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Quantifying the domestic electricity consumption for air-conditioning due to urban heat islands in hot arid regions

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HIGHLIGHTS

- Effects of urban heat islands on domestic electricity consumption for air-conditioning.
- Variation in electricity consumption is a direct result of modifications on urban microclimate.
- The domestic cooling load is up to 17–19% higher than the rural load over the year.
- Domestic electricity consumption in urban centres is higher than the rural consumption by 10%.
- Estimates of urban consumption based on data of airports cause an error that can reach 6%.

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ABSTRACT

Authoritative reports show that building electricity consumption can increase steadily once temperature values within urban regions exceed their rural values. This study first assesses the role of higher temperatures in the variation of Bahrain's domestic electricity consumption for air-conditioning, using the cooling degree days (CDD) as a quantitative index. It then examines how this consumption is affected by urban features. The assessment is performed using established scenarios of the urban heat island (UHI), advanced statistics of building stock and data for electricity consumption. Simple regression equations are developed to predict the effects of temperature alterations on the electricity consumption. This work shows that the variation in CDD is a direct result of modifications to the urban microclimate. The annual total urban CDD value is up to 17% higher than the rural CDD value. A sharp increase of up to 10% in electricity consumption for air-conditioning occurs in urban regions from April to October. Estimates of the electricity demand for dense urban centres that are based on air temperature values measured in open areas, such as airports, can cause an error of almost 6%. The developed statistical equations can be a valuable and convenient method of quantifying the domestic electricity consumption for air-conditioning in Bahrain and other Gulf countries.

1. Introduction

Centres of newly developed built up areas normally experience higher temperatures when compared to their rural surroundings. This difference is what constitutes the urban heat island (UHI) phenomenon. Various factors contribute to the development of this phenomenon. Some are related the nature of the site, such as geographical location and weather. Other factors are related to human activities, such as urban geometry, choice of building materials, anthropogenic heat emissions and the reduction of vegetation areas and bodies of water [1]. In a previous study [2], the authors examined the effects of these factors in a two step analysis. In the first step, the role of urban expansion in the development of UHI was assessed. In the second step, the impact of urban elements on the UHI was evaluated. Master plans, satellite images and geographical information systems (GIS) were first employed to track the process of urbanisation. Measured hourly temperature data were then used to assess the effect of urbanisation on the UHI development. The measured data, in addition to computational fluid dynamics (CFD) applications, were also used to evaluate the effect of urban elements on the UHI. This study showed that metropolitan areas of Bahrain, particularly their centres, experienced higher temperatures compared to rural areas. The UHI was found to be partly influenced by natural factors such as location and sea breezes. However, the appearance of the UHI was mainly reinforced by urban activities such as on-going construction processes, industrialisation, sea reclamation and the shrinkage of green areas.

Authoritative reports have stated that the UHI can affect the quality of human life, particularly in hot arid regions. Examples

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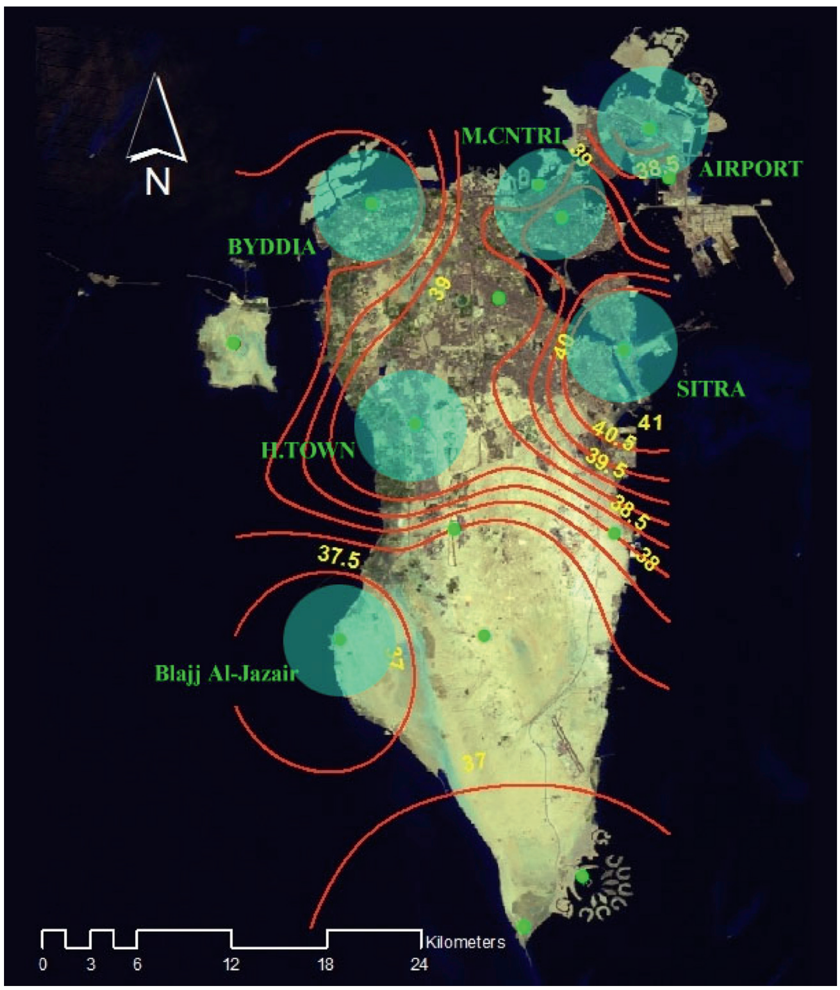
are seen in the compromised thermal comfort conditions and increased energy demand to cool buildings [3]. The variations in thermal conditions and energy demands have recently become a target for scientific research that aims to improve urban environments and the energy efficiency of metropolitan centres. For example, Bouyer et al. [4] used computational fluid dynamics coupled with simulation tools to examine the variation in urban cooling energy and found that the contributions of different physical phenomena were dependent largely upon urban design, surface materials and landscape elements. Flor and Dominguez [5] showed that building energy consumption was related to microclimate aspects of solar loads, wind flow patterns and external air temperatures. These findings indicate that improvements in urban microclimates can have both direct and indirect consequences for energy savings. Hassid et al. [6] examined the effect of UHI on the cooling energy and peak power demand in the Greater Athens area and concluded that calculations made based on the typical meteorological year could misestimate the real energy consumption. In Tokyo metropolis, Huang et al. [7] investigated the actual status of an urban thermal environment in a complex urban area covering a large district heating and cooling system. Kikegawa et al. [8] quantified the possible effects of UHI countermeasures



Scenario	Study site	Temperature
Rural land	Blajj Al-Jazair	Tem (-2)
SCE-1	BYDDIA	Tem (-1)
SCE-2 (BASE)	AIRPORT (Al-Diar Village*)	Tem (+0)
SCE-3	M. CNTRL	Tem (+2)
SCE-4	SITRA	Tem (+3)
SCE-5	H. TOWN	Tem (+1)

*Al-Diar Village is located within 100 m distance from the airport

Fig. 1. Characteristics of adopted UHI scenarios [2].

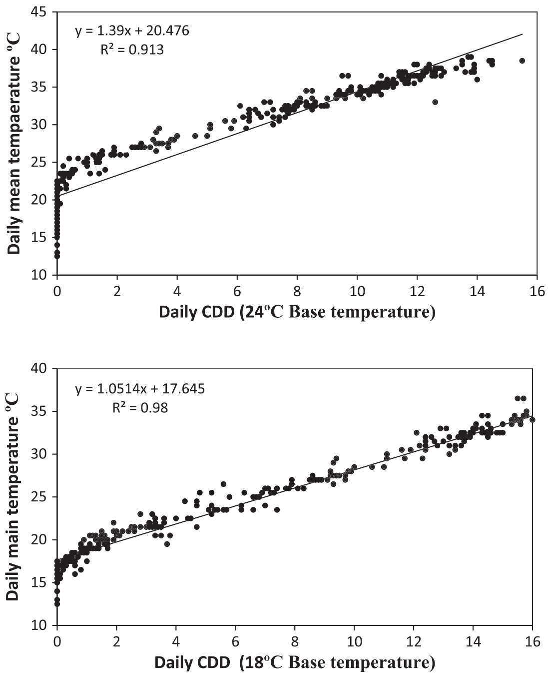


Fig. 2. Correlation between daily mean temperatures and CDD.

upon buildings energy consumption during the summer and suggested two measures to reduce the cooling energy, namely, reducing the air-conditioning anthropogenic heat emissions and increasing the vegetative fraction. Kolokotroni et al. [9] considered summer and winter UHI effects in the UK and found that the urban cooling load in London was up to 25% higher than the rural load over the year, and the annual heating load was reduced by 22%.

Within this context, Kelly et al. [10] used a panel model to estimate the dynamics of internal temperature demand based on the external temperature, combined with important behavioural, socio-demographic and building energy efficiency variables. Hirano and Fujita [11] developed estimation regression models by expressing specific energy consumption as a function of air temperature. The primary advantage of regression models is their simplicity. Once the relationship between the dependent and independent variables is established then the regression equations can be used to estimate the energy consumption. To establish such equations, Al-Garni et al. [12] used standard statistical procedures, while Bianco et al. [13] and Bianco et al. [14] utilised the variance inflation factors. From this perspective, a number of regression equations have been developed. Hirst and Goeltz [15], for instance, formulated a regression equation to examine weather and non-weather sensitive elements of energy consumption by regressing the energy consumption data onto a non-weather dependent constant and a weather dependent coefficient based on heating degree days.

The cooling degree day (CDD) method is a common technique to investigate the effect of higher temperatures on cooling energy consumption [16]. Sailor and Vasireddy [17] presented regression models relating specific energy consumption to wide temperature variables. Akbari and Konopacki [18] developed summary tables to estimate the potential of heat island reduction strategies to reduce cooling energy use in buildings. In addition, Sailor and Muñoz [19] established a methodology for assessing the sensitivity of electricity and natural gas consumption to climate at regional scales. Based on this, Sailor and Dietsch [20] assessed the potential of urban heat island mitigation strategies to affect the urban climate, air quality, and energy consumption within cities.

The current study assesses the role of UHI in the variation of domestic electricity consumption for air-conditioning, using the cooling degree days (CDD) as a quantitative index. The focus of this study is located on Bahrain. This small island state is an interesting place to study UHI implications for several reasons – Bahrain is characterised climatically by hot arid conditions; it currently has one of the fastest growing economies in the Gulf region; it is experiencing an extremely high rate of urban expansion and a rapid increase in electricity consumption.

2. Materials and methods

Fig. 1 shows UHI scenarios established by the authors in a previous study [2]. The current work utilises these scenarios in generating CDD profiles. The CDD profiles, in addition to providing an energy audit database, are used in regression analyses. Simple linear regression equations are developed in order to examine the sensitivity of electricity consumption for particular sites to variations in CDD profiles during the cooling season. The outcomes are validated through comparisons with measured data from real domestic buildings.

2.1. CDD profile generation

Fig. 1 shows that the air temperatures of urban sites increase within the range of 1–5 °C compared with the surrounding rural land. Changes in temperatures of this magnitude will have signifi-

Table 1
The result of regression analyses.

	January	February	March	April	May	June	July	August	September	October	November	December	Annual	Dif(%)
CDD 18 °C														
Blajj Al-Jazair	22	38	111	229	408	471	517	514	444	349	185	51	3339	6.9
BYDDIA	24	40	116	239	421	486	533	529	458	362	193	54	3454	3.3
AIRPORT	25	42	122	248	435	500	548	544	472	374	201	57	3568	BASE
H. TOWN	26	44	128	257	449	514	563	559	486	386	209	60	3682	3.1
M. CNTRL	28	46	133	267	462	529	579	574	500	399	217	63	3797	6.0
SITRA	29	49	139	276	476	543	594	590	514	411	226	66	3911	8.8
CDD 24 °C														
Blajj Al-Jazair	0	2	16	69	226	293	332	329	267	170	41	1	1746	9.7
BYDDIA	0	1.9	18.1	75.1	241.3	310.8	351.9	348	283.4	181.8	45.1	0.9	1858	3.1
AIRPORT	0	2	19	78	249	320	362	358	292	188	47	1	1916	BASE
H. TOWN	0	2.1	19.9	80.9	256.7	329.2	372.1	368	300.6	194.2	48.9	1.1	1974	2.9
M. CNTRL	0	2.2	20.8	83.9	264.5	338.5	382.2	378	309.2	200.4	50.9	1.1	2032	5.7
SITRA	0	2.3	21.6	86.8	272.2	347.7	392.3	388	317.9	206.6	52.8	1.2	2089	8.3

cant effects upon external thermal conditions as well as the internal built environment. Several parameters are of importance, particularly the CDD. They are a measure of the severity of the mean air temperature related to cooling energy consumption. CDD is used to express the amount and length of time when the outside air temperature is below or above a specified base temperature. If the outside air temperature is above a specified base temperature then space cooling is required. There are two problems apply to this method, first, the base point, and second, the calculation method. In this study, two base temperatures are considered in the generation of CDD profiles, 18 °C and 24 °C [21], and the CDD is calculated from the following equation:

$$CDD, i, d = \frac{\sum_{m-1}^{24} (T_m - T_b)((T_m - T_b) > 0)}{24} \tag{1}$$

where CDDi is the cooling degree days for a particular day (d), T_b is the base temperature (18 °C or 24 °C) and T_m is the mean air temperature, considering only the positive values. By using this equation and the corresponding hourly mean air temperature values, it is possible to generate CDD profiles for each UHI scenario. Due to the absence of hourly electricity consumption, this work uses daily, monthly and yearly CDD to be compatible with the available consumption data. The effect of temperature variation (day and night) on the amount of CDD, therefore, is considered at the time of calculation.

The daily, monthly and annual totals of CDD are estimated for the base temperatures 18 °C and 24 °C for all the study sites. Fig 2 shows the correlation between daily mean air temperatures of the AIRPORT (BASE) and CDD with respect to the two base temperatures. Table 1 shows the generated monthly CDD profiles. The representation of these profiles provide the primary method for creating synthetic electricity consumption data with appropriate aggregate daily, monthly and annual profiles.

2.2. Housing stock and electricity consumption

Four key data sources are used in this work: the Results of Population, Housing, Buildings & Establishments Census, which was supplemented by the Central Statistic Origination of Bahrain [22]; an energy audit database provided by the Electricity and Water Conservation Directory [23]; data from the major documents of the literature review [24,25]; and the results of a field survey by the authors. In this survey, detailed architectural, functional and operational data for villas (two storey houses), traditional houses and apartment buildings were obtained from working drawings and utility bills provided by owners, contractors and architects. The accuracy of the obtained data was subject to the supervision of academic advisors and trained energy auditors.

For a number of reasons the focus of this work is the electricity consumed for air-conditioning villas in Bahrain: first, electricity is the major form of energy in Bahrain (over 99%) [26]. Second, the building sector accounts for 83% of the national electricity consumption. Most of this consumption is used for air-conditioning (AC) during the cooling season, and at the hourly level, the proportion of the electricity demand accounted for by AC can approach 80%. Third, buildings, particularly those in the domestic sector, have the largest effect on the electricity demand growth, as 54% of the total electricity is used in this sector. Finally, there is an extremely high expansion in the number of villas that is coupled with a commensurate increase in electricity consumption. Fig. 3 shows the percentage of housing units by housing type.

To develop good representative models for such units, various steps should be undertaken [27]. In the current study, the unit samples were chosen after applying certain criteria and data filters, namely:

1. Location: this filter is applied to select buildings with the same urban boundaries in each study site.
2. Building category: this filter targets the basic typology, size and operation.
3. Age, construction system and materials: this filter is applied to ensure the use of the same construction techniques and building materials. The age of construction is determined to be with no more than 15 years.
4. AC system types: the AC system filter is applied to define the type of AC of the study samples. Window and split units are common in Bahrain, while central AC systems are used in big villas.

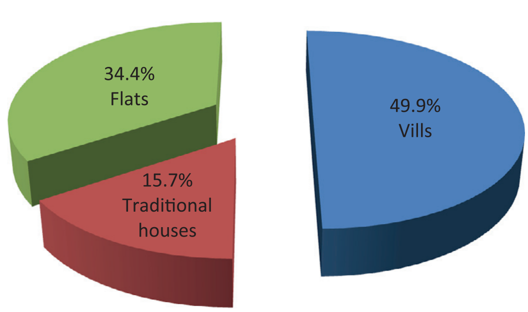


Fig. 3. The percentage of housing units by housing type.

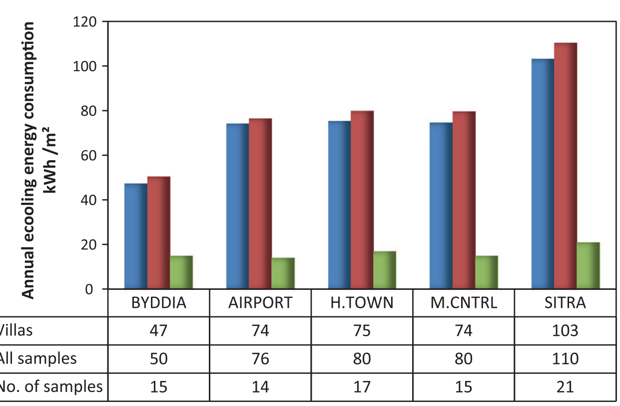


Fig. 4. Annual electricity consumption of samples by urban region.

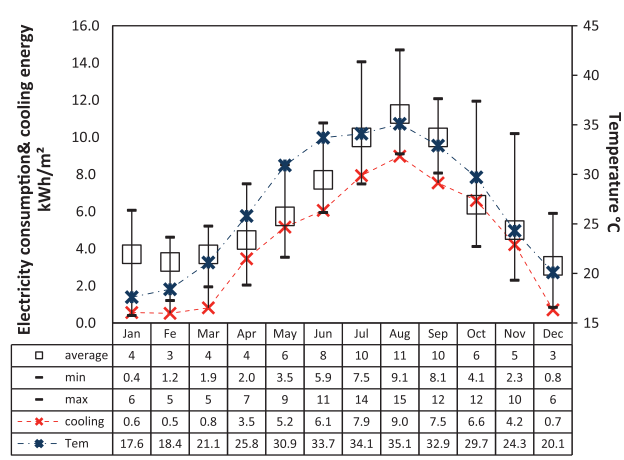


Fig. 5. Monthly normalised electricity consumption for villas in the AIRPORT area.

Table 2
Trend line coefficients of electricity consumption for five scenarios.

Scenario	CDD (Base temperature 18 °C)					CDD (Base temperature 24 °C)				
	BYDDIA	AIRPORT	H. TOWN	M. CNTRL	SITRA	BYDDIA	AIRPORT	H. TOWN	M. CNTRL	SITRA
a	−0.12	2.35	1.79	1.87	4.33	0.89	3.30	2.92	2.89	5.55
b	0.014	0.013	0.015	0.014	0.013	0.020	0.018	0.020	0.020	0.017
R	0.924	0.912	0.925	0.882	0.887	0.944	0.936	0.948	0.927	0.872
R^2	0.854	0.831	0.855	0.778	0.786	0.892	0.875	0.899	0.860	0.761
Adj. R^2	0.840	0.815	0.841	0.755	0.765	0.881	0.863	0.889	0.846	0.737
S. Error	1.216	1.245	1.322	1.652	1.575	1.046	1.071	1.103	1.310	1.665
F	0.000017	0.000036	0.000017	0.000148	0.000121	0.000004	0.000008	0.000003	0.000014	0.000214
P-value	0.000017	0.000036	0.000017	0.000148	0.000121	0.000004	0.000008	0.000003	0.000014	0.000214

a and b are the coefficients of linear regression line $Y = a + bX$.

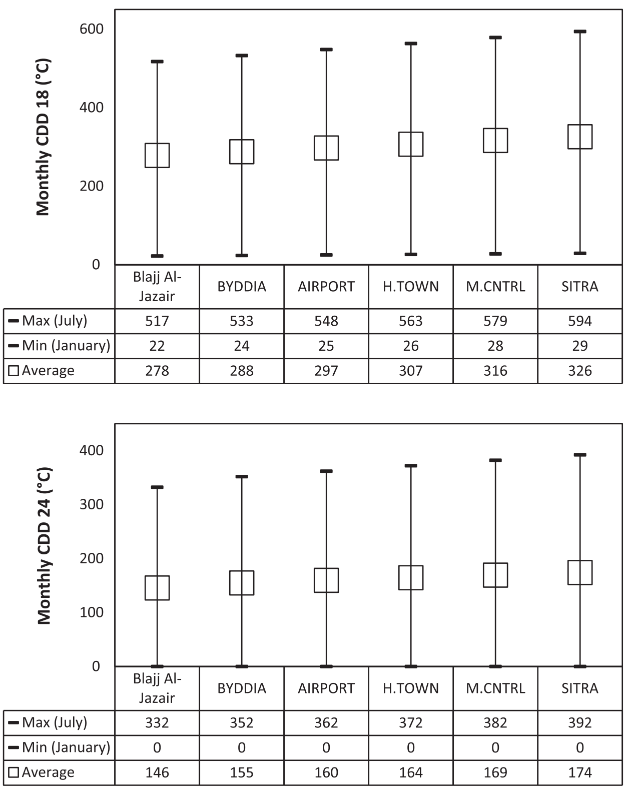


Fig. 6. Monthly average, minimum and maximum CDD for the five studied scenarios.

5. Consumption data: this filter is applied to ensure the availability of complete consumption data for at least two years.

Electricity consumption is primarily analysed on a per square metre of floor area of air-conditioned space basis. This normalisation factor is selected as a way of comparing between different sizes of villas. This work assumes that all villas have the same amount of lighting, appliances and usage patterns, which in fact is probably not the case. This may represent a limitation in using a per unit area basis. The principal benefit of using this unit area basis, however, is its ability to give a simple and easily derived estimate of expected electricity consumption for any given villa.

Fig. 4 illustrates the average annual per square metre electricity consumption of all housing samples. The data were normalised to the square metre of air-conditioned space for 82 houses (villas and traditional houses) located in five major urban regions. Authoritative sources suggest sample sizes greater than ten for any level of confidence in the outcomes [28]. In this work, the sample size of villas at any study site was not less than 11 villas. The normalised electricity consumption values are based on the average of individual consumption values recorded at each site. Given that the ratio of villas between urban centres and suburbs varies, this work calculates the mean weighted by the number of samples in each study site. In the example given in Fig 5, the mean of electricity consumption weighted by the number of villas samples in the AIRPORT area (Al-Dair village) is calculated. The annual range of electricity consumption is between 71 and 78 kW h/m^2. The average of 74 kW h/m^2 is a suitable reference point for villas located in the AIRPORT area. The highest level of this range is primarily for villas with central AC systems, and is most likely due to poor energy management. The principal advantage of this method is that the figures show the realistic variation in electricity consumption, in addition to a close connection with seasonal variations in outdoor ambient temperatures.

2.3. Development of regression equations

Simple estimation equations are developed based on the Princeton scorekeeping model [29]. Eq. (2) is the basic form of regression that allows for the analysis of a dependent variable, such as electricity consumption, subject to an independent variable, such as the CDD.

$$E_{i,t} = a + bCDD\ (ref) \tag{2}$$

The electricity requirement index (E_i) is the dependent (criterion variable) at a particular (t) and the symbols on the right side of the equation signify the independent variable, where (a) represents the intercept, (b) is the slope and CDD is the predictor variable. The E_i is equal to the electricity consumption divided by the gross floor area of the villa in question. In the current case, the equation examines weather variables (temperature) of electricity requirements by regressing the electricity consumption data onto the CDD. When the percentage difference ΔE_i is obtained by the regression equation, the growth or reduction in electricity consumption with respect to two certain periods can be estimated. It is possible then to predict the increase in electricity consumption. The developed equations estimate the consumption of each villa with respect the adopted UHI scenarios. The consumption estimates can then be scaled up to be representative of the study site by multiplying the results by the area of villas.

Table 2 shows the result of regression analyses. A number of observations can be highlighted; first, regressing the monthly E_i onto the generated CDD profiles produced high coefficients of determination R^2 (0.76 to 0.89) and multiple R (0.87–0.94). The high R^2 would indicate a strong relationship between the E_i and CDD, while the high R would confirm the 'strong' correlation between E_i and CDD. Since the values of the coefficient of multiple determinations (R^2) and adjusted R^2 are within the values of 73% and 89%, the regression equations seem to be accurate and to reasonably represent the behaviour of the data. Second, the standard

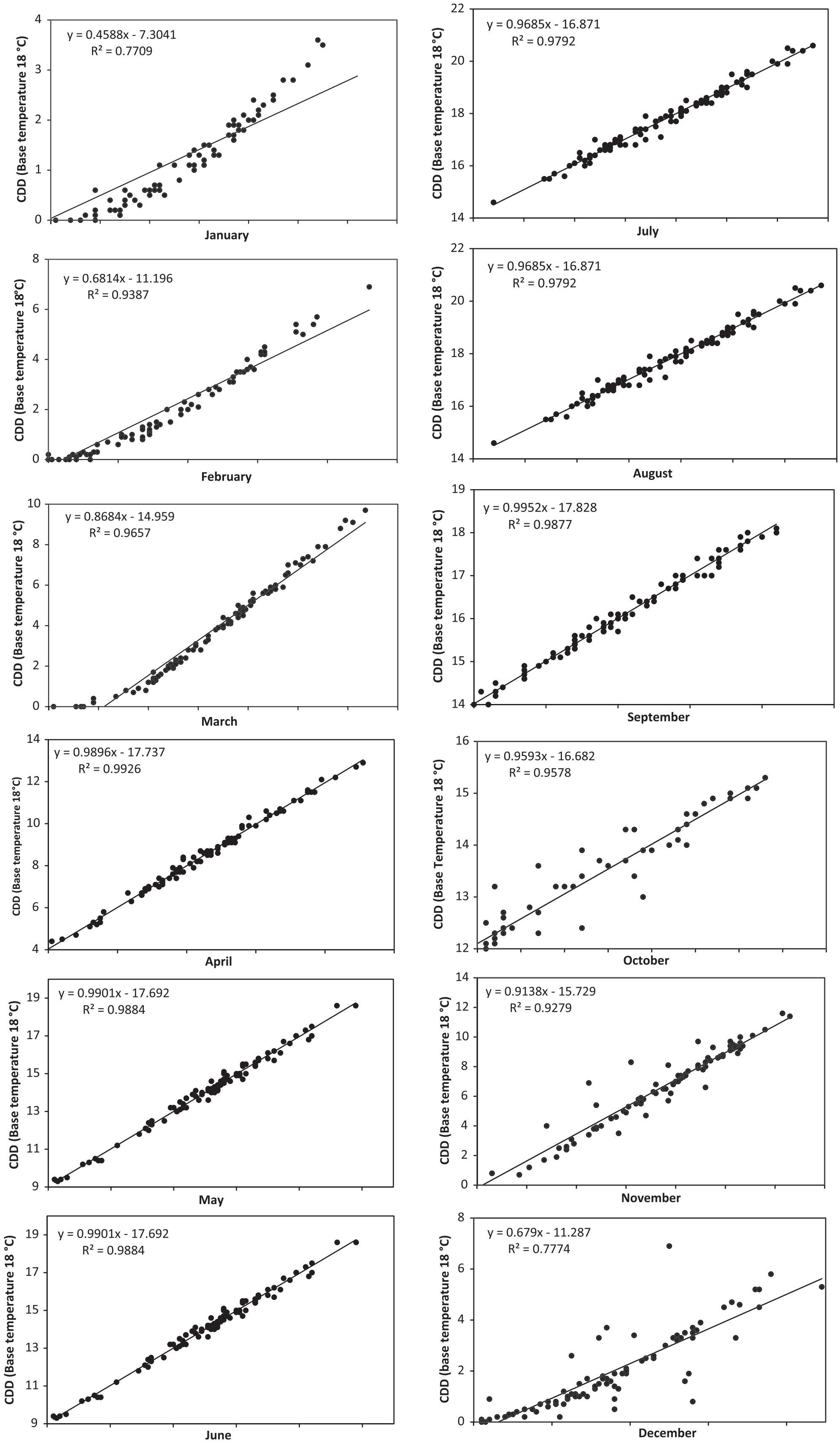


Fig. 7. Correlation between average daily mean temperatures and averages CDDs.

error associated with estimating E_i is within the range of 1–1.6 kW h/m^2. Third, the small P-values imply that the developed equations are statistically valid. Fourth, the significance F with respect to the ANOVA test indicates the goodness-of-fit of the equations. As a rule of thumb, the lower this value then the better the fit. The resultant number assumes that the estimate is asserted as true with a 95% level of confidence. Finally, the correlation between variables varies ranging from 0.26 to 0.75. This implies that CDD and E_i values experience change in the same direction. If one is higher, then so is the other. Based on the above observations, it is possible to say that the regression is significant, well distributed and all coefficients have their expected sign.

2.4. Contribution and novelty

This study employs several techniques including physical measurement, weather normalisation of electricity consumption and thermal analysis. The physical measurements mainly rely upon established database and field surveys of real cases. Weather normalisation of electricity consumption is one of the most common such uses of the CDD method. By using this type of normalisation, it is possible to perform a like-for-like comparison of domestic electricity consumption of urban regions with different temperature values. Weather normalisation is performed using established UHI scenarios for regions with different urban contexts. The simplified CDD method is used to estimate the electricity for air-conditioning due to increases in air temperatures. This method is important to examine the effect of higher temperatures on the thermal behaviour of urban sites.

In many thermal analyses, including the previous works of the authors [2,30], various numerical models were employed in assessing the thermal behaviour of built up environments. A number of difficulties were identified and significant efforts were required to calibrate the numerical models, as can be seen from the high number of numerical inputs. This might represent a disadvantage, as the numerical models required significant computing capability, especially with a great number of scenarios. In contrast, the current work uses the simple linear regression method based on generated CDD profiles. A principal difference of this work is the integration of the CDD method with a simple and flexible statistical technique using billing data and simple survey results. A key advantage of using the statistical technique is that it not only facilitates an estimation of electricity consumption, but that it can also provide an estimate of the uncertainty in the estimation. Furthermore, the developed equations can be used either to make statistical inferences about the effect of different UHI scenarios for explaining electricity consumption or as predictive tools.

3. Results

This section assesses the variation in CDD due to various UHI scenarios and examines the effect of UHI upon domestic electricity consumption for air-conditioning by comparing real consumption data with outcomes based on regression equations.

3.1. Variation in cooling degree days

The daily, monthly and annual totals of the CDD are estimated for the base temperatures 18 °C and 24 °C. Fig. 6 shows monthly average, minimum and maximum CDD for the study sites, including the rural land of Blajj Al-Jazair. From the UHI scenarios in Fig. 1 and the CDD profiles in Table 1, the highest values of the CDD are corresponding to the highest values of UHI scenarios at SITRA, while the lowest values are corresponding with the lowest values of UHI scenarios at Blajj Al-Jazair. A similar type of correspondence is observed at other sites. The highest number of CDD occurs in the month of July and lowest in January. The number of CDD in January is zero based on 24 °C and ranges from 22 to 29 °C based on 18 °C at all the study sites. The cooling duration is less than two days in January, and less than ten days in February, March, November and December. Based on the monthly accumulative total of CDD, it is possible to note that the months of April–October represent the period of the cooling season in Bahrain.

In order to study the variations in CDD at the study sites during a one-year period, the total CDD for each month are plotted and linear regression line coefficients are determined. Fig. 7 shows the correlation between daily CDD and mean air temperatures of the AIRPORT over the year. In a comparison with published CDD values within the Gulf region [21], as shown in Fig. 8, the estimated CDD values are commensurate with these values. The monthly (July) and annual CDD of some neighbouring countries with the

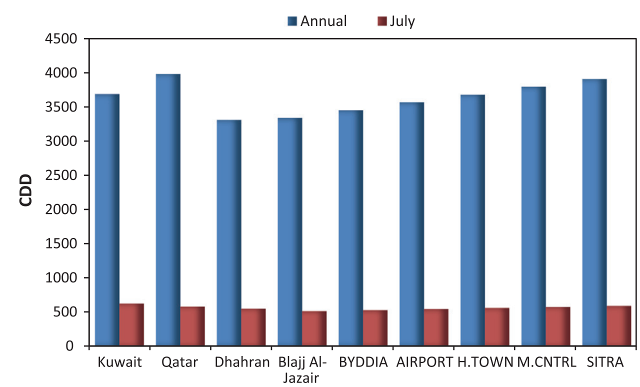


Fig. 8. A comparison between the results and published CDD values.

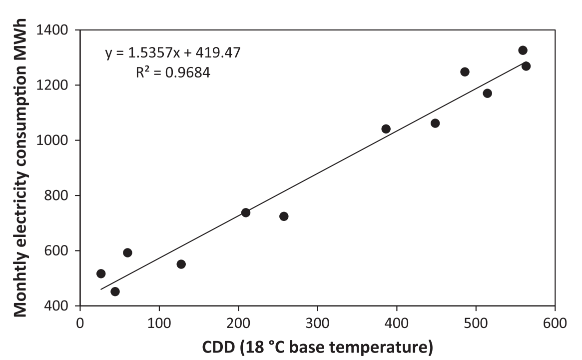
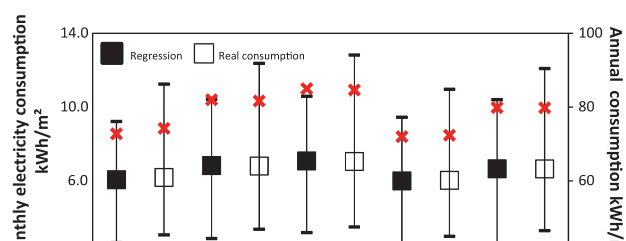


Fig. 9. Correlation between CDD and national domestic electricity consumption.



	AIRPORT		M.CNTRL		SITRA		BYDDIA		H.TOWN	
max	9.2	11.2	10.4	12.4	10.6	12.8	9.5	11.0	10.4	12.1
min	2.7	3.1	2.9	3.4	3.2	3.5	2.3	3.0	2.6	3.3
average	6.1	6.2	6.8	6.8	7.1	7.1	6.0	6.0	6.7	6.7
Annual	72.8	74.2	82.0	81.7	85.0	84.6	72.0	72.4	79.9	79.8

Fig. 10. A comparison between electricity bills and results from regression analyses.

same climatic conditions are almost the same. The magnitude of monthly and annual values is within a comparable range. For example, the annual totals of CDD at BYDDIA and Dhahran were 3314 and 3454, which shows a close agreement between the two close regions. In the case of SITRA and Qatar, the difference in annual CDD is about 2%.

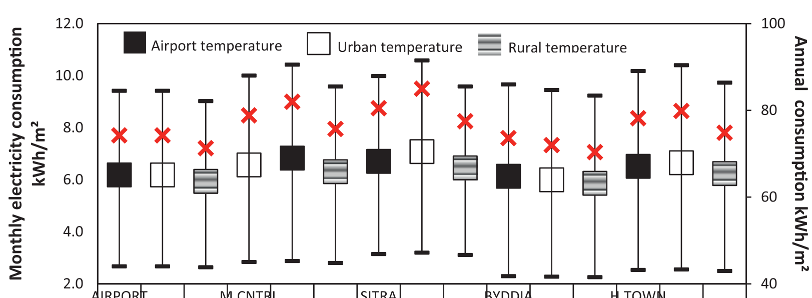
Furthermore, a major monthly and annual variation occurs when the study sites are compared with each other. In Table 1, based on 18 °C, significant increases in the monthly CDD can be noted at H. TOWN, M. CNTRL and SITRA that reach 3%, 6% and almost 9% respectively, when compared to the AIRPORT. In contrast, a major reduction in the monthly CDD can be observed at BYDDIA, with an almost 3.5% reduction. When rural and urban sites are considered, the difference between the maximum (SITRA) and minimum (Blajj Al-Jazair) reaches around 17%. This difference reaches almost 19% when related to a 24 °C base temperature.

Spatial variations of CDD affect human comfort and building electricity consumption. These variations imply that to reach a comfortable internal environment, a dramatic change will occur in the electricity consumption for air-conditioning. The next section examines the effects of CDD growth upon domestic electricity consumption.

3.2. Effect on domestic electricity consumption

The magnitude and spatial trend of monthly CDD (averages of all sites) are found to be very much in line with the national domestic electricity consumption as can be seen in Fig. 9. To estimate the domestic electricity consumption, the generated CDD profiles were used with the developed regression equations. The validity of these equations was verified through a comparison of the estimated results with measured consumption data from a number of new-build villas. Fig. 10 shows the annual electricity consumption as well as the maximum, minimum and average monthly electricity consumptions based on the regression equations and compares them with real consumption data in kW h/m^2. As expected, the estimated figures are quite normally distributed with the corresponding monthly consumption of electricity. However, a moderate variation occurs in which values of real electricity consumption are higher than those derived from the regression equations. The annual maximum variation is found to be 1.5 kW h/m^2 in the AIRPORT area, while the minimum is found to be 0.3 kW h/m^2 in M. CNTRL. This is reasonable since the standard error associated with the regression equations is within the range of 1.0–1.6 kW h/m^2.

Fig. 11 illustrates estimates of domestic electricity demands based on different UHI scenarios. To establish the likely increases in electricity demand for the urban sites the changes were related to the electricity consumption based on the CDD of rural sites. The same technique was applied with respect to the UHI scenario of the airport. In Fig. 11 a sharp increase with various rates can be noted when the results based on rural and urban temperatures are compared. Increases occur in BYDDIA, AIRPORT, H. TOWN, M. CNTRL and SITRA that reach between 4% and 10%. This result confirms the finding of Radhi [30] that domestic electricity consumption can grow between 4.0% and 12.5% if the UAE metropolitan cites warm between 1.6 and 5.9 °C. The illustrated data also show the effect of using temperature data measured in the AIRPORT on the prediction of the electricity consumption of dense urban centres. The prediction of electricity demand in dense urban centres based on air temperature values measured at airports can cause errors within the range of 2–6%. This result is in line with the findings of Hassid et al. [6] that estimates of urban electricity consumption based on measured airport air temperatures can cause errors in the estimates. In addition, domestic buildings in SITRA seem to have the highest difference in electricity demand, followed by M. CNTRL, H. TOWN and BYDDIA in descending order. 5.6%, 4.0% and 2.1% increases in electricity demand are observed at SITRA, M. CNTRL and



	AIRPORT			M.CNTRL			SITRA			BYDDIA			H.TOWN		
max	9.4	9.4	9.0	10.0	10.4	9.6	10.0	10.6	9.6	9.7	9.5	9.2	10.2	10.4	9.7
min	2.7	2.7	2.6	2.8	2.9	2.8	3.1	3.2	3.1	2.3	2.3	2.3	2.5	2.6	2.5
average	6.2	6.2	5.9	6.6	6.8	6.3	6.7	7.1	6.5	6.1	6.0	5.9	6.5	6.7	6.2
Annual	74.2	74.2	71.3	78.9	82.0	75.7	80.5	85.0	77.5	73.6	72.0	70.4	78.2	79.9	74.9
Port(%)				4.0			5.6			2.2			2.1		
Rural(%)			4.1			8.3			9.7			2.3			6.7

Fig. 11. A comparison between consumption results due to different temperature data.

Table 3
Characteristics of study sites.

Area	LON	LAT	ALT	Site description	Sea breeze	Humidity	Land use	Land cover
B. JZR	50.46	25.96	1	Costal	Yea	High	Rural	Sand and gravel road
H. TOWN	50.51	26.11	24	Inland	No	High (±)	Urban-RS	Blocks of buildings, asphalt road
SITRA	50.61	26.15	24	Costal	Yea	High	Urban-RS&IND	Blocks of buildings, factories and asphalt road
BYDDIA	50.46	26.23	8	Coastal	Yes	High	Urban-RS&AG	Blocks of buildings, greenery and asphalt road
M. CNTR	50.56	26.21	5	Inland	Yes	High	Urban-BS&CM	Blocks of buildings and asphalt road
AIRPORT	50.63	26.27	5	Coastal	Yes	High	Urban-SRV	Blocks of buildings and asphalt road
AG: Agriculture				CM: Commercial			±lower relative to other sites	
RS: Residential				BS: Business				
IND: Industrial				SRV: Services				

H. TOWN respectively. In contrast, a reduction in electricity demand is noted in the BYDDIA area with a 2.2% drop.

Having briefly highlighted the results of thermal and statistical analyses, the paper now turns to the discussion. The next section discusses how building electricity consumption is affected by urban activities, particularly the land use and urban surface.

4. Discussion

The UHI phenomenon is created by human factors, such as urbanisation, industrialisation and anthropogenic heat emissions, and by natural factors, such as location and weather. This study emphasises the role of urban activities, particularly the influence of land use and urban surfaces. The results highlighted above show a high correspondence between the CDD, as a function of urban air temperature, and the electricity consumption. To justify such correspondence a brief description of the study sites is essential.

Table 3 shows the characteristics of the study sites. There is a moderate difference in terms of altitude. The maximum is 24 m and the minimum is 1 m above sea level. With the exception of H. Town, all study locations are coastal sites. For example, M.CENTR and its urban boundaries represent the northern coast of Bahrain. Winds from the Northeast direction over the year is a characteristic of these sites; therefore, most of these sites experience favourable sea breezes. Fig. 12 shows average daily values of humidity (January and July) and average daily wind speeds at the study sites. During the winter days there is a minor deviation between the humidity curves of the study sites. The humidity curves in the summer days are also quite normally distributed with minor deviations in the curves of H. Town and BYDDIA. H. Town has the lowest humidity level, while BYDDIA is the highest level. This is because BYDDIA is a coastal land, while H. Town is located in the desert area of Bahrain approximately 5 km from the coast. The highest difference between the two sites in terms of humidity is less than 4%.

The same situation occurs with the wind speed. Two important factors affect the wind flow, including sea breezes, which generally affect the wind and increases its speed, and the presence of urban elements, which act as obstructions that modify the pattern of flow. The urban elements and the convective mixed layers prevent the sea breezes from moving inland towards H. Town. The surface layer in the case of this site is, aerodynamically, slightly rough. The impacts of this roughness are apparent in the lower values of wind speed in H. Town. The difference between this site and the others, nevertheless, is moderate. This is because of the generally low wind speed in Bahrain. In most coastal sites, the average daily wind speed is within the range of 2.5–4.5 m/s, while in H. Town the wind speed is within the range of 2.2–4.0 m/s. In terms of solar irradiation, Bahrain experiences high levels of irradiation. The highest averages of total and direct radiation are 585 W/m^2 and 383 W/m^2 in June and August. Bahrain has almost the same values of irradiation at all of the study sites.

Since the natural factors have almost the same thermal effect on the study sites, the variation in CDD and electricity demand must mainly be related to urban activities such as the urban surface and land use [2]. In terms of urban surfaces, there is a complex link between the temperature of urban surfaces and the external air temperature. Physically, there is no direct link but there are significant influences on each other, especially in the case of surface temperature. An increase in surface temperatures impacts upon the intensity of local and downwind ambient air temperatures because of various convective heat fluxes from the surface. The AIRPORT, for example, is an open site with huge blocks of buildings and asphalt roads, while BYDDIA is a residential district with large green areas. The thermal properties of these surfaces and materials can affect the air temperature and consequently the CDD. BYDDIA is found to have the lowest electricity demand values among other study sites due to the presence of the large green areas.

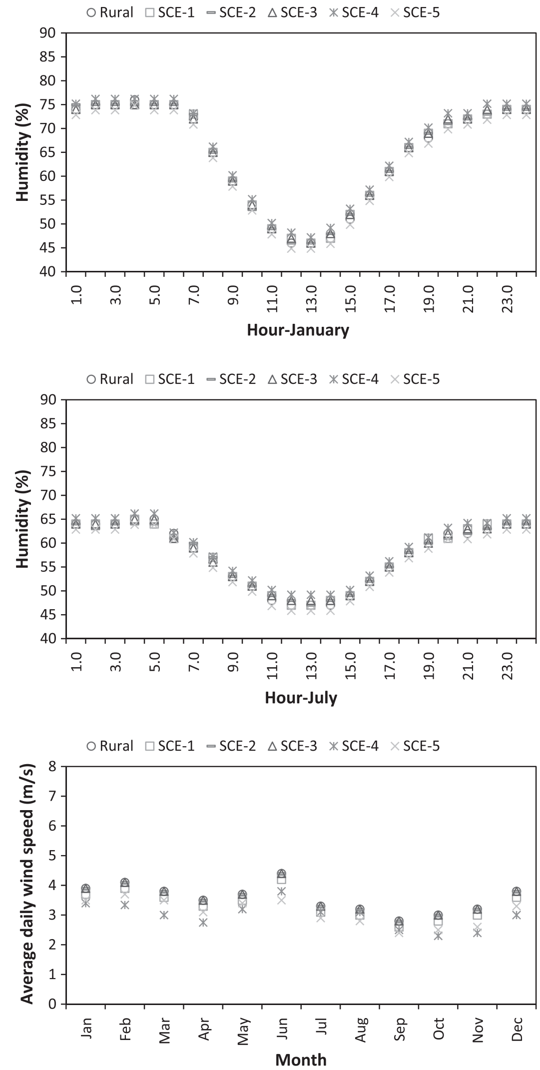


Fig. 12. Weather elements of the study sites.

The variation in electricity demand between the study sites is significant in terms of land use, as illustrated in Table 3. The variation between the maximum (SITRA) and the minimum (BYDDIA) is almost 13 kW h/m^2 due to the relatively large variation in CDD (approximately 575 degree days). The difference in demand between the AIRPORT area and the minimum is 2 kW h/m^2. This difference increases to almost 8 kW h/m^2 and 10 kW h/m^2 when H. TOWN and M. CNTRL are compared with the minimum. Therefore, the land use seems to be a major factor that influences the electricity demand in SITRA (an industrial and residential district) and M. CNTRL (a commercial and residential district). The high consumption in SITRA is affected by the massive domestic construction, anthropogenic heat emissions from factories, cars and AC systems. This analysis reflects the view of Tremeac et al. [31] in which air conditioning systems can increase street temperature and consequently increase the cooling demand. The high electricity demand in M. CNTRL mainly occurs due to the massive business and commercial construction activities, heavy road traffic and sea reclamation. The current urbanisation in M. CNTRL changes its landscape by reclaiming the sea and increasing the surface and air temperatures, and consequently influencing the electricity demand. This echoes the finding of Jusuf et al. [32], where the change of land use from natural surfaces to new built structures results in changes of the urban temperature leading to an increase in energy consumption. The same situation occurs in the densely built district H. TOWN, as natural surfaces are removed and replaced with non-evaporating and non-transpiring surfaces such as metal, asphalt and concrete.

In short, human activities and urban surfaces are contributing to the development of CDD profiles for metropolitan centres. This can cause a steady growth in the domestic electricity demand for air-conditioning.

5. Conclusion

It has been possible to develop varied and representative CDD profiles for various UHI scenarios in Bahrain, and to use these within an electricity prediction context. Simple linear regression equations were developed in order to examine the sensitivity of electricity consumption to variation in CDD profiles. It is important to mention that the developed regression equations are limited to a single type of building and hence it would be useful to examine how much the values of its coefficients change for other types of buildings.

The analysis showed increasing trends of CDD in metropolitan centres at base temperatures of 18 °C and 24 °C. Maximum rates of increase in total CDD at both base temperatures was observed in industrial districts, while the smallest increases occurred in coastal residential districts with large green areas. The rate of annual and monthly trends was found to be relatively decreasing in open areas, such as airports. This work has emphasised the role of urban activities in the increase of domestic electricity consumption. It was noted that the variation in domestic electricity consumption is a direct result of modifications to the urban environment. The influence of natural factors on the domestic electricity consumption was found to be moderates in the case of Bahrain. The variation in consumption values was mainly due to the land use and the thermal properties of urban surfaces. Industrial districts (SITRA) were found to have the highest electricity consumption for air-conditioning, followed by commercial districts (M. CNTRL), residential districts with arid conditions (H. TOWN), airports and, lowest of all, residential districts with greenery (BYDDIA). The findings can be summarised in the following points:

1. The annual urban CDD value is up to 17–19% higher than the rural CDD value over the year.
2. Cooling is required in the period from April to October.
3. An increase of up to 10% in electricity consumption for air-conditioning occurs in metropolitan centres due to the UHI phenomenon
4. Estimation of domestic electricity consumption based on the data measured in airports can cause an error of almost 6%.
5. Industrial districts have the highest domestic electricity consumption, followed by business districts and then residential districts.
6. Costal residential districts have lower domestic electricity consumption than desert residential districts.

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