sp} is the set point temperature, and U' ($\mathrm{kW\ K^{-1}}$) is building heat loss coefficient.

24-hour mean internal temperature can be calculated as:

$$\sum_{t_1}^{t_3}\theta_i = \theta_o(t_3-t_1) + \tau(\theta_{sp}-\theta_o)\left[e^{\left(\frac{t_3-t_2}{\tau}\right)} - e^{-\left(\frac{t_2-t_1}{\tau}\right)}\right] + \frac{\tau\cdot Q_p}{U'}\left[1+\left(\frac{t_3-t_2}{\tau}\right) - e^{\left(\frac{t_3-t_2}{\tau}\right)}\right] \tag{8}$$

$$\bar{\theta}_i = \frac{\sum_{t_1}^{t_3}\theta_i + (\theta\times hours\ \ of\ \ occupancy)}{24} \tag{9}$$

where, $\Sigma\theta_i$ is the sum of the overnight internal temperatures, Q_p is plant output capacity (kW), $(t_3 - t_1)$ is the length of unoccupied period (hours), $(t_3 - t_2)$ is length of the preheat time (hours), τ is the building time constant (hours), $(t_2 - t_1) = (t_3 - t_1) - (t_3 - t_2)$ is the length of time the plant was off (hours), respectively.

τ is the building time constant (h), obtained from:

$$\tau = \frac{C}{3600U'} \tag{10}$$

where, C is the building thermal capacity ($\mathrm{kJ\ K^{-1}}$) and t_2 is the optimum switch-on time, obtained from:

$$t_3 - t_2 = \frac{C}{3600U'}\ln\left[\frac{Q_p - U'(\theta_{sp}-\theta_o)}{Q_p - U'(\theta_{so}-\theta_o)}\right] \tag{11}$$

with the optimum plant switch-on temperature, θ_{so} (*K*), obtained from:

$$\theta_{so} = \theta_o + \frac{Q_p(\theta_{sp}-\theta_o)e^{-\left(\frac{t_3-t_1}{\tau}\right)}}{Q_p + U'(\theta_{sp}-\theta_o)e^{-\left(\frac{t_3-t_1}{\tau}\right)} - U'(\theta_{sp}-\theta_o)} \tag{12}$$

The base temperature can be found as (Day *et al.*, 2003):

$$\theta_b = \bar{\theta}_i - \frac{Q_G}{U'} \tag{13}$$

Calculation of degree days and fuel consumption follow the same procedure as for the continuously heated case with this revised base temperature. The estimated fuel consumption, F(kW·h) is found from:

$$\mathrm{F} = (24\ U'D_m)\ /\ \eta \tag{14}$$

where, η is overall seasonal heating system efficiency, and 24 is the conversion factor from days to hours.

Fuel consumption is converted to cost by:

$$\mathrm{F} \times \text{cost of fuel } (\mathrm{C_g})\ (\$) \tag{15}$$

The fuel consumption can be converted to carbon dioxide (CO_2) emissions by multiplying by the relevant carbon dioxide factor, C_f. Table 9 gives these factors for a range of fuels.

The carbon dioxide emissions, in tonnes, are then given by:

$$\text{Carbon emission} = (\mathrm{C_f}\cdot \mathrm{F})\ /\ 1000\ \text{(tonnes)} \tag{16}$$

$\Psi_{E(95\%)}$, the uncertainty in the energy estimate for 95% of all calculations is defined as:

$$\Psi_{E(95\%)} = 130\ \mathrm{D_m}^{-1.3} \times 100 \tag{17}$$

Similarly, the seasonal uncertainty equation is:

$$\Psi_{E(95\%)} = 1600(\mathrm{D_m})^{-1.35} \times 100 \tag{18}$$

where, D_m is the sum of monthly degree days over the heating season.

Appendix 2. Cooling Energy Estimation

The energy extracted over time can be re-expressed as an integral:

$$\int Q_E dt = \dot{m}c_p \int \left\{\theta_{ao} - \left[\theta_{ai} - \frac{\dot{v}\Delta p}{\dot{m}c_p\eta_{fan}} - \frac{Q_s}{\dot{m}c_p} - \frac{U'}{\dot{m}c_p}(\theta'_{ao(day)} - \theta_{ai}) - 2400(g_o - g_s)\right]\right\}dt \tag{19}$$

where, Q_E is the rate of heat removal from the air (kW), $\dot{m}$ is the mass flow rate of the air ($\mathrm{kg{\cdot}s^{-1}}$), c_p is the specific heat of air ($\mathrm{kJ{\cdot}kg^{-1}{\cdot}K^{-1}}$), θ_{ao} is the outside air temperature (K), $\dot{v}$ is the volume flow rate of air ($\mathrm{m^3{\cdot}s^{-1}}$) and it is assumed as 20 $\mathrm{m^3/s}$ for this study, ΔP is the pressure rise across the fan (kPa), η_{fan} is the fan efficiency, θ_{ai} is the occupied internal air temperature (K), $\theta'_{ao(day)}$ is the monthly daytime outdoor temperature, Q_s is the combination of the solar gain and the internal sensible gain (kW), and g_o and g_s are the outside and off-coil moisture contents respectively (kg (water vapour)$\cdot\mathrm{kg^{-1}}$ (dry air)).

The integral on the right hand side of Eq. (19) (i.e., in the curly brackets) is the cooling degree day total, with the term inside the square brackets being the base temperature. In order to find the monthly cooling degree days average monthly values of the variables in the square brackets can be used. In the case of moisture, the average difference can be found from a form of Hitchin's formula (1983):

$$\overline{(g_O - g_S)} = \frac{\overline{g_O} - g_S}{1 - e^{-k(\overline{g_O} - g_S)}} \tag{20}$$

where, $\overline{g_O}$ is the mean monthly outdoor moisture content (kg·kg$_{\text{dry air}}^{-1}$) and g_s is the supply air moisture content (kg·kg$_{\text{dry air}}^{-1}$).

Mean notional temperature rise due to latent load on the coil (K):

$$\overline{\Delta\theta'_L} = 2400 \times \overline{(g_O - g_S)} = 2400 \times \frac{\overline{g_O} - g_S}{1 - e^{-k(\overline{g_O} - g_S)}} \tag{21}$$

k_m (hitchen constant at moisture) is found from:

$$k_m = \frac{2.5}{\sigma_{gO}} \tag{22}$$

where, σ_{gO} is the standard deviation of outdoor monthly moisture content. For London, k lies in the region 1220 to 2300 with a mean value of 1700 (Day *et al.*, 2000).

Depending on the thermal capacity of the exposed mass the load on the cooling system can be mitigated if these gains can be stored and effectively released outside of occupancy hours.

$$\Delta\theta_i = (\theta_{i(3)} - \theta_{sp}) = \left(e^{-\frac{t_3 - t_1}{\tau}} - 1\right)(\theta_{sp} - \theta'_{ao(night)}) \tag{23}$$

where, $\Delta\theta_i$ is the change in the temperature of the building fabric (K) and $(t_3 - t_1)$ is the unoccupied period (h).

In this case, $\theta'_{ao(night)}$ should be the average overnight outdoor air temperature in K. This change in fabric temperature can be multiplied by the thermal capacity of the structure, and divided by 24 × 3600 to give the average rate of gain that will be absorbed by the structure, Q_C, during the whole day:

$$Q_C = \frac{C(\Delta\theta_i)}{24 \times 3600} \tag{24}$$

Q_C will have the opposite sign to the gains as it is mitigating the load on the plant.

The mitigation of gains due to night-time cooling of the fabric:

$$\frac{Q_C}{\dot{m}c_p} = -\frac{C}{\dot{m}c_p \times 24 \times 3600} \times e^{-\frac{t_3 - t_1}{\tau}} (\theta_{sp} - \theta'_{ao(night)}) \tag{25}$$

where, $\theta'_{ao(night)}$ is the mean monthly overnight outdoor temperature.

Base temperature is;

$$\theta_b = \theta_{ai} - \frac{\dot{v}\Delta p}{\dot{m}c_p\eta_{fan}} - \frac{Q_S}{\dot{m}c_p} - \frac{U'}{\dot{m}c_p}(\theta'_{ao(day)} - \theta_{ai}) - 2400(g_O - g_S) - \frac{Q_C}{\dot{m}c_p} \tag{26}$$

Cooling degree days:

$$D_m = \frac{N(\overline{\theta}_{om} - \theta_b)}{1 - e^{-k(\overline{\theta}_{om} - \theta_b)}} \tag{27}$$

where, $\overline{\theta}_{o,m}$ is the mean monthly outdoor temperature.

According to the first law of thermodynamics, in a reversible system we can show that:

$$Q_{hot} = Q_{cold} + W \text{ and } W = Q_{hot} - Q_{cold} \tag{28}$$

where, Q_{hot} is the heat given off by the hot heat reservoir and Q_{cold} is the heat taken in by the cold heat reservoir.

$$CoP_{cooling} = Q_{cold}/(Q_{hot} - Q_{cold}) = T_{cold}/(T_{hot} - T_{cold}) \tag{29}$$

where, CoP is the plant average Coefficient of Performance, T_{hot} and T_{cold} are the absolute temperatures (K) of the hot and cold heat reservoirs respectively, $CoP_{cooling}$ applies to air conditioners or refrigerators.

Energy consumption of the chiller is calculated by:

$$F_{chiller} = \frac{24 \times \dot{m}c_p \times D_m}{CoP} \tag{30}$$