CLIMATE ENERGY INDEX AND BUILDING ENERGY INDEX: NEW INDICES TO ASSESS AND BENCHMARK BUILDING ENERGY PERFORMANCE

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ABSTRACT

Two globally applicable energy indices, Climate Energy Index (CEI) and Building Energy Index (BEI) were developed as a means of quantifying the climate impact on building energy performance and distinguishing climate related and climate unrelated energy end uses. It provides a common basis for comparisons of building energy performance and different design strategies in a simple and independent fashion. The paper describes the derivation of the indices calculation methods and presents case study results based on two types of building models. Results of a series of independently peer reviewed validation tests are also presented.

INTRODUCTION

One of the fundamental requirements of buildings is to provide a sheltered living and working space from the extremes of climate. The objective of environmental building design is the creation of a comfortable yet energy efficient internal environment. The successful design of comfortable buildings relies on an appropriate understanding of the climate. Climate underlies building energy use and it should be possible to compare designs relative to climate, visualize where design emphasis needs to be placed. However, in practice, it is difficult to translate a climate data into meaningful information that can capture the local climatic characteristics. There have been numerous attempts (Olgyay V. 1963, Koenigsberger, et al., 1973, Givoni B. 1976, Milne M. et al., 1979, Szokolay, S.V. 1986, Visitsak, S. 2004, Evans, J.M. 2007 and etc.) to establish a relationship between comfort, climate and built form and to explore various climatic design strategies. These approaches are limited in a variety of ways such as to certain building types or climate types. In addition, these approaches are still relatively complex and require a high level of interpretation to be correctly utilised in the design process.

In 2004 IES conducted some internal research and defined a methodology that could enable climate to be used as a simpler and more transparent benchmark for procedures such as LEED and Building Regulations (McLean, 2004). This work has resulted in the derivation of two globally applicable energy indices as interactive holistic design tools to assess, clarify and compare any worldwide climate data and hence to quantify the climate impact on building energy performance. They are the Climate Energy Index (CEI) and the Building Energy Index (BEI).

The Climate Energy Index (CEI) provides an indication of the consequence of climate with respect to building performance at an accepted standard of comfort at a particular geographic location. It represents an annual sum of energy required to condition 1m^3 of air at any weather hourly ordinate to the nearest boundary of a human comfort zone. The human comfort zone is determined based on ISO 7730 occupant comfort standard using Predicted Mean Vote (PMV). The CEI can be calculated for all hours or hours of use for a particular building. Based on a unitary air-flow, it operates on the air point only and there is no inclusion for building thermal process. In contrast the Building Energy Index (BEI) is an overall performance indicator for building design strategy. It comprises the climate related and climate unrelated energy loads, which are respectively derived from the CEI and benchmark data for non-space conditioning energy uses. The BEI can be compared directly with simulated or measured energy consumption data of a proposed building to benchmark its energy performance.

In this paper, the theoretical basis of the Climate Energy Index (CEI) and Building Energy Index (BEI) are described, followed by the implementation of the CEI and BEI into a dynamic thermal simulation software IES Virtual Environment (IES VE). Based on a wide range of climate data and two types of building models, the corresponding CEI and BEI were calculated respectively and their results are presented and discussed. Finally, a set of independently peer reviewed validation tests have been carried out to verify the scientific soundness and ease of applicability of the CEI and BEI.

METHODOLOGY

Calculation of Climate Energy Index (CEI)

The Climate Energy Index (CEI) provides an indication of the consequence of climate with respect to building performance at an accepted standard of comfort at a particular geographic location. It is solely based on climate data for a location and hours of use of a building. The CEI operates at the air point and excludes building thermal processes such as gains, conduction and infiltration; therefore, it is independent from building form, occupancy, use and HVAC system. It intends to provide a clear understanding of the effects of climate and locality without requiring a building design. This capability also facilitates comparative studies of climate throughout the world.

The fundamental premise of the CEI is that humans require a reasonably consistent degree of comfort and the energy required to achieve the comfort can be used to quantify the climatic impact on a building by outside air. The CEI is calculated based on psychrometric chart. It calculates the energy required to condition any weather hourly ordinate to the nearest boundary of a human comfort zone and operates on a unitary air flow. The human comfort zone was derived from existing comfort ranges including ASHRAE Standard 55 and previous research outcomes (Humphreys, M.A. 1978, Szokolay, S.V. 1985, Auliciems, A. 1981, Nicol, J.F. et al. 2002). The subsequent, the human comfort zone of the CEI is defined based on the following assumptions:

PMV: -0.5 to +1.0

Moisture content: 0.004 kg/kg

Relative humidity: 70 %

Ta (air temperature) = Tr (mean radiant temperature)

Clothing insulation: 1.0

Metabolic rate: 1.1

Air velocity: 0.1 m/s

It is noted that the upper limit of PMV is set as +1.0, which is higher than that in ASHRAE Standard 55. This takes into account the actual acclimatization and comfort expectations of the inhabitants and also reflects slightly relaxed summer conditions which are generally accepted in sustainable building designs. In addition, in contrast to ASHRAE standard, there is a lower limit of moisture content (0.004 kg/kg) introduced to the comfort zone to address some potentially discomfort factors, such as skin drying, irritation of mucus membranes, dryness of the eyes and static electricity generation. This figure has also been adopted in previous research work carried out by Givoni (Givoni, B. 1976) and Szokolay (Szokolay, S.V. 1986). Overall, the human comfort zone used in the CEI provides a reasonable representation of good human comfort on a global scale. Boundaries of the human comfort zone are therefore determined using the PMV formula which is set out in ISO 7730 along with the above assumptions, as shown in Figure 1.

Figure 2 shows a flow diagram for calculating the climate energy index. First of all, a weather data file needs to be selected, which can include air point information such as air temperature and moisture content. An occupancy schedule also needs to be specified which indicates the level of occupancy in a building. The CEI can be calculated for all 8760 hours in the year to consider the effect of the weather file when conducting the CEI calculation or it can be calculated only for hours of building operation.

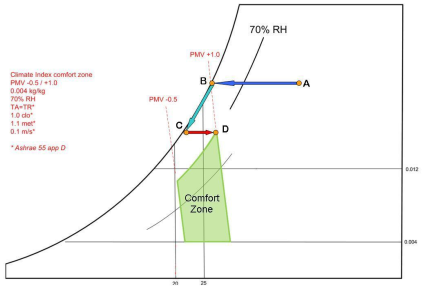


Figure 1 Human comfort zone of the climate energy index

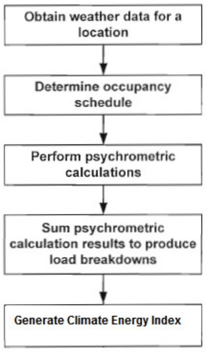


Figure 2 Flow diagram of calculating Climate Energy Index

For each hour under consideration a psychrometric calculation can then be performed. The psychrometric calculation provides an indication of the amount of energy that is required to bring or move an outside air point to a point on the boundary of the defined human comfort zone. The calculation can be conducted for each energy load type that is used to reach the desired comfort point, such as cooling energy, heating energy, humidification energy and dehumidification energy. For example, a summer weather ordinate is located at point A in Figure 1. To determine the amount of energy required to move from point A to the nearest boundary in the comfort zone, three steps can be taken. It starts from point A to point B which requires a certain amount of sensible cooling energy, then from point B to point C which demands a certain amount of cooling and dehumidification energy and in the end from point C to point D on the boundary of the comfort zone which requires a certain amount of sensible heating energy. Once the amount of energy required for each energy load type is determined for a particular weather file hourly ordinate, a similar calculation can be performed on the remaining weather file hourly ordinates. For an annual weather data file having hourly ordinates, a total of 8760 calculations can be conducted. The totals for each energy load type can be added and then used to determine the climate energy index which is the sum of the annual totals of all the energy load types. The unit of the climate energy index is kWh/yr per (m^3/hr).

Calculation of Building Energy Index (BEI)

Climate is the basic determinant for the design and operation of buildings. To measure the efficacy of a building design relative to a climate baseline, it is important to recognise climate related and climate unrelated energy end uses. Whereas the development of the Climate Energy Index (CEI) enables the climate based energy demand for maintaining a 1m^3 of ambient air within a comfort zone to be calculated, we need to modify this approach when applied to a real building. However, in order to use the CEI as a benchmark for direct comparison with a specific building design, it needs to scale up the CEI by taking account of building airflow and non-space conditioning benchmark loads, which forms the concept of the Building Energy Index (BEI).

The Building Energy Index was developed in an attempt to be used as an overall performance indicator for building design strategy. It comprises the climate related and climate unrelated energy loads, which are respectively derived from the Climate Energy Index and benchmark data for non-space conditioning energy uses. Figure 3 illustrates the calculation procedure of the Building Energy Index. For a particular building location of interest, the climate related energy part in the BEI is calculated as follows:

1. Determine the Climate Energy Index of the location for building design hours
2. Specify the building design airflow, which is a sum of infiltration and ventilation airflow
3. Scale up the CEI via multiplying the CEI by building design airflow divided by the floor area

The climate unrelated energy part is calculated based on the non-space conditioning benchmark load data, such as hot water load, equipment load, lighting load and process load. The non-space conditioning benchmark data can be normalized to reflect the same occupancy hours as the specific building being assessed so that the building energy index can be directly compared to the building simulated or measured data. For example, the non-space conditioning benchmark data for this building type is 82 kWh/m^2.yr based on 2000 hours/yr. The assessed building is actually used for 2200 hours/yr. Thus, the normalized benchmark data would be 82 x 2200/2000 = 90.2 kWh/m^2.yr. As a result, the total Building Energy Index can be expressed as:

BEI= CEI x building design airflow/Floor area +
Normalized non-space conditioning benchmark load

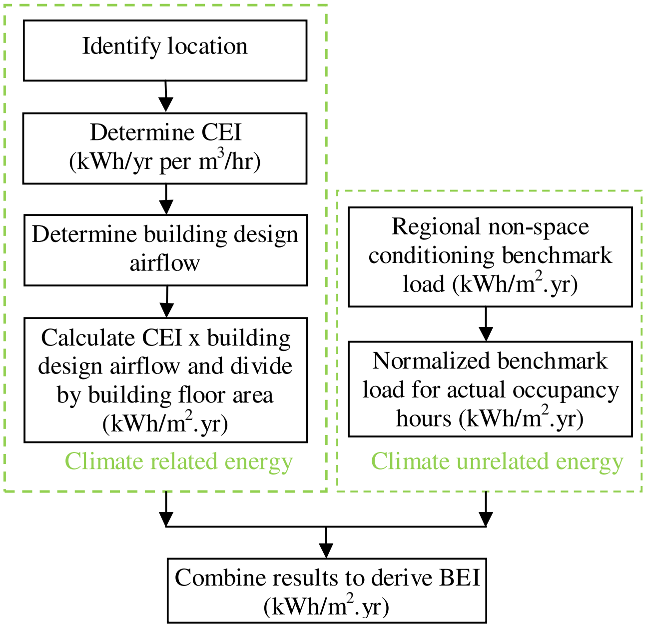


Figure 3 Flow diagram of calculating Building Energy Index

It is worth mentioning that the CEI and BEI are still under development, therefore the calculation methodology described above was based on the current research outcomes, which might be adjusted due to the future research work.

Implementation

The Climate Energy Index (CEI) and Building Energy Index (BEI) have been implemented into dynamic thermal simulation software IES Virtual Environment (IES VE). This enables calculations of the CEI and BEI to be accomplished effectively and quickly. All the inputs required for generating the CEI are simply weather data of a particular location and building hours of use. IES VE provides a worldwide range of hourly weather data. Standard formats of weather files such as EnergyPlus Weather (EPW) are employed. It is also possible to convert other formats to these formats using 3rd party products.

Since the BEI is in conjunction with the CEI, the weather data and hours in use are also required for calculating the BEI along with the information of building design air exchange rates, floor area and building type. The building type determines the default benchmark figures of non-space conditioning loads. Calculation results of the CEI and BEI can then be easily compared with simulated energy consumption data of a proposed building to benchmark its energy performance. The energy performance of the proposed building can be dynamically simulated in parallel by other integrated thermal modules within the software.

Case study

To provide a worldwide perspective of building energy use resulted from the climate impact, 14 global locations were selected to calculate the Climate Energy Index values. These locations represent the most common climate types, from cold climate, temperate climate to hot and humid climate, which are Fairbanks, Minneapolis, Boston, Baltimore, Glasgow, London, Los Angeles, Sydney, Phoenix, Houston, Abu Dhabi, Miami, Bangkok and Singapore. Calculations were conducted based on 24-hour use.

Furthermore, two types of building models which are a school and an office building were chosen to calculate the Building Energy Index values based on the 14 locations mentioned above. The main data information required for the calculations, such as floor area, volume, building design airflow (infiltration plus ventilation airflow) and non-space conditioning benchmark loads are shown in Table 1.

Table 1Main data information for case study calculations

Parameters		Office	School
Floor area (m^2)		2089	2041
Volume (m^3)		7558	7101
Building design airflow	Infiltration(ACH)	0.15 (314.9 l/s)	0.15 (295.9 l/s)
	Fresh air requirement ((l/s.p))	10	10
	Occupancy density (m^2/p)	12	7.4
Benchmark Non-space conditioning loads (W/m^2)	DHW	2.7	17.7
	Lighting	10	6.9
	Equipment	15	6.2
	Auxiliary energy	0.9	3.1
	Process	8.6	8.5
Occupancy hours (h)		2200	1300

RESULTS AND DISCUSSION

CEI calculation results

Figure 4 presents the climate energy index of monthly breakdown by energy load type for Miami based on 24-hour use. It can be seen that the annual climate energy index for Miami was calculated to be 36.46 kWh/yr per m^3/hr and the annual breakdowns for each energy load type were 12.2 kWh/yr per m^3/hr for sensible heating, 12.72 kWh/yr per m^3/hr for sensible cooling, 11.51 kWh/yr per m^3/hr for dehumidification and 0.03 kWh/yr per m^3/hr for humidification. As indicated in Figures 5 and 6 which show hourly dry-bulb air temperature and relative humidity of Miami over a year respectively, Miami has a warm, humid climate with hot, humid summers and short, warm winters. The relative humidity is mostly around 60% - 95% over the year and the air temperature is generally between 18°C - 32°C. Therefore, it is not surprising to see from Figure 4 that both sensible cooling and dehumidification are distributed over the 12 month. It is also noted that there has been a large amount of sensible cooling, dehumidification and sensible heating energies were predicted to be consumed from May to October. This is due to the fact that this period of time features high temperatures accompanied by high humidity which requires cooling, dehumidifying and reheating procedures to take place to bring the external condition to the comfort zone. There are red and blue curved lines which are also shown in Figure 4. They are trend lines for the monthly energy totals to assist users to quickly understand the basic pattern of the heating and cooling loads.

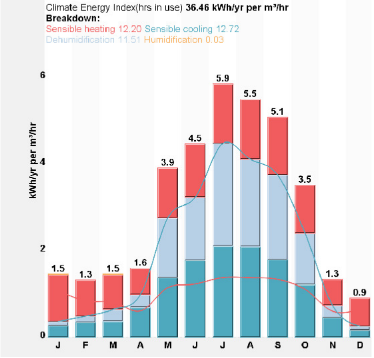


Figure 4 Monthly breakdown of climate energy index for Miami based on 24-hour use

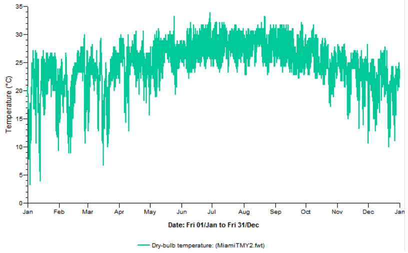


Figure 5 Hourly dry-bulb temperatures of Miami over a year

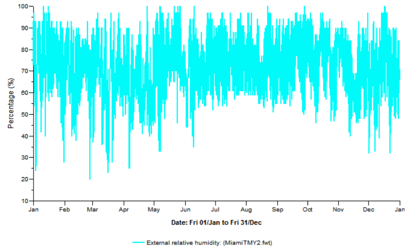


Figure 6 Hourly relative humidity of Miami over a year

It is worth addressing that all the energy loads predicted by the Climate Energy Index for a particular location is solely dependent on the climate data and hours of use of a building. Therefore, the CEI can be used as an indicator to offer a fair idea for architects and engineers of what type of energy loads might be involved and what period of a year they might be required even before considering the building form, constructions and HVAC systems. It provides a clear intuitive understanding of basic building energy use with respect to climate impact. This would allow various building design strategies to be explored at the very early design stage.

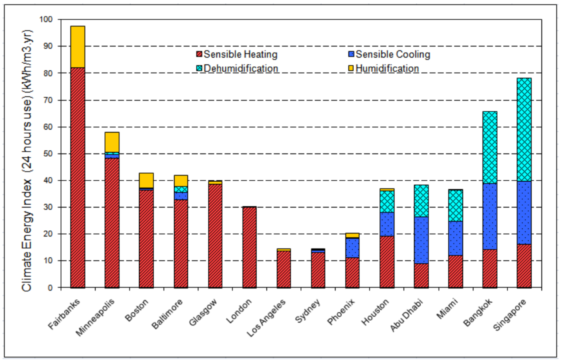
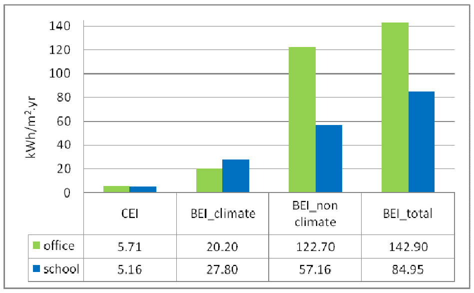


Figure 7 Climate energy index variation for 14 worldwide locations based on 24-hour use

With an attempt to provide an example of worldwide climate perspective, Figure 7 shows climate energy index variations with a detailed breakdown by energy load type for the selected 14 locations based on 24-hour use. Table 2 lists the corresponding values for 24-hour use. It can be observed that the climate energy index and energy load type breakdown vary significantly by locations. Extreme climates tend to have large climate energy indices. For example, for Fairbanks which has an extremely cold climate, the climate energy index for 24-hour use was calculated to be 97.58kWh/yr per m^3/hr. It included both sensible heating and humidification. For Singapore which has an extremely hot climate, the climate energy index for 24-hour use was predicted to be 78.28 kWh/yr per m^3/hr. It required sensible cooling, dehumidification and sensible heating. However, for weather conditions in Los Angeles which has the climate energy index of 14.48 kWh/yr per m^3/hr, it required the least amount of energy to achieve the desired level of comfort from among the various locations included as it has a benign climate. Thus, it is interesting to note that for the location of London, its climate energy index is about 39% of that in Singapore and about 210% of the climate energy index for Los Angeles.

BEI calculation results

Figure 8 shows the Climate Energy Index (CEI) and Building Energy Index (BEI) values of the school and the office building models together with energy breakdown of the BEI by climate related and unrelated load based on London weather data. As expected, the CEI values for both building models are very similar. Owing to the longer occupancy period used in the office model as shown in Table 1, the CEI value for the office building is slightly higher. As displayed in Figure 8, the climate related energy loads of the BEI for both building models are similar too. However, the climate based energy component for the office building is lower than that of the school building. This can be explained by that the office building model has an overall smaller ratio of the building design airflow to the floor area. In addition, the climate unrelated energy loads of the BEI are observed to be considerably high in the office building. This was caused by the large load from the non-space conditioning energy use. As a result, the BEI was predicted to be 142.9kWh/m^2.yr for the office building and 84.95kWh/m^2.yr for the school building.



	CEI	BEI_climate	BEI_non climate	BEI_total
office	5.71	20.20	122.70	142.90
school	5.16	27.80	57.16	84.95

Figure 8 CEI and BEI values of the school and office building models based on London climate

Variation of the BEI and its climate related energy component for both building models are plotted in Figure 9 against the 14 global locations. Consistent with the findings in Figure 8, the climate related energy loads of the office building model stay close to those of the school building model with the change in climatic conditions. What's more, Figure 9 also indicates the sensitivity of the climate related energy load to the different climate types. As can be seen, the climate related energy load is much higher in the extreme climate, such as dry and cold climate or hot and humid climate, than that in the mild climate. For example, the climate based energy load of the office model in Singapore was predicted to be 18 times higher than that in Sydney. Overall, The BEI values of the two building models follow the same variation trend with the change in the climate types, but different magnitudes mainly due to the non-space conditioning energy loads.

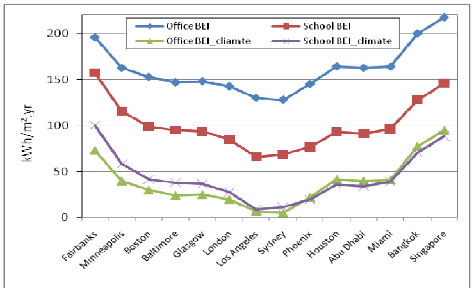


Figure 9 Variation of the BEI and its climate related energy component for both building models

VERIFICATION

A series of independent peer review and detailed validation tests have been carried out by School of Built and Natural Environment, Glasgow Caledonia

Table 2 Climate energy indices based on 24-hour use for selected representative locations

Location	CEI	Sensible Heating	Sensible Cooling	De-humidification	Humidification
Fairbanks	97.58	82.08	0.01	0	15.49
Minneapolis	58.05	48.24	1.38	0.94	7.49
Boston	42.74	36.38	0.62	0.17	5.58
Baltimore	42.13	32.89	2.74	2.19	4.3
Glasgow	39.66	38.55	0	0	1.11
London	30.4	29.97	0.05	0	0.41
Los Angeles	14.48	13.7	0.07	0	0.71
Sydney	14.57	13.11	0.95	0.37	0.13
Phoenix	20.44	11.25	7.27	0.17	1.76
Houston	37	19.29	8.92	8.1	0.7
Abu Dhabi	38.38	8.99	17.46	11.92	0
Miami	36.46	12.2	12.72	11.51	0.03
Bangkok	65.93	14.22	24.63	27.07	0
Singapore	78.28	16.29	23.49	38.51	0

University to verify the scientific soundness and robustness of the Climate Energy Index (CEI) and Building Energy Index (BEI). The following section presents their validation results (Kumar, B. et al. 2010).

Verification of the Climate Energy Index (CEI)

Climate Energy Index (CEI) was compared to one of the previously developed, well known climate quantification indices, Mahoney tables (Koenigsberger, et al., 1973). Due to the fact that CEI is a single number index while Mahoney tables employ six indicators which are H1 (ventilation essential), H2 (ventilation possible), H3 (rain protection essential), A1 (thermal mass essential), A2 (outdoor activity possible) and A3 (heating essential), therefore, it needs to convert Mahoney tables to a single number output. Given that the six indicators have different impacts on building designs, the Mahoney tables were modified by applying different weighing factors, which can be expressed as:

$$\text{Modified Mahoney model} = [(H1 \times 2) + (H2 \times 1) + (H3 \times 2) + (A1 \times 2) + (A2 \times 1) + (A3 \times 2)]/10$$

Thus, the modified Mahoney tables can be used to predict CEI by simple regression and then examine the anomalies. If any, it would be compared against a bioclimatic chart to explain the 'severity' of the climatic load. The bioclimatic chart chosen in this study was the most widely used Givonis Chart (Givoni, B. 1976).

Figure 10 shows a comparison of CEI numbers with the modified Mahoney model for the selected 14 locations as mentioned previously. As can be seen from Figure 10 the match between the two indices is not very good. However, the situation improved dramatically when an outlier (in this case, Phoenix, USA) was removed (see Figure 11). This anomaly might be caused by the extreme nature of the climate of Phoenix. Figure 12 plots the monthly weather data for Phoenix on Givoni's Bioclimatic chart. As can be seen from Figure 12, the monthly climatic conditions vary widely from very hot, dry in July and August daytimes to very cold, humid nights in December to February. Thus, any attempt to look at the annual climatic burden will tend to gloss over the extreme variations in monthly climatic requirements, such as the dehumidification need in the winter will be cancelled by the humidification need in the summer. On the other hand, a mild climate such as in Glasgow or Sydney has less seasonality and therefore a more uniform climatic burden.

As a result, it can be concluded as follows:

1. CEI has a good match with previous attempts at quantifying the climate impact on buildings with one exception: Phoenix (PHX). The outlier case may be explained by the unusually low humidification energy need for PHX.
2. CEI can be a good indicator of the 'climatic burden' imposed on buildings by mild external climates, such as climate that has a more predictable variation in their monthly climatic burden on buildings.
3. Its performance may be improved by examining any data anomaly especially with respect to extreme climate conditions. This will be the future work to be carried out.

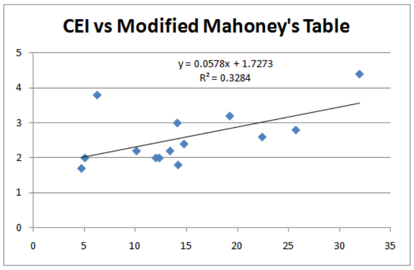


Figure 10 Correlation between CEI and modified Mahoney's Table

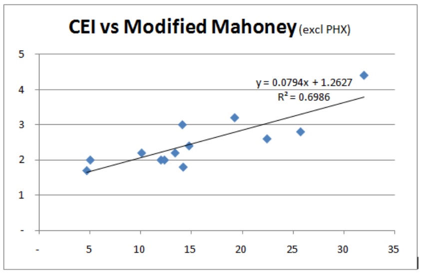


Figure 11 Improved correlation between CEI and modified Mahoney's Table

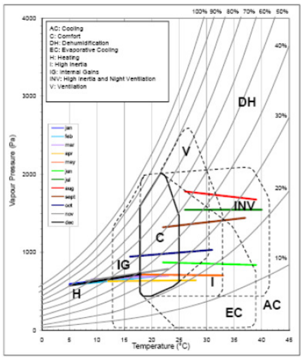


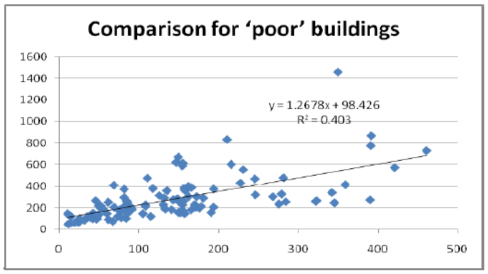
Figure 12 Bioclimatic need in an extreme climate (Phoenix, USA)

Verification of the Building Energy Index (BEI)

To be able to carry out a detailed validation for the Building Energy Index, 9 different building types ranging from single family residential buildings to very large office and institutional buildings were examined for each of the 14 climatic locations. The validation was conducted following the procedure below:

1. Compare BEI of the 9 different types of buildings for each of the 14 locations, against building energy performance for 'Poor' and 'Great' buildings. 'Poor' buildings are defined as buildings designed for basic standards currently prevalent in the developing world which have the thermal comfort index of Predicted Mean Vote (PMV) within ±1.5, while 'Great' buildings refer to those designed for meeting the 'Best' practice in the developed world assuming the PMV index lies within -0.5 to +1.0. A building that falls into 'Good' category in this context is to be designed for basic code standards as applicable in most developed countries (i.e. designs fulfilling the adaptive comfort standards ASHRAE 55-2004 and is defined by ASHRAE 55:2004, Figure 5.3 with 80% acceptability).
2. Compare all of the BEI with energy performance estimated by a generic building simulation software (DEROB-LTH) output

The software DEROB-LTH was developed by the Lund University, Sweden, which is capable of simulating the indoor thermal comfort and building heating/cooling energy needs. Figure 13 shows the comparison of building energy performance vs. BEI for 'Poor' and 'Great' buildings respectively. It is clear that the 'Great' buildings fall into the same thermal comfort zone as what is defined for BEI. As expected, the predictive ability of the BEI for 'Poor' buildings is not good (R^2=0.403), but is very good for 'Great' buildings (R^2=0.8039). It is therefore safe to say that the BEI index is a good predictor of the likely energy performance of buildings that fulfils the current best practices. In this sense, it can be used as a benchmark to assess building energy performance.



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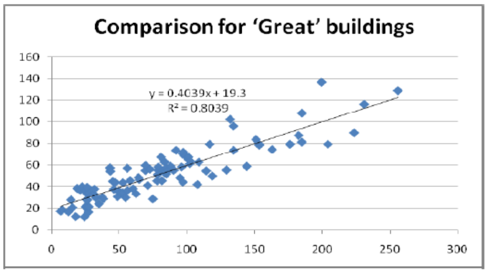
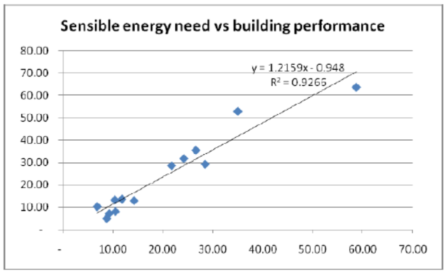


(b)

Figure 13 BEI performance validations

Figure 14a shows the relationship between the BEI and sensible building energy need (sensible heating or cooling) and Figure 14b shows the BEI vs. latent building energy need (humidification or dehumidification) over the 14 climatic locations. This was carried out based on a single family residential building whose energy performance falls into 'Great buildings' category. Table 3 shows the main building specifications based on the types of the 14 climates. As shown in Figure 14, the BEI has a better correlation with the sensible energy need than that with the latent energy need. This might indicate a possible link to the issue of the extreme climatic conditions as addressed in the CEI validation.



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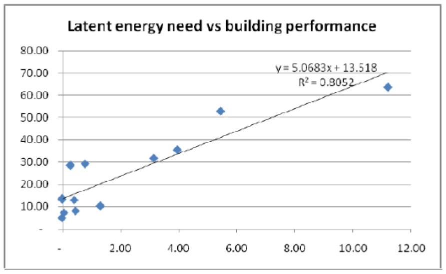

(b)

Figure 14 BEI and the sensible/latent building energy needs

Table3 Specifications of the residential building

Parameters	Cold climate	Temperate climate	Hot climate
Wall U-value (W/m^{2}K)	0.13	0.15	0.17
Floor U-value (W/m^{2}K)	0.13	0.13	0.16
Roof U-value (W/m^{2}K)	0.11	0.11	0.14
Window U-value (W/m^{2}K)	1.2	1.3	1.4
Window SGF	0.5004	0.5207	0.5642
Thermal mass	Light	Heavy	Heavy
Infiltration rate (ACH)	0.15	0.15	0.15
Ventilation rate	Set to NCM (NCM Modelling Guide, 2010) ventilation rate		
Internal gains	Set to NCM internal gains		

Note:
Cold climate: Fairbanks, Minneapolis and Boston
Temperate climate: Baltimore, Glasgow, London, Los Angeles and Sydney
Hot Climate: Phoenix, Houston, Abu Dhabi, Miami, Bangkok and Singapore

CONCLUSION

In this study, a set of energy indices which are Climate Energy Index and Building Energy Index were developed with an attempt to quantify the climate impact on building energy performance and distinguish climate related and climate unrelated energy end uses in a simple manner. They were independently peer reviewed and also implemented into dynamic thermal simulation software IES VE. The results of the study at the current stage are extremely encouraging. It can be concluded that the Climate Energy Index and Building Energy Index can provide a common basis for comparisons of building energy performance and different design strategies in a simple and independent fashion. However, it still requires a certain attention to examine the methodology of the BEI development in order to use the BEI as a benchmark for direct comparison with a specific building design accurately. It also requires a further assessment of the variance in the BEI values depending upon climate and or classification of buildings. Since this paper was drafted, the research of the BEI development has been continuously carried out. As a result, there are some new and positive outcomes which will be documented in a different paper.

ACKNOWLEDGEMENT

We would like to acknowledge the verification work carried out by Prof. Bimal Kumar and Dr. Rohinton Emmanuel from the School of Built & Natural Environment, Glasgow Caledonian University.

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