Solar Energy

Unravelling the Relationship Between Energy and Indoor Environmental Quality in Australian Office Buildings

--Manuscript Draft--

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Abstract:	Green building studies generally focus on singular performance aspects (e.g., energy, waste, water, indoor environment) with few tackling the relationships between each other, particularly the relationship between indoor environmental quality (IEQ) and building energy consumption. This study aims to explore the relationship between IEQ performance and energy consumption in National Australian Built Environment Rating System (NABERS) certified buildings. A verified climate normalization factor was localized to standardize energy use intensity in buildings from different climate zones of Australia. The normalized energy use intensity (NEUI) was calculated for all office buildings and correlated with their NABERS Energy and IE rating scores. Multivariate linear regression results reveal that one unit increase in NABERS Energy rating score and IE score can reduce NEUI by 21.98 kWh/m 2 and 9.88 kWh/m 2 per annum, respectively. Also, this study develops an Energy and Indoor Environment Index to benchmark the energy and IEQ performance of Australian office building. Buildings with excellent NABERS Energy and IE ratings (scores equal to/higher than 5) have been classified as high-performance NABERS buildings (HNBs) and the rest as low-performance NABERS buildings (LNBs). A comparison between 49 HNBs and 48 LNBs demonstrates that, on average, HNBs can deliver 12.6% better indoor environment quality with 35.9% less energy consumption than LNBs. In contrast, many LNBs either use excessive energy to provide a sufficient IEQ, or sacrifice IEQ to reduce energy costs and/or achieve a high NABERS Energy rating.

Unravelling the Relationship Between Energy and Indoor Environmental Quality in Australian Office Buildings

Ref. No.: SEJ-D-21-01114

RESPONSE TO REVIEWERS (R1)

The authors appreciate all of the thoughtful comments presented by the reviewers. Corrections made have been highlighted in yellow throughout the manuscript.

Reviewer 1

Reviewer #1 overall comment*: This is an interesting paper that aims to investigate the relationship between energy and indoor environmental quality in Australian office buildings. The paper will benefit from the following clarifications and revisions:*

Comment 1.1: *A key factor that makes it difficult to find tangible benefits of buildings that are designed in keeping with green standards/certifications, is the problem of the performance gap that is well covered in the literature and very relevant to the literature review part of this paper. However, this has not been addressed. It would be helpful to reflect on this literature in the final revision.*

Response 1.1: Thank you for this thoughtful comment. One additional paragraph has been added to the revised manuscript (sections 1.2. of revised manuscript) explaining the performance gap between green building design, construction, and management. Many buildings which have been designed to perform in accordance with best practice were constructed inappropriately or have not been suitably maintained.

Comment 1.2: *Further clarification is required about equation (5). How could weather normalization factor be determined (e.g. the values listed in the last column of Table 3.)? The rationale behind summing up heating and cooling degree-days to determine NEUI needs to be provided. Equation (1) referenced from previous work in the UK is based on heating degree-days only and does not include adjustment for cooling degree-days. Whilst this could, to some extent, be explained by the fact that the heating mode is more dominant in the UK, it is also notable that cooling energy in offices is not only driven by outdoor conditions. An office building may be in cooling mode even in winter as a result of internal heat gains. Weather correction of energy based on cooling degree-days therefore needs to be carefully considered and justified (e.g. the correlation between HDDs and energy use vs. correlation between CDDs or total degree-days and energy use).*

Response 1.2: We really appreciate your thoughtful comment. We completely agree that the previous normalization procedure (Bordass, 2020) considered only HDD because heating was the prominent energy demand in United Kingdom. Therefore, we decided to replace the normalization method with a modified procedure used by Geng et al. (2020). We changed the CDD setpoint according to the Bureau of Meteorology of Australia, to 24C for cooling (BOM.gov.au)

$$Normalization\ factor = W_h . \frac{HDD_{18,base}}{HDD_{18,ac}} + W_c . \frac{CDD_{24,base}}{CDD_{24,ac}}$$

$HDD_{18,base}$ and $CDD_{24,base}$ represents the heating and cooling degree days. Baseline values used the average HDD and CDD of 6 major Australian cities.

$HDD_{18,ac}$ and $CDD_{24,ac}$ represent the actual heating and cooling degree days of the considered city.

W_h and W_c represent the weights of heating and cooling degree days. To derive these weighting values, a simulation was conducted for a case-based office building located in Australia. The simulation was conducted in each of the 6 major cities and weights were determined by determining the ratio of months of heating and cooling that was needed for each city.

As wisely mentioned by the reviewer, the cooling in office buildings is not only related to the outdoor temperature. Simulation of a real office building in Australia (with all indoor heat gains including lighting, devices, people, etc.) ensured that an accurate assessment could be conducted.

This method has two benefits, when compared to the approach employed by Bordass (2020).

1. Both CDD and HDD are considered for energy consumption normalization based on weather.
2. The impact of internal gains and high humidity in summer is considered.

For further clarification please refer to Appendix 2 which provides in-depth explanation of normalization method and the reason why humidity is not included in normalizing approach.

Comment 1.3: *The definition put forward to differentiate 'Green' NABERS buildings and 'Non-green' NABERS buildings seems a bit arbitrary. Why was the rating of 5 used as the cut off point for NABERS Energy and NABERS IE? (Why not 4 or 4.5 for example?) The branding is also a bit contentious and needs further justification. NABERS is a green sustainability rating scheme similar to other green certification schemes cited in the literature review. To define green and non-green NABERS buildings seems a bit contradictory and can create confusion in the market. You may wish to re-consider the branding, whilst applying the interesting and important criterion of achieving both high ratings for energy and IEQ and differentiating these buildings from other buildings.*

Response 1.3: Thank you for your helpful comment. We have changed the ‘branding’ in our revised R1 manuscript. The ‘green NABERS building’ is now changed to ‘high-performance NABERS building (HNB)’ and ‘non-green NABERS building’ is corrected to ‘low-performance NABERS building (LNB)’. Also regarding the cut off point for NABERS, based on my recent discussion with Mr. Pulido (NABERS expert), the average Energy and IE rating for offices is currently 4.5 Stars, and we want to distinguish average buildings and exceptional ones in this study and compare them.

Comment 1.4: *The language quality is generally very good. However, the text will benefit from another round of proof reading. Some acronyms are also not defined and are not quite clear (e.g. what is VC in the first row of Table 1?).*

Response 1.4: We appreciate your comment. The manuscript has been reviewed again and refined to improve its quality.

Reviewer 2

Comment 2.1*: The relationship between energy consumption and green buildings/non-green buildings is an exciting issue, and the accurate description requires the integration of knowledge from many fields of science. At the same time, researchers' approach in different parts of the world differs significantly. Therefore, the bifurcation of literature opinions observed by the authors regarding the differences between energy consumption in green buildings and other buildings should not come as a surprise. The primary reason is the lack of a commonly accepted definition of a green building. The explanation for these differences may be the share of individual assessment categories in the final result. At BREEAM, LEED, Green Star, energy matters more than the indoor environment. While in many European rating systems e.g., DGNB (Germany), Miljöbyggnad (Norway), HQE (France), the indoor environment is more crucial than energy consumption.*

Response 2.1: We appreciate your comment. It has helped us to better understand the bifurcation of literature opinions when comparing Green and Non-green buildings. Benefitting your comment, we have added two following paragraphs (added into section 1.2 in page 5) explaining why there is a difference between the outcomes of previous research studies.

> There are some reasons behind these diverse results. The lack of a commonly agreed definition or evaluation method of green buildings is one of the main reasons. Most GB rating schemes have different categories for assessment, e.g., energy, indoor environment quality, water, materials, waste, etc. However, the weighting of these categories might be distinct in different rating schemes. At BREEAM, LEED, and Green Star, energy is more important than the IEQ. While in some European rating systems e.g., DGNB (Germany), Miljöbyggnad (Norway), and HQE (France), IEQ is more decisive than the energy consumption (Heincke and Olsson, 2012).
>
> Another reason could be the gap between the buildings' designed and actual performance. Some buildings were designed to be green buildings, but not finally constructed or managed to perform as expected. Desmarais et al. evaluate some problems in construction and operation of green buildings(Desmarais and Gonçalves, 2010). They mentioned being green does not rely severely on looks or high-tech gadgets, or the total points achieved by a specific green rating system. Instead, an integrated and inclusive method is needed with the accurately designed systems for buildings' global context. This includes employing building science to assess and find beneficial solutions (Desmarais and Gonçalves, 2010).

Comment 2.2: *The methodology used does not raise any objections. However, it should be noted that it is deeply based on the Chinese method described by Geng et al., 2020, derived from the earlier Japanese CASBEE building assessment method. The commercially successful LEED and BREAM methods would not be better as benchmarks. Perhaps due to the differences in the environmental assessment methods, the literature analysis seems somewhat chaotic.*

The conclusions of some studies are also probably not quite accurately summarized. Sample quote "One possible reason for high EUI in GBs, as proposed by Geng et al. (Geng et al., 2020), could be the considerable amount of wasted energy through overcooling or overheating to ensure a suitable indoor thermal environment in certified buildings." (page 4).

Geng's article often mentions the level of control of the thermal environment. Geng observed that in China, in type B buildings (public buildings with central air conditioning and mechanical ventilation operate all year round), the control systems are not fully capable of controlling technical parameters. Consequent overheating or overcooling leads to high energy consumption. The sentence in the submitted text does not fully reflect the meaning of this conclusion from the research of Geng et al.

Response 2.2: Thank you for your comment. We read the paper by Geng and improved the manuscript (section 1.2. page 5) according to your comment.

> As proposed by Geng et al. (Geng et al., 2020), the level of control over the indoor thermal environment can be one possible reason for high EUI in GBs. They found that in Chinese public buildings with central air conditioning and mechanical ventilation operating throughout the year (type B buildings), the controller systems are not efficient enough to control the indoor environment as they are supposed to be. Therefore, subsequent overheating or overcooling can cause high energy consumption.

Comment 2.3: *A separate problem is an issue of normalizing energy consumption in buildings. Energy is not only used to ensure the proper air temperature. In modern buildings, it is also essential to maintain an appropriate relative air humidity. While air humidification is required in cold season climates, the air needs to be dehumidified in humid and hot climates. The mild climate of Great Britain means that the importance of these processes is low. In Scandinavia, humidification during the cold season may be a significant additional component in energy consumption. On the other hand, in Singapore or Brisbane (!), dehumidification may be a problem. Unfortunately, the authors do not mention anything about this process, very briefly analyze the climate of selected cities in this respect, and do not justify the omission of this phenomenon.*

Response 2.3: The authors appreciate your thoughtful comment. We completely agree that the previous normalization procedure (Bordass, 2020) considered only HDD because it was the prominent energy demand in UK. Therefore, based on respected reviewers' comments, we decided to replace the normalization method with a modified procedure used by Geng et al. 2020. We changed the CDD setpoint according to the Bureau of Meteorology of Australia, to 24C for cooling (BOM.gov.au)

$$Normalization\ factor = W_h.\frac{HDD_{18,base}}{HDD_{18,ac}} + W_c.\frac{CDD_{24,base}}{CDD_{24,ac}}$$

$HDD_{18,base}$ and $CDD_{24,base}$ represent the heating and cooling degree days using as the baselines which is the average HDD and CDD of 6 major Australian cities.

$HDD_{18,ac}$ and $CDD_{24,ac}$ represent the actual heating and cooling degree days of the considered city;

W_h and W_c represent the weights of heating and cooling degree days. For this regard an actual office building in Australia is simulated in each 6 cities and weights were determined by ratio of months heating and cooling is needed in each city.

As you wisely mentioned the cooling in office buildings is not only related to the outdoor temperature and relative humidity would be a problem in some cities. Simulation of a real office building in 6 cities with all indoor gains (lighting, devices, people, etc.) helped us consider all the facts.

This method has two benefits comparing to the (Bordass 2020).

1- Both CDD and HDD are considered for energy consumption normalization based on weather.

2- The impact of relative humidity in cities is considered.

Based on ASHRAE Standard 2013b "Thermal Environmental Conditions for Human Occupancy", depending on the operative temperature, the minimum and maximum acceptable relative humidity in office buildings is 30% and 65%, respectively. Figure 1 shows the monthly average relative humidity for 6 investigated cities. Adelaide and Brisbane have the lowest and highest annual relative humidity, respectively.

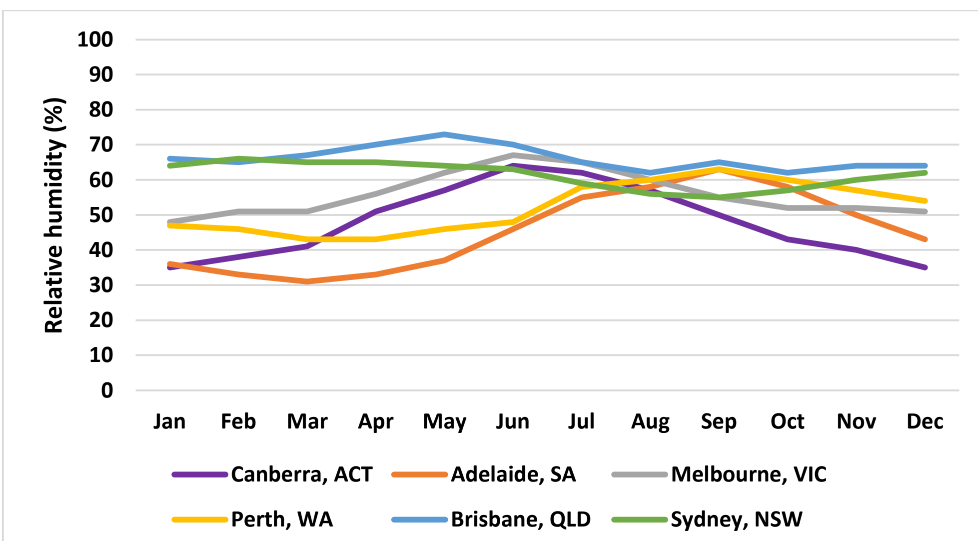

Figure 1. Average monthly relative humidity in 6 Australian cities

In Adelaide the relative humidity is always over 30%. Therefore, humidification is not required. Humidity is usually a problem when it occurs in conjunction with a high temperature. In Brisbane the highest relative humidity occurs between April to June (winter in Australia with temperature below 20 ˚C). While, as you mentioned there is need for dehumidification, it is not comparable with Singapore with average monthly relative humidity of 80% and steady temperature around 27 ̊C all over the year.

Most commercial buildings in Australia do not have independent humidity control. In order to quantify the impact of dehumidification on building energy use, as a worst-case scenario, we have assumed that the above case study building, located in Brisbane, has an independent humidity control and have simulated the building energy consumption spent on dehumidifying the indoor air to 60% relative humidity.

Table 1. Energy demand for cooling in the simulated office building in Brisbane

	Dehumidification (Kwh/m^2)	Total (Kwh/m^2)	Share of dehumidification (%)
Jan	3.88	21.28	18.2
Feb	3.59	19.04	18.8
Mar	2.42	17.28	14.0
Apr	1.91	12.36	15.5
May	0.53	6.51	8.2
Jun	0.25	2.31	11.0
Jul	0.31	3.36	9.4
Aug	0.19	4.63	4.2
Sep	0.21	6.48	3.2
Oct	0.21	10.46	2.0
Nov	3.12	17.68	17.6
Dec	2.55	18.28	13.9
Annual	19.17	139.68	**13.7**

Based on the simulation result (Table 1), the energy needed for the dehumidification is 13.7% of total cooling demand (less than 9.5% of total final energy demand in building). Therefore, this influence of relative humidity is neglected, and weather normalization is only based on temperature.

We added a new paragraph in **Section 2.2 (page 9)** of the revised manuscript, explaining why relative humidity was not considered in the weather normalization process based on your comment. An in-depth analysis and explanation are provided in **Appendix 2** of the revised R1 manuscript.

Comment 2.4: *The authors should also assess the validity of such a statement in a slightly broader context "The severe cold days in UK result in large number of degree days while six Australian cities considered in this research have mostly moderate weather." (page 9) This sentence seems untrue for many researchers from Northern and Eastern Europe or North America. Seen from their point of view, severe cold days do not occur in Great Britain.*

Response 2.4: This is a highly relevant comment. We have omitted this misleading statement in the revised R1 manuscript.

Comment 2.5: *What is meant by actual energy consumption is also not specified: delivered energy (?), primary energy (?). Does Australia use any conversion factors for primary energy? How the actual energy use was calculated in the case of more than one source (e.g., electricity and gas)?*

Response 2.5: We appreciate your helpful comment. By actual energy consumption we meant delivered energy to the office buildings. We revised the manuscript and replaced "actual energy consumption" with "delivered energy consumption" to make it more understandable.

NABERS assessors look at all energy use in the operation of the building, including gas, electricity, and diesel for standby generators. NABERS uses the National Greenhouse and Energy Reporting Scheme (NGERS) to convert different sources of energy to final delivered energy. Based on the states and territory of Australia where the building is located, the conversion factors vary, and it is accessible by using the guidance provided at this link:

https://www.energy.gov.au/sites/default/files/guide-to-australian-energy-statistics-2017.pdf.

Comment 2.6: *Nevertheless, the final results are valuable and definitely worth publication. The main question is, however, of the journal in which the findings should be presented. When preparing the text, the Authors made practically no efforts to present the research as belonging to the Solar Energy area.*

Response 2.6: Thanks for your opinion. We believe that this work suitably fits the scope of the journal of 'Solar Energy' since it is a multidisciplinary journal attracting researchers with various research interests in the energy domain.

Comment 2.7: *The relationship between the NABERS IE rating and NEUI shown in Figure 3 is worth presenting. Still, it seems more natural to present NABRES IE results on the x-axis in ascending order.*

Response 2.7: Figure 3 has been edited based on the comment. The NABERS IE in the x-axis has been represented in ascending order in the revised R1 manuscript.

Comment 2.8: *Equation 6 an error term ε is not explained*

Response 2.8: Thank you for the comment. We explained the term accordingly.

Comment 2.9: *Lack of consistency in using capital vs. small letters "Green building Council Australia" (page 3), "Building Energy performance" (equation 7)*

Response 2.9: We appreciate your precise comment. The manuscript has been checked and edited.

Reviewer 8

Reviewer #8 overall comment: This study reveals the relationship between energy and IEQ in Australian office buildings. The topic is interesting and meaningful. The paper is well written with clear methodologies and results. The conclusion arouses a great attention on both energy and IEQ certificates for commercial buildings. However, I have some concerns that should be addressed by the authors.

Comment 8.1: *Section 1.4: The authors mentioned the NABERS IE scheme, but some important information is missing. For example, what is the criteria of IEQ measurement? How many sensors are in a building? How many occupants are surveyed in a building? What's the grading scheme of each IEQ factor? (Which comfort standards are the scores based on?) Only Table 2 is not enough, the authors should add an appendix to give us a detailed introduction. Such information is very necessary, because it determines whether the IEQ rating results are scientific or not.*

Response 8.1: Thank you for this comment. Appendix 1 has been added to the revised manuscript, which explains the Base building rating in the NABERS IE scheme. It includes standards used in NABERS IE, criteria of IEQ measurement, measuring devices requirements and locations in certified buildings. For more clarification we refer you to the main resource:

https://www.nabers.gov.au/file/1336/download?token=zkaI5EUH

Comment 8.2: *Second paragraph in Section 2.1: The units for annual energy consumption and EUI are MWh and MWh/m2, respectively. However, in other parts, MJ and MJ/m2 are used. They are not consistent! The authors are suggested to transfer MJ to MWh, and MJ/m2 to MWh/m2.*

Response 8.2: We appreciate your precise comment. All units have been changed to kWh and kWh/m^2 to make the manuscript consistent.

Comment 8.3: *Equation 5 in Section 2.2: In terms of the energy normalization formula, it seems better to consider CDD and HDD separately, rather than combing them to a comprehensive ATDD, because cooling and heating energy have different intensities and characteristics with weather. The reference (Bordass, 2020) can use a single ATDD, because it is in the UK and the climate determines HVAC energy is almost heating. However, in Australia, heating and cooling are important equally.*

Response 8.3: We thank you for your thoughtful comment. We totally agree that the previous normalization procedure (Bordass, 2020) considered only HDD because it was the prominent energy demand in United Kingdom. Therefore, it is decided to replace the normalization method with a modified procedure used by Geng et al. 2020. We only changed the CDD setpoint according to the Bureau of Meteorology of Australia, to 24C for cooling (BOM.gov.au)

$$Normalization\ factor = W_h.\frac{HDD_{18,base}}{HDD_{18,ac}} + W_c.\frac{CDD_{24,base}}{CDD_{24,ac}}$$

$HDD_{18,base}$ and $CDD_{24,base}$ represent the heating and cooling degree days using as the baselines which is the average HDD and CDD of 6 major Australian cities.

$HDD_{18,ac}$ and $CDD_{24,ac}$ represent the actual heating and cooling degree days of the considered city;

W_h and W_c represent the weights of heating and cooling degree days. For this regard an actual office building in Australia is simulated in each 6 cities and weights were determined by ratio of months heating and cooling is needed in each city.

This method has two benefits comparing to the (Bordass 2020).

1- Both CDD and HDD are considered for energy consumption normalization based on weather.
2- The impact of internal gains and high humidity in summer is considered.

For further clarification please check the appendix 2.

Comment 8.4: *Table 3: According to Equation 5, different buildings will have different η, due to different values of F and V. Why is η a constant value within a state? Is the η given in Table 3 the average value?*

Response 8.4: We appreciate this helpful comment. Unfortunately, we do not have access to fixed and variable energy consumption of 97 investigated buildings. To normalize energy consumption based on climates the correction factor should only apply to the energy consumption of HVAC systems. Thus, we used an Australian government document (Department of the Environment and Energy- HVAC fact sheet - Energy breakdown) to divide fixed and variable energy consumptions. Therefore, η in Equation 7 is a function of HDD, CDD and the weighting factors of heating and cooling needed based on simulation result for each city.

Comment 8.5: *The paragraph above Table 7: The statement that "the influence of overall indoor comfort on NABERS Energy is negligible" is wrong. It should be "the influence of NABERS Energy on overall indoor comfort".*

Response 8.5: Thank you for the comment. We edited the manuscript accordingly.

Unravelling the Relationship Between Energy and Indoor Environmental Quality in Australian Office Buildings

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Abstract

Green building studies generally focus on singular performance aspects (e.g., energy, waste, water, indoor environment) with few tackling the relationships between each other, particularly the relationship between indoor environmental quality (IEQ) and building energy consumption. This study aims to explore the relationship between IEQ performance and energy consumption in National Australian Built Environment Rating System (NABERS) certified buildings. A verified climate normalisation factor was localized to standardize energy use intensity in buildings from different climate zones of Australia. The normalised energy use intensity (NEUI) was calculated for all office buildings and correlated with their NABERS Energy and IE rating scores. Multivariate linear regression results reveal that one unit increase in NABERS Energy rating score and IE score can reduce NEUI by 21.98 kWh/m^2 and 9.88 kWh/m^2 per annum, respectively. Also, this study develops an Energy and Indoor Environment Index to benchmark the energy and IEQ performance of Australian office building. Buildings with excellent NABERS Energy and IE ratings (scores equal to/higher than 5) have been classified as high-performance NABERS buildings (HNBs) and the rest as low-performance NABERS buildings (LNBs). A comparison between 49 HNBs and 48 LNBs demonstrates that, on average, HNBs can deliver 12.6% better indoor environment quality with 35.9% less energy consumption than LNBs. In contrast, many LNBs either use excessive energy to provide a sufficient IEQ, or sacrifice IEQ to reduce energy costs and/or achieve a high NABERS Energy rating.

Keywords: energy consumption; office buildings; NABERS; indoor environment quality; energy-IEQ index.

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Acronyms		LEED	Leadership in energy and environment design
AC	Acoustic comfort	LNB	Low-performance NABERS building
ANOVA	Analysis of variance	NABERS	National Australian built environment rating system
BREEAM	Building research establishment environmental assessment method	NEUI	Normalized energy use intensity
CASBEE	Comprehensive assessment system for built environment efficiency	NF	Weather normalization factor
CDD	Cooling degree days	NGB	Non-green building
EUI	Energy use intensity	TC	Thermal comfort
GB	Green building	VC	Visual comfort
GBEL	Green building energy label		
GBI	Green building index	**Symbols**	
HDD	Heating degree days	η	Energy normalization factor
HNB	High-performance NABERS building		
HVAC	Heating, ventilation, and air conditioning	**Subscripts**	
IAQ	Indoor air quality	ac	Actual delivered energy
IEQ	Indoor environmental quality	m	Measurement
IEQS	IEQ score	s	Survey

1. Introduction

1.1. Evaluation of building energy and IEQ performance

Energy consumption in buildings is growing steeply, and the resulting air pollution is a global problem(Yousefi et al., 2018). While the main purpose of a building is to guarantee a safe, convenient and healthy space for occupants, many buildings with high energy consumption inadequately service their occupants (Lee et al., 2019; Roumi et al., 2019). A significant number of studies have explored illnesses caused by buildings providing inadequate air temperature, light, humidity, and so on (Dutton et al., 2013; Joshi, 2008; Thach et al., 2019; Wong et al., 2009). The notion of indoor environmental quality (IEQ) has developed in recent decades and represents a building's quality concerning the wellbeing, comfort, and productivity of its occupants(Al horr et al., 2016). Improving IEQ can enhance occupants' work performance and generate productivity benefits for organisations (Thach et al., 2020; Tham et al., 2015). IEQ is usually evaluated based on four main environmental categories: (1) thermal comfort; (2) indoor air quality (IAQ); (3) lighting; and (4) acoustics.

Recognised international standards such as those imposed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), International Organization for Standardization (ISO) and European Standards (EN) determine proper indoor environmental conditions based on the occupants' needs (Almeida, Laura et al., 2020). Among these various bodies, the European Committee for Standardization (CEN) and ISO have attempted to combine all factors into a single set of standards. Although they successfully addressed thermal comfort and IAQ requirements, they have not established comprehensive requirements for lighting or acoustics (Thatcher and Milner, 2016). The focus of such standards is mainly on specifying minimum requirements for specific IEQ factors. There is a lack of guidelines to cross-link energy and IEQ performance, and some papers have mentioned this gap and the importance of research in this field (Elnaklah et al., 2020; Sediso and Lee, 2016).

1.2. Comparing energy usage and IEQ performance for GB and NGB

The Green building (GB) concept was introduced as a potential solution to overcome high energy consumption and low efficiency in buildings. Recently, the impact of GB on occupant satisfaction and health has become an area of interest for scholars(Cheung et al., 2021; Lee, J.-Y. et al., 2020; Pei, Z.F. et al., 2015; Wang and Zheng, 2020). In addition, GB design, construction and operation are intended to reduce natural resource consumption and ecological impact (Zuo and Zhao, 2014). Several voluntary assessment tools have been established to contribute to GB developments. The commonly used GB assessment tools are LEED (United States) (U.S green building Council), GBEL (China) (Ministry of Housing and Urban-Rural Development of the People's Republic of China), BREEAM (United Kingdom) (BREEAM international new construction), Green Star (Australia) (Green building Council Australia), KGBCC (South Korea) (Yeom and Lee, 2015), CASBEE (Japan)(CASBEE), GBI (Malaysia) (Green Building Index) and Green Mark (Singapore) (BCA Green Mark Scheme).

By identifying certified GB projects through rating systems around the world, scholars have investigated the impact of green certifications on buildings' energy use intensity (EUI) and/or IEQ. The studies presented in **Table 1** evaluated GBs' performance and compared with Non-green Buildings (NGBs) and other green ratings.

Table 1. Comparison of evaluated GBs' performance with standards, NGBs and other green ratings.

Paper	Rating tool	Buildings evaluated	Building performance	Comparison with	Findings
(Lim et al., 2017)	GBI	2 GBs	Energy, IEQ Occupant satisfaction	Malaysian standard (MS1525:2014)	Office buildings showed 41-53% energy savings from the standard threshold. 20% of GB occupants were dissatisfied with VC.
(Suzaini et al., 2017)	GBI	1 GB and 1 NGB	Energy	Malaysian standard (MS1525:2007) and NGB	Although both GBs and conventional buildings consume less energy than the national standard, the conventional building outperforms GB.
(Khoshbakht et al., 2018)	Green Star	5 GBs and 9 NGBs	IEQ	NGBs	Although overall TC and IAQ in Air-conditioned GBs achieved considerably higher satisfaction in comparison to NGBs, there was no major difference in overall TC and IAQ satisfaction scores in mix-mode office buildings.
(Almeida, Laura et al., 2020)	Green Star	1 GB and 1 NGB	Energy and Occupant satisfaction	NGB	EUI of GB was 2% less than NGB. GBs have higher occupant satisfaction compared to the average condition buildings.
(Thatcher and Milner, 2016)	Green Star	3 GBs and 1 NGB	IEQ and Occupant satisfaction	NGB	GBs possess significantly higher IAQ satisfaction than the NGBs. There is a significant improvement in self-report productivity and physical wellbeing in GBs.
(Elnaklah et al., 2020)	LEED	5 GBs and 5 NGBs	IEQ	LEED/ASHRAE 55 (2017) and LEED/ASHRAE 62.1 (2019) and NGBs	While occupant satisfaction with IAQ, TC, and VC was greater in the NGBs, GBs perform better in AC.
(Altomonte et al., 2019)	LEED	93 GBs	IEQ and Occupant satisfaction	Rating class	Achieving a specific IEQ credit did not practically affect occupant satisfaction.
(Gou et al., 2012b)	LEED	2 GBs and 1 NGB	IEQ	NGB	There was no significant difference in the overall IEQ satisfaction among GBs and NGB.
(Gou et al., 2013)	LEED and GBEL	9 (5 GBEL and 4 LEED) GBs and 5 NGBs	IEQ and Occupant satisfaction	NGBs	GB occupants are more forgiving of the indoor environment. The satisfaction scores spread widely for the GBs.
(Gou et al., 2012c)	LEED and GBEL	2 GBs and 1 NGB	IEQ	NGB	While GBs performed better on the comfort and satisfaction with the TC and IAQ in the summer, they poorly functioned in winter.

(Geng et al., 2020)	GBEL	20 GBs	Energy and IEQ	China's national Standards (GB/T 18883-2002, GB 50034-2013, GB/T51161-2016) and NGB	High-EUI buildings have a better compliance rate of the TC compared to the low-EUI buildings. Although both groups met local standards, no significant difference was found between the two groups regarding IAQ and VC.
(Zhou et al., 2020)	GBEL	1 GB	Energy, IEQ and Occupant satisfaction	China's national Standard (GB/T50378-2014)	EUI in GB was lower than the national standard. IAQ and VC were consistent with the design goals, however, GB could not provide TC in comparison with the standard. The satisfaction ratio of TC, IAQ, and VC is 94.1%, 90.5%, and 82.5%, respectively.
(Liu et al., 2018)	GBEL	12132 responses from GBs and 13633 from NGBs	IEQ and Occupant satisfaction	NGBs, Other rating schemes	The green rating tool has a statistically small impact on occupant satisfaction. The differences between GBs and NGBs in providing occupant satisfaction in the three-star certification are more pronounced than LEED and NREEAM certifications.
Gou et al.,) (2012a	GBEL	1 GB	IEQ and Occupant satisfaction	China's national Standard (GB50189-2005)	The occupant survey revealed there was a high level of satisfaction with TC, IAQ and overall comfort and perceived health and productivity.
(Lin et al., 2016)	GBEL	31 GBs and 481 NGBs	Energy and Occupant satisfaction	China's national Standard (GB/T 50378-2014), NGBs and Other rating schemes	EUI of Chinese GBs is almost 1/3 of US LEED-certified buildings. Average EUI of GBs are close to suggested values by the national standard, however, in some zones, the EUI of GBs are higher than the limit. A higher occupant satisfaction level of TC and IAQ was observed in GBs compared with NGBs.
(Gou and Siu-Yu Lau, 2013)	GBEL	1 GB	IEQ and Occupant satisfaction	China's national Standard (GB50189-2005)	12% and 20% dissatisfaction were reported with summer and winter temperatures, respectively.
(Pei, Z. et al., 2015)	GBEL	10 GBs and 2 NGBs	IEQ and Occupant satisfaction	China's national Standard (GB50189-2005) and NGBs	The survey shows that the GBs in China have significantly greater satisfaction level than NGBs. The actual performance of green buildings achieves the design goal (*The Green Building Evaluating Standard*) in terms of TC, IAQ, VC and AC.

As it is presented in **Table 1**, energy-focused GB publications have reported that most GBs have excelled in energy performance compared to national standards (Lim et al., 2017; Suzaini et al., 2017; Zhou et al., 2020); however, by evaluating 31 GBs, Lin et al. expressed that the energy consumption of GBs is sometimes higher than the national standard limits (Lin et al., 2016).

Literature comparing EUI in GBs and NGBs is inconsistent. Although the expectation is that GBs would generally consume less energy than their counterparts—and some studies do reveal slightly higher energy performance in GBs (Almeida, Laura et al., 2020)—many studies have found no consistent superiority in GBs (Scofield, 2009; Suzaini et al., 2017). Moreover, Scofield and Doane (Scofield and Doane, 2018) stated that although LEED-certified buildings use up to 10% less site energy than conventional buildings, their source energy consumption is comparatively higher than non-LEED certified buildings.

The literature is bifurcated regarding the impact of green certification levels on EUI in GBs. Although Lin et al. (Lin et al., 2016) argued that there is no correlation between the two, other papers demonstrated a direct relationship between certification level and EUI (Gui and Gou, 2020; Turner and Frankel, 2008).

There are some reasons behind these diverse results. The lack of a commonly agreed definition or evaluation method of green buildings is one of the main reasons. Most GB rating schemes have different categories for assessment, e.g., energy, indoor environment quality, water, materials, waste, etc. However, the weighting of these categories might be distinct in different rating schemes. At BREEAM, LEED, and Green Star, energy is more important than the IEQ. While in some European rating systems e.g., DGNB (Germany), Miljöbyggnad (Norway), and HQE (France), IEQ is more decisive than the energy consumption (Heincke and Olsson, 2012).

Another reason could be the gap between the buildings' designed and actual performance. Some buildings were designed to be green buildings, but not finally constructed or managed to perform as expected. Desmarais et al. evaluate some problems in construction and operation of green buildings(Desmarais and Gonçalves, 2010). They mentioned being green does not rely severely on looks or high-tech gadgets, or the total points achieved by a specific green rating system. Instead, an integrated and inclusive method is needed with the accurately designed systems for buildings' global context. This includes employing building science to assess and find beneficial solutions (Desmarais and Gonçalves, 2010).

As proposed by Geng et al. (Geng et al., 2020), the level of control of the thermal environment can be one possible reasons for high EUI in GBs. They observed that in type B buildings in China (public buildings with central air conditioning and mechanical ventilation operating throughout the year), the control systems are not fully capable of controlling the thermal environment as they are supposed to be. Consequent overheating or overcooling may lead to high energy consumption.

Also, the inconsistency may result partly from insufficient consideration of climatic differences in which buildings are located. The climatic condition has usually a considerable impact on energy consumption in office buildings. While buildings in some cities can use natural ventilation throughout a year, buildings in other locations need mechanical systems to provide a suitable working environment. While the comparison of building energy consumption across different geographical locations could be beneficial, it is impossible to make any meaningful comparison without weather normalization (Berardi, 2017; Gui and Gou, 2020). Also, it is important to apply the weather normalization factor to climate-sensitive energy use only, e.g., building energy dedicated for cooling, heating and ventilation (Geng et al., 2020; Zhengrong et al., 2010).

Geng et al. introduced an energy normalization method to eliminate the impact of outdoor weather on building energy consumption and compared 20 green buildings located in 6 different cities in China (**Eqs 1-2**) (Geng et al., 2020).

$$E_n = E_{ac} \times NF \tag{1}$$

$$NF = W_h . \frac{HDD_{18,base}}{HDD_{18,ac}} + W_c . \frac{CDD_{26,base}}{CDD_{26,ac}} \tag{2}$$

E_n and E_{ac} in **Eq. 1** represent normalized energy and actual delivered energy consumption, respectively. Energy Normalization factor is signified by NF. $HDD_{18,base}$ and $CDD_{18,base}$ are heating degree days and cooling degree days of the base city. Also, $HDD_{18,ac}$ and $CDD_{18,ac}$ denote actual heating degree days and cooling degree days of the studied city, respectively. While this method is a practical approach to minimize climatic influences on energy consumption in buildings, the weighting factors for heating and cooling (W_h and W_c) were constant numbers (3/7 and 4/7) for all cities, even though the cooling and heating demand may vary from different climates.

Focusing on each IEQ aspect presents interesting results (**Table 1**). Most scholars have found that GBs provide better thermal conditions than NGBs (Geng et al., 2020; Gou et al., 2012a; Gou and Siu ‐ Yu Lau, 2013; Liang et al., 2014; Lin et al., 2016; Sediso and Lee, 2016; Zhou et al., 2020), though some researchers have stated that there is no significant difference (Elnaklah et al., 2020; Gou et al., 2012c; Pastore and Andersen, 2019). For example, (Gou et al., 2012a; Khoshbakht et al., 2018) explained that GBs' performance in air-conditioned mode was ideal, while mixed-mode ventilation was unsatisfactory. The majority of GBs had better IAQ than national standards and conventional buildings (Gou et al., 2012a; Gou and Siu ‐ Yu Lau, 2013; Lee, J.Y. et al., 2020; Liang et al., 2014; Lin et al., 2016; Sediso and Lee, 2016; Thatcher and Milner, 2016; Zhou et al., 2020), although some studies conflicted with this claim (Elnaklah et al., 2020; Gou et al., 2012c; Pastore and Andersen, 2019). Furthermore, a few studies have mentioned that GBs provide a better lighting environment (Liang et al., 2014; Zhou et al., 2020), but other scholars have maintained that the visual comfort of certified buildings is not significantly better (Gou et al., 2012c; Lee, J.Y. et al., 2020; Lim et al., 2017) and is sometimes even worse than NGBs (Elnaklah et al., 2020; Gou et al., 2012a). Conflicting results have also been presented on acoustic comfort (Elnaklah et al., 2020; Gou et al., 2012a; Gou et al., 2012c; Lee, J.Y. et al., 2020; Sediso and Lee, 2016). Notably, while the physical measurements of (Liang et al., 2014) supported that the acoustic environment of conventional buildings is better than GBs, the satisfaction survey results were in favour of certified buildings.

Though the results of previous studies have been inconsistent regarding GBs' performance after occupancy, the contribution of previous research comparing the green rating types (Gou et al., 2012a; Lin et al., 2016; Liu et al., 2018), classes (Altomonte et al., 2019; Geng et al., 2020; Lin et al., 2016; Pastore and Andersen, 2019) and assessments with national standards (Elnaklah et al., 2020; Hwang and Kim, 2011; Lee, J.Y. et al., 2020; Liang et al., 2014; Lim et al., 2017; Suzaini et al., 2017; Zhou et al., 2020) and conventional buildings (Almeida, Laura et al., 2020; Almeida, Laura et al., 2020; Gou et al., 2012c; Gou et al., 2013; Khoshbakht et al., 2018; Sediso and Lee, 2016; Thatcher and Milner, 2016) is extremely valuable in promoting GBs and their evaluation.

1.3. Building energy-IEQ index

Building energy consumption and IEQ are both critical factors for evaluating building performance. Ideally, a unified energy-IEQ index would help building managers assess the current building condition continuously and to plan possible operational, maintenance and retrofit programs.

Being inspired by the Built Environment Efficiency (BEE) index introduced by CASBEE (CASBEE), Geng et al. (Geng et al., 2020) introduced the Environmental Energy Efficiency (EEE) index, which evaluates the ratio between normalized IEQ performance and building energy. The detailed calculation procedure is presented in **Eqs. 3-5**.

$$EEE = \frac{Normalized\ IEQ\ Performance}{Normalized\ Building\ Energy} \quad (3)$$

$$Normalized\ IEQ\ Performance = \sum_{i=1}^{n} \alpha_i \cdot [\beta_i \cdot IEQ_{i,ob} + (1-\beta_i) \cdot IEQ_{i,sub}] \quad (4)$$

$$Normalized\ Building\ Energy = \frac{Delivered\ Energy}{Energy\ constraint\ value} \quad (5)$$

In **Eq. 4**, $IEQ_{i,ob}$ denotes the physical performance of IEQ factor *i*. $IEQ_{i,sub}$ denotes the subjective acceptance of IEQ factor *i* and it is determined using occupant surveys; α_i signifies the weight of each IEQ factor; β_i represents the weight of the objective performance in the IEQ factor and (Geng et al., 2020) considered it equal to 0.5 for all IEQ factors. While this method gives a comprehensive evaluation of indoor environment, It is more time consuming and the result is dependent on the number of occupant responds.

To normalize the building energy consumption in **Eq. 5**, the delivered energy is divided by an energy constraint value which is reliant on the building category in China. it was selected as 85 kWh/m^2 and 110 kWh/m^2 for type A and B in hot summer cold winter zone of China.

1.4. NABERS Energy and IE ratings

As an initiative of the Council of Australian Governments (COAG), the Commercial Building Disclosure (CBD) program requires the building's NABERS Energy star rating to be included in any advertising material for the sale, lease or sublease of commercial office space of 1,000 m^2 or more (CBD, 2010), intending to improve the energy efficiency of Australia's large office buildings and to ensure an informed market. In contrast, other aspects of building performance, such as indoor environmental quality (IEQ), is less concerned by the government, despite a wealth of research demonstrating significant correlations between IEQ and occupant health, comfort and productivity (e.g., Newsham et al.(Newsham et al., 2008); Al horr et al.(Al horr et al., 2016); Wang et al.(Wang et al., 2021)).

The NABERS ratings (ranging from 1–6 stars) evaluate energy, water, waste, and indoor environment (NABERS, 2015a). By considering both building performance and user preferences, NABERS provides a comprehensive environmental assessment (Fay et al., 2004). NABERS has three different rating scopes to reflect the split of responsibilities of different stakeholders: base building (building owners and managers), whole building (building owners, managers and tenants) and tenancy (tenants).

The NABERS Energy tool benchmarks the energy usage performance of buildings in Australia. Based on the Investment Property Database, best-performance office buildings have a greater return on investment compared to conventional lower quality buildings (Lee et al., 2017). As a certification tool, NABERS Energy is calibrated considering various operational correction factors such as climate, service hours and net lettable floor, all of which are considered in base building schemes (Bannister, 2012).

The NABERS IE scheme measures indoor environmental conditions in office buildings. NABERS IE considers five key indoor environmental factors (thermal services, indoor air quality, acoustic comfort, lighting and office layout). Factors are evaluated separately to identify areas that need improvement, and their weighting in the total score is based on their impact on occupants (NABERS, 2015b).

NABERS IE rating combines on-site measurement (quantitative) as well as occupants' satisfaction surveys (qualitative). The NABERS IE satisfaction surveys quantify occupants' satisfaction levels with many aspects of the indoor environment. Depending on the specific rating scope, NABERS IE requires different types of data and their weighting is different, shown in Table 2 (Residovic, 2017). The final score received for each IEQ factor represents the ranking of that specific building compared with the NABERS IE benchmark (NABERS, 2015c).

Table 2. Data required for NABERS IE rating for different rating scopes (Residovic, 2017)

	Base building	Tenancy	Whole building

	Data	Weighting	Data	Weighting	Data	Weighting
Thermal services	M	40%	-	-	M, S	30%
Indoor air quality	M	40%	M, S	40%	M, S	30%
Acoustic comfort	M	20%	M, S	25%	M, S	15%
Lighting	-	-	M, S	25%	M, S	15%
Office layout	-	-	S	10%	S	10%

(M denotes on-site measurement; S represents Occupant survey; - represents no measurements.)

For more detailed information regarding the NABERS IE scheme (Base building rating) refer to Appendix 1.

1.5. Aims of the current research

The gaps which have been found by conducting literature review are:

- The absence of an appropriate energy normalization method for Australian buildings to compare energy consumption across different climate zones;
- The lack of investigation on the relationship between energy consumption in buildings and the NABERS IE certificate(Geng et al., 2020; Gui and Gou, 2020; Liu et al., 2018);
- The need for a more comprehensive Building Energy Efficiency Certificate (BEEC) incorporating both energy and indoor environmental quality in Australia's Commercial Building Disclosure (CBD) program.

The above-mentioned gaps evident in the existing literature inspired the current study, which focuses on the following three core objectives:

1) Adapt Geng et al. (2020)'s method to Australian context for normalizing energy use intensity in NABERS buildings located in different climatic zones; 2) Explore the statistical correlations between normalized EUI, IEQ score, NABERS IE rating stars, and NABERS Energy rating stars; 3) Develop an Energy and Indoor Environment Index to benchmark the energy and IEQ performance of Australian office buildings certified by NABERS Energy and IE.

This paper is arranged into five sections. Section 2 details the materials and methods in this research, Section 3 outlines the results of the analysis, Section 4 discusses the findings and compares them with the results of previous studies, and Section 5 provides the main conclusions and future research directions.

2. Materials and methods

2.1. Building data source

The database used in this research is publicly available on NABERS website, which is updated continuously throughout the year and offers information about buildings which have valid NABERS certification(NABERS, 2015a). Information in the dataset includes building geographical information (latitude, longitude, premise number, street name, city and state), NABERS rating type (energy, water, IEQ or waste), rating scope (base building, tenancy, or whole building), Energy rating information (energy rating score, annual energy consumption, CO_2 emission, energy use intensity), IEQ rating information (IEQ rating score, thermal comfort score, air quality score, acoustic comfort score, lighting score, office layout score), water rating information and waste rating information. In this study, only NABERS Energy and IE ratings are of interest, and solely building with base buildings certificate are selected for analysis due to their large sample sizes in the database.

As presented in **Table 2**, thermal comfort, IAQ and acoustic comfort represent 40%, 40% and 20% of the total base building IEQ score (IEQS), respectively. Based on the NABERS online database (accessed October 2020), 1,089 and 112 buildings were certified by NABERS Energy and NABERS IE, respectively (NABERS, 2015a). In addition, annual energy consumption (MWh) and EUI (MWh/m^2) of certified buildings are presented as energy performance indicators. Given that most certified buildings are in the six capital cities of Australia, namely, Adelaide, Brisbane, Canberra, Melbourne, Perth and Sydney, only buildings in these 6 cities have been selected for further analysis.

2.2. Energy normalisation method

The evaluated office buildings were constructed in different years, have variate HVAC systems and are located in six different cities. A significant part of total building energy consumption is related to HVAC systems. A typical HVAC system in a mechanically ventilated building is responsible for nearly 40% of total building energy consumption and 70% of base building energy consumption (Department of the Environment and Energy, 2013; Ma et al., 2015). Therefore, it is imperative to carry out normalization of HVAC energy use in buildings across different Australian cities. To accurately compare energy use in these buildings, we tried to eliminate the impact of buildings' geographical location and climates on buildings' energy consumption as much as possible.

Based on the Köppen-Geiger climate classification, Australia has 15 different climate divisions (Every et al., 2020). While the northern part of the continent has a tropical savanna climate, the southern part is generally warm and oceanic. The western side of Australia has a hot, semi-arid and Mediterranean climate, and the eastern side is mostly humid with a subtropical climate (Beck et al., 2018).

According to the Bureau of Meteorology of Australia, the comfort level values are considered as 18 ̊C and 24 ̊C for heating and cooling, respectively (Bureau of Meteorology, 2020). The 30-year average HDD and CDD of 6 major Australian cities were adopted as a baseline value for the weather normalisation process. Therefore, **Eq. 2** climate normalisation factor (NF) was localized to standardize energy use intensity in buildings from different climate zones of Australia.

$$NF = W_h . \frac{HDD_{18,base}}{HDD_{18,ac}} + W_c . \frac{CDD_{24,base}}{CDD_{24,ac}} \quad (6)$$

There are two differences between **Eq. 2** and **Eq.6.** First, the CDD setpoint is changed to 24 ̊C according to the Bureau of Meteorology of Australia (Bureau of Meteorology, 2020). Second, the constant weighting for cooling and heating purposes (W_h=3/7 and W_c=4/7) for cities investigated by (Geng et al., 2020) is modified based on climatic condition of each Australian city. For this purpose, an actual office building in Australia was simulated in each of 6 cities and weights (W_h and W_c) were determined by ratio of months heating and cooling is needed in each city. The simulation was conducted using SketchUp and TRNSYS software (**Fig. 1**). The simulated building has four floors, with a total floor area of 2717.2 m^2 and useful office area of 2177.9 m^2 (**Fig. 2**).

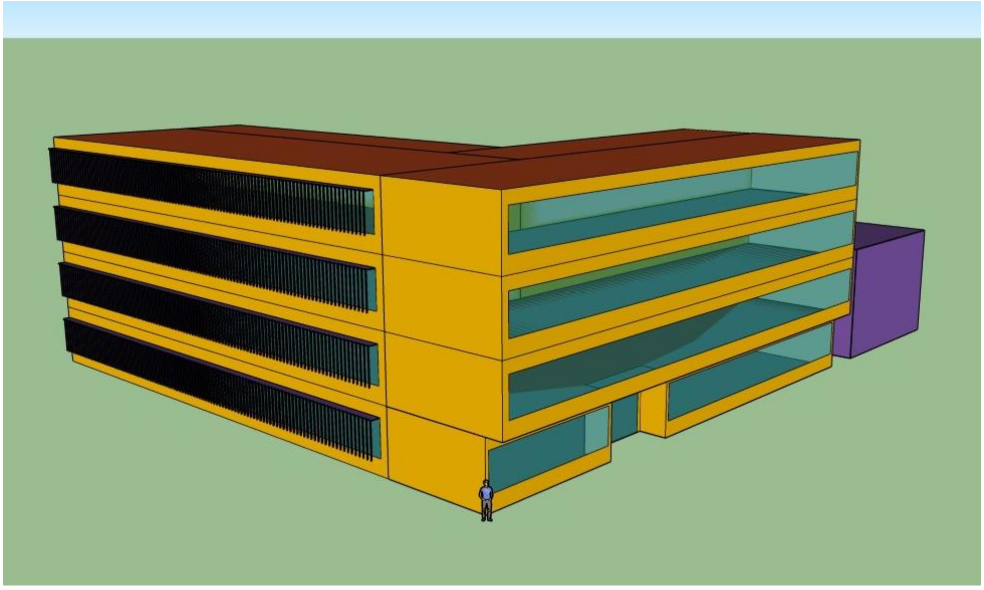

Figure 1. South-western view of the simulated office building model

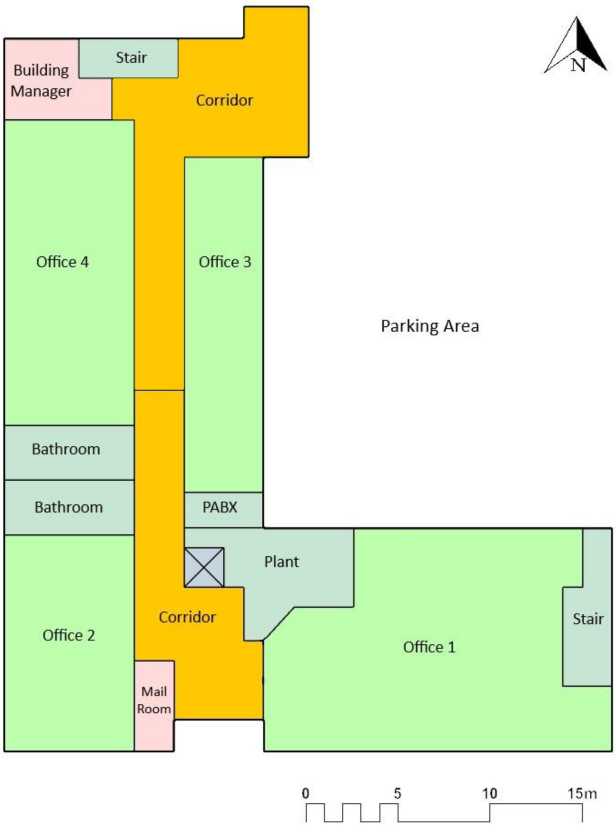

Figure 2. Floor plan of the simulated office building model

The details of simulated office building are presented in **Table 3.**

Table 3. Key information of the simulated building

Gross floor area	2717.2 m^2
Useful area	2177.9 m^2
Building height	21 m
Occupancy schedule	7:30 am – 6 pm (Monday to Friday)
Occupancy rate	1 person per 25m^2
HVAC system	Reverse cycle air-cooled systems and air handling units
Cooling setpoint	23.9 ̊C
Heating setpoint	21.0 ̊C
Equipment load	16.1 W/m^2
Lighting load	12 W/m^2
External walls (R-Value)	Brick + Airspace + Brick (0.55 m^2.K/W)
External roof (R-Value)	Finish +light concrete + Plaster (0.5 m^2.K/W)
Windows (U-Value)	double-glazed (1.37 W /m^2.K)
Window to wall ratio	0.4

The 30-year average CDD and HDD values of the Australian cities were obtained from the Bureau of Meteorology of Australia website and are presented in **Table 4**.

Table 4. Climate characteristics and Weather normalization factor in studied cities(BizEE)

City, state	Dominant load	Climate	HDD	CDD	NF	η
Canberra, ACT	Heating load	Cold	1,984	58	1.42	1.29
Adelaide, SA	Mixed load	Mixed	918	185	0.75	0.82
Melbourne, VIC	Heating load	Cold	1,206	67	1.38	1.27
Perth, WA	Mixed load	Hot	663	192	0.70	0.79
Brisbane, QLD	Cooling load	Hot/humid	269	136	0.90	0.93
Sydney, NSW	Mixed load	Mixed	503	94	1.35	1.24

Heating load = Annual conditioning load >67% heating
Cooling load = Annual conditioning load >67% cooling
Mixed load = Annual heating load 33-66%

HVAC systems are responsible for roughly 70% of the base energy consumption in office buildings (Department of the Environment and Energy, 2013). Therefore, Energy normalizing factor (η) can be calculated using **Eq. 7.**

$$\eta = \frac{(0.3 \times total\ energy\ consumption) + (0.7 \times total\ energy\ consumption \times NF)}{total\ energy\ consumption} = 0.3 + 0.7 \times NF \quad (7)$$

It is noteworthy to mention that the high humidity is another factor influencing the building energy consumption in office buildings located in tropical and subtropical climates. Most commercial buildings in Australia do not have independent humidity control. In order to quantify the impact of dehumidification on building energy use, as a worst-case scenario, we have assumed that the above case study building, located in Brisbane, has an independent humidity control and have simulated the building energy consumption spent on dehumidifying the indoor air to 60% relative humidity. Based on the simulation result, the energy used for dehumidification accounts for less than 9.5% of the total building energy use. Therefore, this influence of relative humidity is neglected for all Australian office buildings in the energy normalization process. Detailed explanation of weather normalization method and humidity influences is presented in Appendix 2.

2.3. Building sample descriptive statistics

Nighty-seven office buildings that have both NABERS Energy and IE certifications were studied to evaluate the relation between energy consumption and IEQ (**Fig. 3)**. While the NEUI of mentioned buildings is 98.3 kWh/m^2 and its distribution is positively skewed, the mean IEQS is 81.1% and its distribution is almost normal. The key NEUI and IEQS statistics of different buildings considered in this research are presented in **Table 5**.

Table 5. Key statistics of NABERS-rated buildings

	Annual NEUI (kWh/m^2)	IEQ score (%)
Mean	98.3	81.1
Max	264.6	96.7
Min	31.2	61.3
Median	92.7	81.3
Standard deviation	36.2	9.2

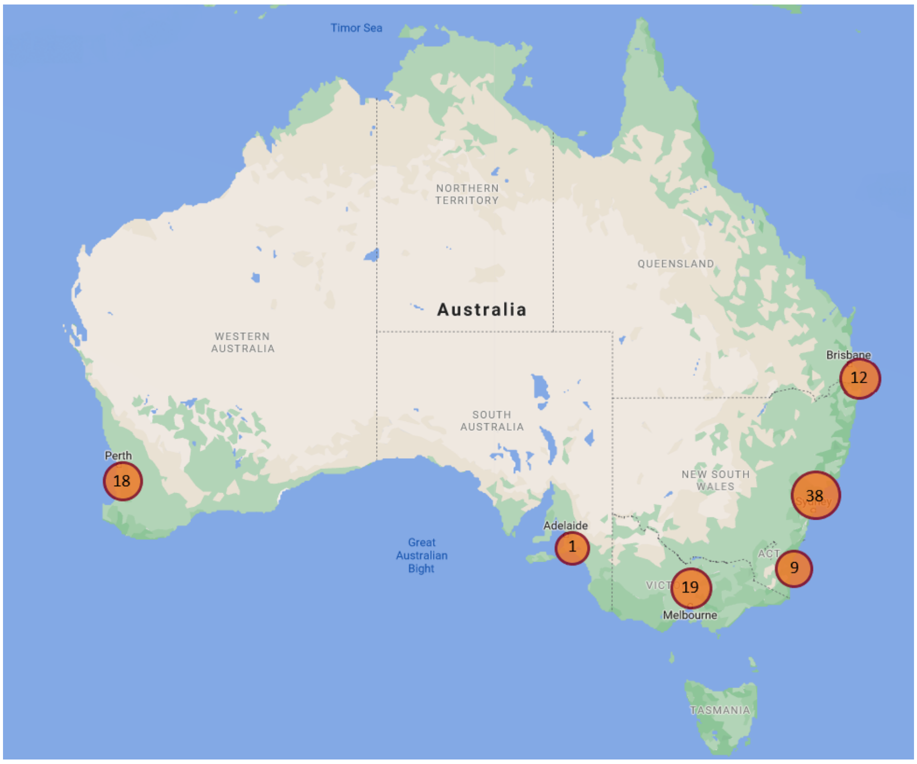

Figure 3. Distribution of buildings with both NABERS Energy and IE certifications

2.4. Analytical techniques

The correlation between NABERS Energy and NABERS IE with their indicator (Energy consumption and IEQS) have been investigated by Gui and Gou(Gui and Gou, 2020). In this study, the possible relationship between the NEUI and NABERS IE will be investigated. Also, in the promising relation between IEQS and NABERS Energy rating would be evaluated in this stage.

The analysis of variance (ANOVA) and Kruskal-Wallis tests investigate the significance of the differences between variables. Where the normal distribution of samples is a preliminary assumption for ANOVA, the Kruskal-Wallis test still functions even when data is not distributed normally (Gui et al., 2020). The statistical analysis of ANOVA and the Kruskal-Wallis test were performed to determine whether there was a significant difference in NEUI and IEQS values for the various NABERS levels.

Since a sufficiently large sample in a statistical test usually demonstrates a significant difference result (i.e. $p < 0.05$), "Effect size" should be calculated as a secondary assessment. Effect size (η^2) is referred as standardized measures of effect to the raw difference between groups (Sullivan and Feinn, 2012). Based on (Schagen and Elliot, 2004), effect sizes could be categorized as small ($\eta^2 \geqslant 0.2$), medium ($\eta^2 \geqslant 0.5$), and large ($\eta^2 \geqslant 0.8$). Therefore, the effect size of NABERS IE on NEUI and NABERS Energy on IEQS was calculated.

In this section, linear regression models were analysed to evaluate the variation of NEUI with NABERS IE levels and the dependency of IEQS to NABERS Energy rating. The level of NABERS certification (Energy and IE) served as the independent variable in the regression models, while NEUI and IEQS served as the dependent variables. The regression model is presented in **Eq. 7**.

$$Y = \alpha x + \beta + \varepsilon \quad (7)$$

Where Y is the dependent variable (NEUI and IEQS) and x the related NABERS rating (Energy and IE).

In **Eq. 7**, α is known as the regression coefficient, which means the amount of dependency of the dependent variable fluctuation by a single unit increase in the independent variable. Moreover, β, or the 'Intercept', is the value of the dependant variable when the independent variable is zero, and ε is standard error (the amount of information that the model fails to explain).

ANOVA and Kruskal-Wallis tests were conducted to investigate the relationship between Energy and IEQ. Additionally, effect sizes were calculated to evaluate the impact of NABERS IE rating on NEUI(R_1) and NABERS Energy rating on IEQS (R_2). Then, a linear regression was conducted (**Fig. 4**).

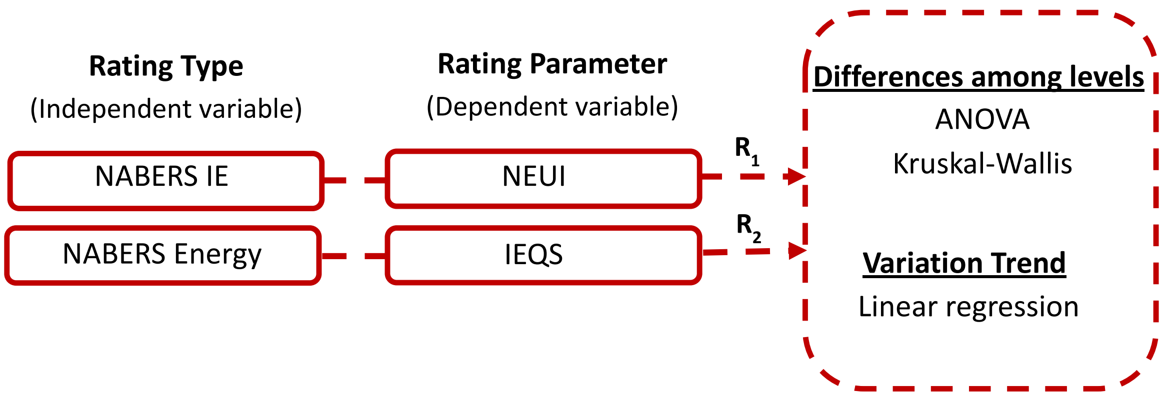

Figure 4. Secondary rating parameters analysis over NABERS certifications

The combined effect of NABERS certificates on NEUI was also explored to investigate the effect size of different certificates on NEUI. Firstly, assumptions of linearity, normality, and absence of multicollinearity, were examined. Linearity means that the predictor variables in the regression have a straight-line relationship with the outcome variable. The Variance inflation factor (VIF) method was selected to check the absence of multicollinearity.

2.5. Development of Energy and Indoor Environment index (EIEI)

To benchmark the energy and IEQ performance of office buildings in Australia, we introduce a new *Energy and Indoor Environment Index (EIEI)*, which is a ratio between the IEQ scores awarded by NABERS IE (NABERS, 2015c), and the building energy performance (**Eq. 8**). This index can be used for both 'base building' and 'whole building' rating scopes. The 'whole building' rating scope refers to rating for organisations that both manage and occupy their office space, or in some cases where a single tenant occupies the entirety of a building.

The EIEI index has two main advantages compared with the previous indexes. Firstly, the normalized EUI is considered in the calculation of building energy performance which results in more accurate results. Secondly, this index is based on NABERS IE ratings, and IEQS can be obtained once the NABERS IE rating is available.

$$EIEI = \frac{IEQS}{Building\ energy\ performance} \quad (8)$$

IEQS in **Eq. 9** is the accumulative impact of IEQ factors and it is revealed by NABERS database for each NABERS IE certified building (NABERS, 2015a). For the calculation of IEQS, $IEQ_{i,m}$ denotes the physical performance and $IEQ_{i,s}$ is the result of subjective surveys of IEQ factor *i*. Also, α_i and β_i represent the weight of each IEQ factor and weight of the physical measurement in the IEQ factor, respectively. Based on the building rating categories, n, α and β are presented in **Table 6**(NABERS, 2015a).

$$IEQS = \sum_{i=1}^{n} \alpha_i \cdot \left[\beta_i \cdot IEQ_{i,m} + (1-\beta_i) \cdot IEQ_{i,s}\right] \quad (9)$$

Table 6. Coefficients used in IEQS calculation(NABERS, 2015a)

IEQ factor	Base building		Whole building	
	n=3		n=5	
	α	β	α	β
Thermal services	0.4	1	0.3	0.5
IAQ	0.4	1	0.3	0.5
Acoustic comfort	0.2	1	0.15	0.5
Lighting comfort	-	-	0.15	0.5
Office layout	-	-	0.1	1

The building energy performance is calculated by the building's normalised energy use intensity divided by the baseline energy consumption in Australian commercial buildings (COAG, 2012) (**Eq. 10**), in which η represents the weather normalization factor, which can be obtained from **Table 4**. Also, based on the different building ownership type and rating categories, the '*energy constraint value*' can be selected from **Table 7**.

$$Building\ Energy\ Performance = \frac{\eta \times EUI}{Energy\ constraint\ value} \quad (10)$$

Table 7. The energy constraint value based on the building ownership and category (COAG, 2012)

Ownership type	Category	Energy constraint value (kWh/m^2.a)
Government	Base building	132.6
	Whole building	204.8
Private	Base building	156.5
	Whole building	262.9

3. Data analysis and results

3.1. Relationship between Energy and IEQ (R_1 and R_2)

By investigating NABERS certified buildings, it becomes evident that there is a possible relationship between the NABERS IE rating and NEUI (**Fig. 5**). The number of buildings with NABERS IE certificate is presented at the top of each group. Based on the NABERS IE rating category boxplots, it can be deduced that the highest-quality NABERS IE buildings consume less energy while providing a better IE for occupants. In other words, thermal comfort and IAQ (which are the main criteria to reach a high NABERS IE rating) can be provided with low energy requirements.

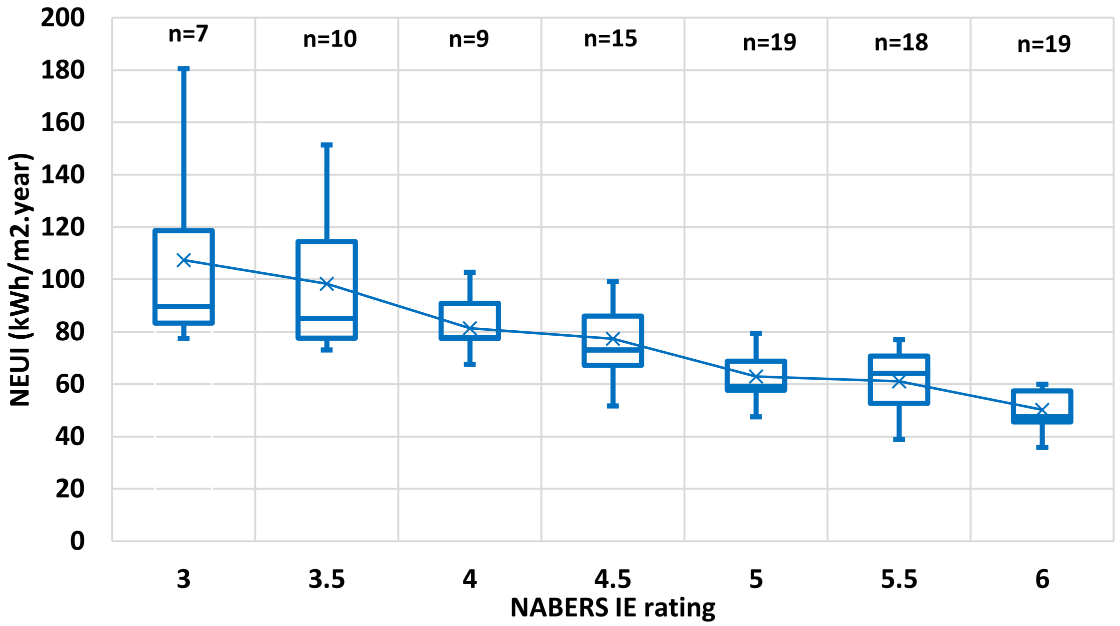

Figure 5. Normalised EUI comparison of sample buildings

The results of the ANOVA and Kruskal–Wallis tests for sample buildings are presented in **Table 8**. The outcome indicates that there is a significant difference (p<0.001) between the average normalized EUI of buildings with different levels of NABERS IE ratings and this represents a large-size effect (η^2 = 0.51). The NABERS Energy ratings do not have any significant impact (p=0.195) on the buildings' IEQ scores.

Table 8. ANOVA and Kruskal-Wallis results for secondary relationships (R_1 and R_2)

	Independent variable	NABERS IE	NABERS Energy
	Dependent variable	NEUI	IEQS
ANOVA	DF	6	8
	SS	354,430	931
	MS	5,905	116
	F value	14.626	1.43
	P-value	<0.001	0.195
	η^2	0.51	0.11
Kruskal-Wallis	Chi-squared	57.5	9.954
	DF	6	8
	P-value	<0.001	0.268

To evaluate the impact of NABERS IE certificate on NEUI, regression analysis was performed. Table 9 demonstrates the estimates of the regression model. It can be seen that about 45% of the variance in the NEUI is predictable from the NABERS IE rating. A single unit increase in NABERS IE certification can reduce NEUI by 19.79 kWh/m^2 annually (**Table 9**).

Table 9. Regression analysis between NABERS IE and NEUI (R_1)

Dependent variable	Independent variable	Estimate α	Intercept β	Standard error ε	R^2	Adjusted R^2	Sig.
NEUI	NABERS IE	-19.79	167.55	20.30	0.455	0.449	<0.001

Therefore, it is rational to evaluate the combined impact of NABERS Energy and IE certificates on prediction of energy use in buildings.

3.2. The combined impact of NABERS IE and Energy on NEUI

Based on the result of previous section and study by Gui and Gou (Gui and Gou, 2020), it is evident that both NABERS Energy and IE can be used to predict the NEUI in certified buildings. In this section, their combined effect on energy use in office buildings was investigated.

The normal predicted probability analysis showed that the residuals are normally distributed, and preliminary assumptions of linearity and normality were met. Also, the analysis demonstrated the absence of multicollinearity (VIF=1.22) **(Table 10)**. The results of multiple linear regression are shown in **Table 10.** The result indicates that NABERS Energy has a more influential contribution to NEUI than NABERS IE. The *p*-value is less than 0.001 and adjusted R^2 is 0.920, indicating that 92% of the variance in NEUI can be explained by the building's NABERS IE and Energy ratings, with the latter having a greater impact. Therefore, for the Australian sample analysed, it is evident that a building's NEUI can be accurately predicted by its NABERS Energy and IE certifications (**Eq. 11**).

Table 10. Multivariate regression analysis between NABERS IE, NABERS Energy and NEUI

Dependent variable	Independent variable	Estimate α	Intercept β	Standard error ε	R^2	Adjusted R^2	Sig.	VIF
NEUI	NABERS IE NABERS Energy	-9.88 -21.98	228.12	6.847	0.922	0.920	<0.001	1.22

$$NEUI = 228.12 - 21.98 \times NABERS\ Energy - 9.88 \times NABERS\ IE \quad (11)$$

3.3. EIEI in NABERS buildings

To further compare energy and IEQ performance within 97 NABERS buildings with both Energy and IE certifications, they were categorised into high-performance NABERS buildings (HNBs) and low-performance NABERS buildings (LNBs). The rationale behind this separation is based on the NABERS database showing the average Energy and IE rating for offices is 4.5 Stars. Therefore, HNBs refers to buildings that have an excellent performance in both energy rating (i.e., 5-6 stars) and IE rating (5-6 stars)(NABERS, 2015a).

A total of 49 market-leading buildings were considered as HNBs (**Fig. 6**). Another 48 buildings were deemed as LNBs, which were categorised into three groups. High Energy NABERS (N=24) had a high NABERS Energy rating (i.e., 5-6 stars) but a relatively low NABERS IE rating (i.e., 3-5 stars). Likewise, 7 high IE NABERS buildings had an excellent IE rating but poor energy rating. The rest 17 buildings performed moderately or poorly in both energy and indoor environment aspects.

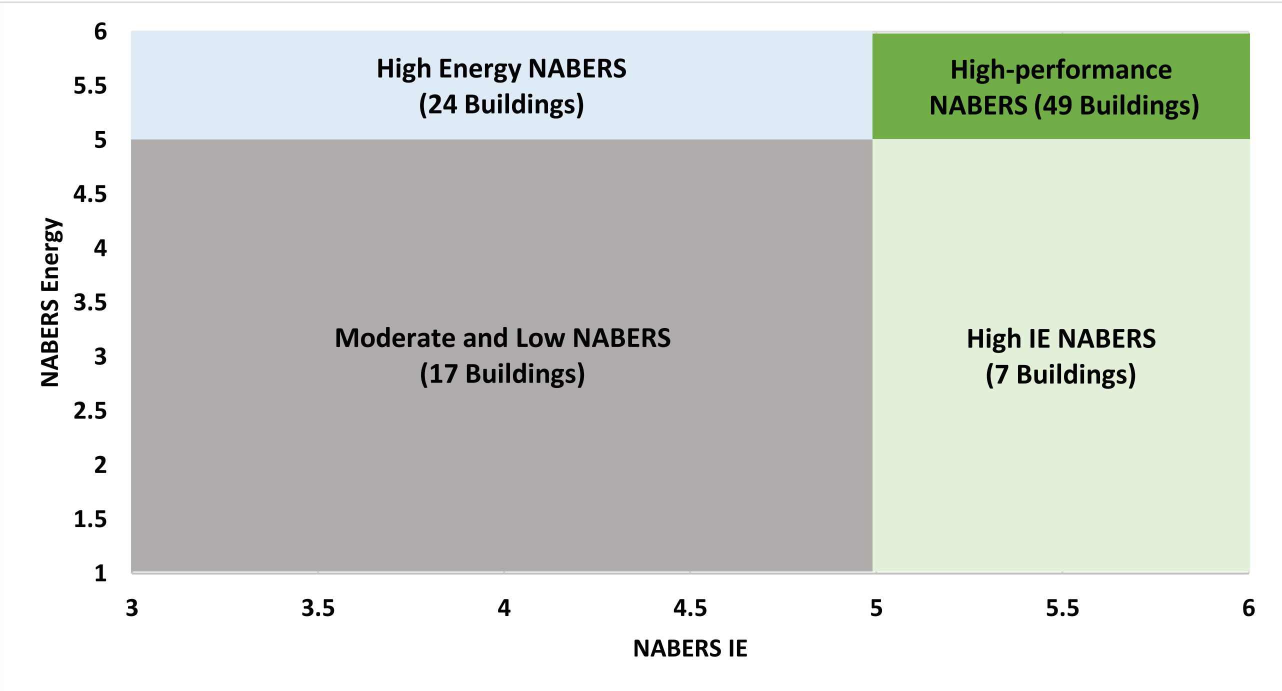

Figure 6. The categorisation of NABERS buildings based on Energy and IE certifications

As is presented in **Table 11**, HNBs consume 55.5 kWh/m^2 of energy per annum, which is 35.9% less than the normalised EUI of LNBs, 86.7 kWh/ m^2. The standard deviation of NEUI in high-performance NABERS buildings and low-performance NABERS buildings are 8.9 kWh/m^2.a and 23.7 kWh/m^2.a, respectively. The lower standard deviation of HNBs means that the data are closely clustered around the mean. Also, the average IEQS in HNBs is 87.3%, which is 12.6% higher than their counterpart (74.7% for LNBs).

Table 11. Key descriptive statistics for sample buildings

Parameter	NEUI (kWh/m^2.a)		IEQS (%)	
	HNBs	LNBs	HNBs	LNBs
Number of buildings	49	48	49	48
Mean	55.5	86.7	87.3	74.7
Max	69.7	180.6	96.7	91.7
Min	35.8	51.7	76.8	61.3
Median	57.2	78.5	86.1	75.1
Standard deviation	8.9	23.7	5.4	7.8

Fig. 7 illustrates different levels of energy and IEQ performance in sample buildings. The vertical and horizontal axis in **Fig. 7** represent IEQS (**Eq. 9**), and building energy performance (**Eq. 10**), respectively. Thresholds in this figure are based on the method introduced by (Geng et al., 2020). Moreover, horizontal thresholds were added to illustrate the importance of indoor environment in buildings. Hence, when a building is located on the left side of the graph, it indicates the building consumes a small amount of energy per square meter. Also, points which are in the top of **Fig. 7** represents buildings that provide excellent indoor environment. The thresholds divide the graph into 5 distinct zones where A and E zones represent the best and worst building performance, respectively.

Fig. 7 demonstrates that most of the HNBs are within Zone A in EIEI, meaning that they can provide the best indoor environment with reasonable energy consumption. A few LNBs located inside zone A, as well. All HNBs which failed to achieve grade A had EIEI value lower than 2. In other words, while they perform well in providing indoor environment (IEQS > 80%), they consume excessive energy to provide such an environment. The majority of LNBs were within Zone B and C in EIEI, with only a few in Zone D. There is just one building in Perth that has a building energy performance (**Eq. 10**) of more than 1. This building's NABERS Energy and IE are 1 and 3, respectively. This NABERS building is a good example of a rated building that uses excessive energy to provide an adequate indoor environment quality. Scenarios like this and issues pertaining to excessive energy consumption to provide indoor environment satisfaction are discussed in the following section.

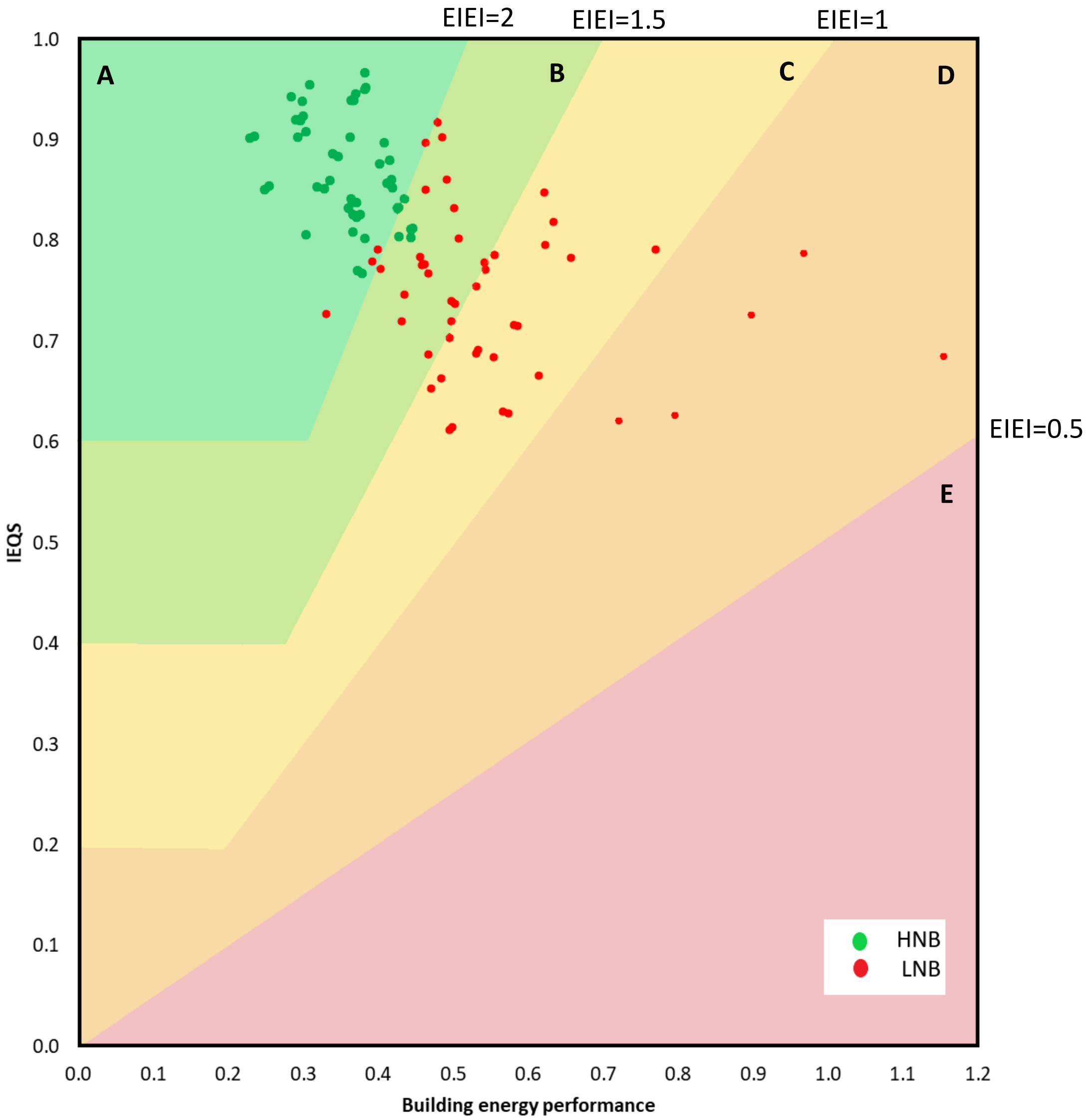

Figure 7. Energy and indoor environment index for HNBs and LNBs

4. Discussion

4.1. Comparison with previous studies

The current research evaluates Energy and IEQ in buildings rated by NABERS which is not a widely discussed rating scheme in previous studies. This study further advances the research by Gui and Gou (Gui and Gou, 2020). The use of energy normalization factors enables the comparison of building energy use between different climate zones and facilitates the exploration of more accurate relationships between normalized building energy and NABERS certifications. It is found that NABERS IE and NEUI are inversely correlated. In contrast, the study does not identify any significant relationship between NABERS Energy and IEQ score. Finally, a strong multivariate correlation is found between NEUI and both NABERS IE and Energy certificates, with the latter being a more significant contributor; this relationship has not previously been investigated.

The study also reveals that HNBs consume less energy than LNBs, which was also confirmed by (Almeida, Laura et al., 2020). Moreover, the mean IEQS in high-performance NABERS buildings is 12.6% higher than that in low-performance NABERS buildings. This resonates with the previous finding that buildings with high energy performance can provide a better indoor environment than low quality non-green ones (Lee, J.Y. et al., 2020; Sediso and Lee, 2016).

4.2. Implications for policy and practice

Inspired by Geng et al. (Geng et al., 2020), The Energy and Indoor Environment index was designed to comprehensively evaluate building performance. This comprehensive index would normalize IEQ and EUI factors for buildings and rank them accordingly. Many low-performance NABERS buildings needed to consume more electricity than best-practice buildings due to a range of factors including poor building design, construction, or operational management (see: buildings graded D in **Fig. 7)**. On the other hand, due to the Commercial Building Disclosure (CBD) program of Australia, sellers and lessors of office space of 1,000m^2 or more have to obtain a Building Energy Efficiency Certificate (BEEC) before the building goes on the market for sale, lease or sublease (CBD, 2010). This biased rule motivates some building managers to focus efforts purely on energy efficiency to obtain a high NABERS Energy rating at the expense of indoor environment quality and occupants' health, satisfaction, and wellbeing (see: buildings in the bottom of grade C in **Fig. 7)**. This issue is not exclusive to the Australian context, but also identified in other countries with other rating systems (Ncube, 2012). Therefore, there is a modification needed in BEEC to require office buildings to have both NABERS Energy and IE certificates. In this way, building performance can be evaluated in a more comprehensive way.

The analysis not only proves that there is a relationship between NABERS ratings (Energy and IE) with NEUI but also confirms a linear relationship between them. Importantly, the developed prediction model helps building managers compare their delivered energy consumption with the NABERS benchmarks. In this way, facility managers would discover if excessive energy were being consumed to provide an adequate indoor environment quality, and they could subsequently adjust the indoor conditions to achieve more reasonable levels of energy consumption.

4.3. Study limitations

Although NEUI had a negative linear relationship with the NABERS Energy and IE certificates, the lack of buildings with both certificates could have biased the results. Most building managers preferred to acquire the NABERS Energy certification, and only 97 buildings had both Energy and IEQ certifications. It is notable that this study only considered NABERS 'Base building certificates' to make the buildings comparable. There are not enough buildings with NABERS 'Whole building' and 'Tenancy' certificates in the database. This issue resulted in other important IEQ factors (i.e., lighting and layout) being neglected, along with occupant satisfaction. These factors should be evaluated in future studies when more buildings have the NABERS IE certificates. Moreover, future studies should evaluate whether the impacts of energy and IEQ on total EUI differ from various climatic conditions. In addition, post-occupancy evaluation of building occupants' satisfaction and physical measurements of IEQ and energy should be conducted and correlated with the NEUI.

5. Conclusion

This study has developed a method to normalize energy use intensity in NABERS buildings located in different climatic zones in Australia. It also explored the statistical correlations between normalized EUI, IEQ score, NABERS IE rating stars, and NABERS Energy rating stars. Also, a new benchmarking method was presented to evaluate and compare buildings in Australia.

The major findings of the study can be summarised as follows:

1. Analysis of sample buildings revealed a moderate correlation between NEUI and NABERS IE rating (R^2=0.455, p<0.001).
2. A multivariate regression between NEUI and NABERS certificates (Energy and IE) demonstrated that, on average, a one-level rise in the NABERS Energy and IE reduced NEUI in Australian office buildings by 21.98 kWh/m^2 and 9.88 kWh/m^2, respectively (R^2=0.922, p<0.001).
3. Moreover, this study compared high-performance NABERS buildings with low-performance ones. The result revealed that, on average, high-quality buildings can deliver 12.6% better IEQ with 35.9% less energy consumption in comparison with low-performance ones.

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- The indoor environment quality in office buildings has an impact on energy consumption
- One unit increase in NABERS Energy and IE rating score can reduce normalized energy use intensity by 21.98 kWh/m^2 and 9.88 kWh/m^2 per annum, respectively
- High-performing NABERS buildings can deliver 13% better IEQ with 36% less energy consumption than their low-performing counterparts
- Government regulations should request both Energy and IEQ certificates for commercial buildings.

Unravelling the Relationship Between Energy and Indoor Environmental Quality in Australian Office Buildings

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Abstract

Green building studies generally focus on singular performance aspects (e.g., energy, waste, water, indoor environment) with few tackling the relationships between each other, particularly the relationship between indoor environmental quality (IEQ) and building energy consumption. This study aims to explore the relationship between IEQ performance and energy consumption in National Australian Built Environment Rating System (NABERS) certified buildings. A verified climate normalization factor was localized to standardize energy use intensity in buildings from different climate zones of Australia. The normalized energy use intensity (NEUI) was calculated for all office buildings and correlated with their NABERS Energy and IE rating scores. Multivariate linear regression results reveal that one unit increase in NABERS Energy rating score and IE score can reduce NEUI by 21.98 kWh/m^2 and 9.88 kWh/m^2 per annum, respectively. Also, this study develops an Energy and Indoor Environment Index to benchmark the energy and IEQ performance of Australian office building. Buildings with excellent NABERS Energy and IE ratings (scores equal to/higher than 5) have been classified as high-performance NABERS buildings (HNBs) and the rest as low-performance NABERS buildings (LNBs). A comparison between 49 HNBs and 48 LNBs demonstrates that, on average, HNBs can deliver 12.6% better indoor environment quality with 35.9% less energy consumption than LNBs. In contrast, many LNBs either use excessive energy to provide a sufficient IEQ, or sacrifice IEQ to reduce energy costs and/or achieve a high NABERS Energy rating.

Keywords: energy consumption; office buildings; NABERS; indoor environment quality; energy-IEQ index.

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Acronyms		LEED	Leadership in energy and environment design
AC	Acoustic comfort	LNB	Low-performance NABERS building
ANOVA	Analysis of variance	NABERS	National Australian built environment rating system
BREEAM	Building research establishment environmental assessment method	NEUI	Normalized energy use intensity
CASBEE	Comprehensive assessment system for built environment efficiency	NF	Weather normalization factor
CDD	Cooling degree days	NGB	Non-green building
EUI	Energy use intensity	TC	Thermal comfort
GB	Green building	VC	Visual comfort
GBEL	Green building energy label		
GBI	Green building index	**Symbols**	
HDD	Heating degree days	η	Energy normalization factor
HNB	High-performance NABERS building		
HVAC	Heating, ventilation, and air conditioning	**Subscripts**	
IAQ	Indoor air quality	ac	Actual delivered energy
IEQ	Indoor environmental quality	m	Measurement
IEQS	IEQ score	s	Survey

1. Introduction

1.1. Evaluation of building energy and IEQ performance

Energy consumption in buildings is growing steeply, and the resulting air pollution is a global problem(Yousefi et al., 2018). While the main purpose of a building is to guarantee a safe, convenient and healthy space for occupants, many buildings with high energy consumption inadequately service their occupants (Lee et al., 2019; Roumi et al., 2019). A significant number of studies have explored illnesses caused by buildings providing inadequate air temperature, light, humidity, and so on (Dutton et al., 2013; Joshi, 2008; Thach et al., 2019; Wong et al., 2009). The notion of indoor environmental quality (IEQ) has developed in recent decades and represents a building's quality concerning the wellbeing, comfort, and productivity of its occupants(Al horr et al., 2016). Improving IEQ can enhance occupants' work performance and generate productivity benefits for organisations (Thach et al., 2020; Tham et al., 2015). IEQ is usually evaluated based on four main environmental categories: (1) thermal comfort; (2) indoor air quality (IAQ); (3) lighting; and (4) acoustics.

Recognised international standards such as those imposed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), International Organization for Standardization (ISO) and European Standards (EN) determine proper indoor environmental conditions based on the occupants' needs (Almeida, Laura et al., 2020). Among these various bodies, the European Committee for Standardization (CEN) and ISO have attempted to combine all factors into a single set of standards. Although they successfully addressed thermal comfort and IAQ requirements, they have not established comprehensive requirements for lighting or acoustics (Thatcher and Milner, 2016). The focus of such standards is mainly on specifying minimum requirements for specific IEQ factors. There is a lack of guidelines to cross-link energy and IEQ performance, and some papers have mentioned this gap and the importance of research in this field (Elnaklah et al., 2020; Sediso and Lee, 2016).

1.2. Comparing energy usage and IEQ performance for GB and NGB

The Green building (GB) concept was introduced as a potential solution to overcome high energy consumption and low efficiency in buildings. Recently, the impact of GB on occupant satisfaction and health has become an area of interest for scholars(Cheung et al., 2021; Lee, J.-Y. et al., 2020; Pei, Z.F. et al., 2015; Wang and Zheng, 2020). In addition, GB design, construction and operation are intended to reduce natural resource consumption and ecological impact (Zuo and Zhao, 2014). Several voluntary assessment tools have been established to contribute to GB developments. The commonly used GB assessment tools are LEED (United States) (U.S green building Council), GBEL (China) (Ministry of Housing and Urban-Rural Development of the People's Republic of China), BREEAM (United Kingdom) (BREEAM international new construction), Green Star (Australia) (Green building Council Australia), KGBCC (South Korea) (Yeom and Lee, 2015), CASBEE (Japan)(CASBEE), GBI (Malaysia) (Green Building Index) and Green Mark (Singapore) (BCA Green Mark Scheme).

By identifying certified GB projects through rating systems around the world, scholars have investigated the impact of green certifications on buildings' energy use intensity (EUI) and/or IEQ. The studies presented in **Table 1** evaluated GBs' performance and compared with Non-green Buildings (NGBs) and other green ratings.

Table 1. Comparison of evaluated GBs' performance with standards, NGBs and other green ratings.

Paper	Rating tool	Buildings evaluated	Building performance	Comparison with	Findings
(Lim et al., 2017)	GBI	2 GBs	Energy, IEQ Occupant satisfaction	Malaysian standard (MS1525:2014)	Office buildings showed 41-53% energy savings from the standard threshold. 20% of GB occupants were dissatisfied with VC.
(Suzaini et al., 2017)	GBI	1 GB and 1 NGB	Energy	Malaysian standard (MS1525:2007) and NGB	Although both GBs and conventional buildings consume less energy than the national standard, the conventional building outperforms GB.
(Khoshbakht et al., 2018)	Green Star	5 GBs and 9 NGBs	IEQ	NGBs	Although overall TC and IAQ in Air-conditioned GBs achieved considerably higher satisfaction in comparison to NGBs, there was no major difference in overall TC and IAQ satisfaction scores in mix-mode office buildings.
(Almeida, Laura et al., 2020)	Green Star	1 GB and 1 NGB	Energy and Occupant satisfaction	NGB	EUI of GB was 2% less than NGB. GBs have higher occupant satisfaction compared to the average condition buildings.
(Thatcher and Milner, 2016)	Green Star	3 GBs and 1 NGB	IEQ and Occupant satisfaction	NGB	GBs possess significantly higher IAQ satisfaction than the NGBs. There is a significant improvement in self-report productivity and physical wellbeing in GBs.
(Elnaklah et al., 2020)	LEED	5 GBs and 5 NGBs	IEQ	LEED/ASHRAE 55 (2017) and LEED/ASHRAE 62.1 (2019) and NGBs	While occupant satisfaction with IAQ, TC, and VC was greater in the NGBs, GBs perform better in AC.
(Altomonte et al., 2019)	LEED	93 GBs	IEQ and Occupant satisfaction	Rating class	Achieving a specific IEQ credit did not practically affect occupant satisfaction.
(Gou et al., 2012b)	LEED	2 GBs and 1 NGB	IEQ	NGB	There was no significant difference in the overall IEQ satisfaction among GBs and NGB.
(Gou et al., 2013)	LEED and GBEL	9 (5 GBEL and 4 LEED) GBs and 5 NGBs	IEQ and Occupant satisfaction	NGBs	GB occupants are more forgiving of the indoor environment. The satisfaction scores spread widely for the GBs.
(Gou et al., 2012c)	LEED and GBEL	2 GBs and 1 NGB	IEQ	NGB	While GBs performed better on the comfort and satisfaction with the TC and IAQ in the summer, they poorly functioned in winter.

(Geng et al., 2020)	GBEL	20 GBs	Energy and IEQ	China's national Standards (GB/T 18883-2002, GB 50034-2013, GB/T51161-2016) and NGB	High-EUI buildings have a better compliance rate of the TC compared to the low-EUI buildings. Although both groups met local standards, no significant difference was found between the two groups regarding IAQ and VC.
(Zhou et al., 2020)	GBEL	1 GB	Energy, IEQ and Occupant satisfaction	China's national Standard (GB/T50378-2014)	EUI in GB was lower than the national standard. IAQ and VC were consistent with the design goals, however, GB could not provide TC in comparison with the standard. The satisfaction ratio of TC, IAQ, and VC is 94.1%, 90.5%, and 82.5%, respectively.
(Liu et al., 2018)	GBEL	12132 responses from GBs and 13633 from NGBs	IEQ and Occupant satisfaction	NGBs, Other rating schemes	The green rating tool has a statistically small impact on occupant satisfaction. The differences between GBs and NGBs in providing occupant satisfaction in the three-star certification are more pronounced than LEED and NREEAM certifications.
Gou et al.,) (2012a	GBEL	1 GB	IEQ and Occupant satisfaction	China's national Standard (GB50189-2005)	The occupant survey revealed there was a high level of satisfaction with TC, IAQ and overall comfort and perceived health and productivity.
(Lin et al., 2016)	GBEL	31 GBs and 481 NGBs	Energy and Occupant satisfaction	China's national Standard (GB/T 50378-2014), NGBs and Other rating schemes	EUI of Chinese GBs is almost 1/3 of US LEED-certified buildings. Average EUI of GBs are close to suggested values by the national standard, however, in some zones, the EUI of GBs are higher than the limit. A higher occupant satisfaction level of TC and IAQ was observed in GBs compared with NGBs.
(Gou and Siu-Yu Lau, 2013)	GBEL	1 GB	IEQ and Occupant satisfaction	China's national Standard (GB50189-2005)	12% and 20% dissatisfaction were reported with summer and winter temperatures, respectively.
(Pei, Z. et al., 2015)	GBEL	10 GBs and 2 NGBs	IEQ and Occupant satisfaction	China's national Standard (GB50189-2005) and NGBs	The survey shows that the GBs in China have significantly greater satisfaction level than NGBs. The actual performance of green buildings achieves the design goal (*The Green Building Evaluating Standard*) in terms of TC, IAQ, VC and AC.

As it is presented in **Table 1**, energy-focused GB publications have reported that most GBs have excelled in energy performance compared to national standards (Lim et al., 2017; Suzaini et al., 2017; Zhou et al., 2020); however, by evaluating 31 GBs, Lin et al. expressed that the energy consumption of GBs is sometimes higher than the national standard limits (Lin et al., 2016).

Literature comparing EUI in GBs and NGBs is inconsistent. Although the expectation is that GBs would generally consume less energy than their counterparts—and some studies do reveal slightly higher energy performance in GBs (Almeida, Laura et al., 2020)—many studies have found no consistent superiority in GBs (Scofield, 2009; Suzaini et al., 2017). Moreover, Scofield and Doane (Scofield and Doane, 2018) stated that although LEED-certified buildings use up to 10% less site energy than conventional buildings, their source energy consumption is comparatively higher than non-LEED certified buildings.

The literature is bifurcated regarding the impact of green certification levels on EUI in GBs. Although Lin et al. (Lin et al., 2016) argued that there is no correlation between the two, other papers demonstrated a direct relationship between certification level and EUI (Gui and Gou, 2020; Turner and Frankel, 2008).

There are some reasons behind these diverse results. The lack of a commonly agreed definition or evaluation method of green buildings is one of the main reasons. Most GB rating schemes have different categories for assessment, e.g., energy, indoor environment quality, water, materials, waste, etc. However, the weighting of these categories might be distinct in different rating schemes. At BREEAM, LEED, and Green Star, energy is more important than the IEQ. While in some European rating systems e.g., DGNB (Germany), Miljöbyggnad (Norway), and HQE (France), IEQ is more decisive than the energy consumption (Heincke and Olsson, 2012).

Another reason could be the gap between the buildings' designed and actual performance. Some buildings were designed to be green buildings, but not finally constructed or managed to perform as expected. Desmarais et al. evaluate some problems in construction and operation of green buildings(Desmarais and Gonçalves, 2010). They mentioned being green does not rely severely on looks or high-tech gadgets, or the total points achieved by a specific green rating system. Instead, an integrated and inclusive method is needed with the accurately designed systems for buildings' global context. This includes employing building science to assess and find beneficial solutions (Desmarais and Gonçalves, 2010).

As proposed by Geng et al. (Geng et al., 2020), the level of control of the thermal environment can be one possible reasons for high EUI in GBs. They observed that in type B buildings in China (public buildings with central air conditioning and mechanical ventilation operating throughout the year), the control systems are not fully capable of controlling the thermal environment as they are supposed to be. Consequent overheating or overcooling may lead to high energy consumption.

Also, the inconsistency may result partly from insufficient consideration of climatic differences in which buildings are located. The climatic condition has usually a considerable impact on energy consumption in office buildings. While buildings in some cities can use natural ventilation throughout a year, buildings in other locations need mechanical systems to provide a suitable working environment. While the comparison of building energy consumption across different geographical locations could be beneficial, it is impossible to make any meaningful comparison without weather normalization (Berardi, 2017; Gui and Gou, 2020). Also, it is important to apply the weather normalization factor to climate-sensitive energy use only, e.g., building energy dedicated for cooling, heating and ventilation (Geng et al., 2020; Zhengrong et al., 2010).

Geng et al. introduced an energy normalization method to eliminate the impact of outdoor weather on building energy consumption and compared 20 green buildings located in 6 different cities in China (**Eqs 1-2**) (Geng et al., 2020).

$$E_n = E_{ac} \times NF \tag{1}$$

$$NF = W_h . \frac{HDD_{18,base}}{HDD_{18,ac}} + W_c . \frac{CDD_{26,base}}{CDD_{26,ac}} \tag{2}$$

E_n and E_{ac} in **Eq. 1** represent normalized energy and actual delivered energy consumption, respectively. Energy Normalization factor is signified by NF. $HDD_{18,base}$ and $CDD_{18,base}$ are heating degree days and cooling degree days of the base city. Also, $HDD_{18,ac}$ and $CDD_{18,ac}$ denote actual heating degree days and cooling degree days of the studied city, respectively. While this method is a practical approach to minimize climatic influences on energy consumption in buildings, the weighting factors for heating and cooling (W_h and W_c) were constant numbers (3/7 and 4/7) for all cities, even though the cooling and heating demand may vary from different climates.

Focusing on each IEQ aspect presents interesting results (**Table 1**). Most scholars have found that GBs provide better thermal conditions than NGBs (Geng et al., 2020; Gou et al., 2012a; Gou and Siu‐Yu Lau, 2013; Liang et al., 2014; Lin et al., 2016; Sediso and Lee, 2016; Zhou et al., 2020), though some researchers have stated that there is no significant difference (Elnaklah et al., 2020; Gou et al., 2012c; Pastore and Andersen, 2019). For example, (Gou et al., 2012a; Khoshbakht et al., 2018) explained that GBs' performance in air-conditioned mode was ideal, while mixed-mode ventilation was unsatisfactory. The majority of GBs had better IAQ than national standards and conventional buildings (Gou et al., 2012a; Gou and Siu‐Yu Lau, 2013; Lee, J.Y. et al., 2020; Liang et al., 2014; Lin et al., 2016; Sediso and Lee, 2016; Thatcher and Milner, 2016; Zhou et al., 2020), although some studies conflicted with this claim (Elnaklah et al., 2020; Gou et al., 2012c; Pastore and Andersen, 2019). Furthermore, a few studies have mentioned that GBs provide a better lighting environment (Liang et al., 2014; Zhou et al., 2020), but other scholars have maintained that the visual comfort of certified buildings is not significantly better (Gou et al., 2012c; Lee, J.Y. et al., 2020; Lim et al., 2017) and is sometimes even worse than NGBs (Elnaklah et al., 2020; Gou et al., 2012a). Conflicting results have also been presented on acoustic comfort (Elnaklah et al., 2020; Gou et al., 2012a; Gou et al., 2012c; Lee, J.Y. et al., 2020; Sediso and Lee, 2016). Notably, while the physical measurements of (Liang et al., 2014) supported that the acoustic environment of conventional buildings is better than GBs, the satisfaction survey results were in favour of certified buildings.

Though the results of previous studies have been inconsistent regarding GBs' performance after occupancy, the contribution of previous research comparing the green rating types (Gou et al., 2012a; Lin et al., 2016; Liu et al., 2018), classes (Altomonte et al., 2019; Geng et al., 2020; Lin et al., 2016; Pastore and Andersen, 2019) and assessments with national standards (Elnaklah et al., 2020; Hwang and Kim, 2011; Lee, J.Y. et al., 2020; Liang et al., 2014; Lim et al., 2017; Suzaini et al., 2017; Zhou et al., 2020) and conventional buildings (Almeida, Laura et al., 2020; Almeida, Laura et al., 2020; Gou et al., 2012c; Gou et al., 2013; Khoshbakht et al., 2018; Sediso and Lee, 2016; Thatcher and Milner, 2016) is extremely valuable in promoting GBs and their evaluation.

1.3. Building energy-IEQ index

Building energy consumption and IEQ are both critical factors for evaluating building performance. Ideally, a unified energy-IEQ index would help building managers assess the current building condition continuously and to plan possible operational, maintenance and retrofit programs.

Being inspired by the Built Environment Efficiency (BEE) index introduced by CASBEE (CASBEE), Geng et al. (Geng et al., 2020) introduced the Environmental Energy Efficiency (EEE) index, which evaluates the ratio between normalized IEQ performance and building energy. The detailed calculation procedure is presented in **Eqs. 3-5**.

$$EEE = \frac{Normalized\ IEQ\ Performance}{Normalized\ Building\ Energy} \tag{3}$$

$$Normalized\ IEQ\ Performance = \sum_{i=1}^{n} \alpha_i \cdot \left[\beta_i \cdot IEQ_{i,ob} + (1-\beta_i) \cdot IEQ_{i,sub}\right] \tag{4}$$

$$Normalized\ Building\ Energy = \frac{Delivered\ Energy}{Energy\ constraint\ value} \tag{5}$$

In **Eq. 4**, $IEQ_{i,ob}$ denotes the physical performance of IEQ factor *i*. $IEQ_{i,sub}$ denotes the subjective acceptance of IEQ factor *i* and it is determined using occupant surveys; α_i signifies the weight of each IEQ factor; β_i represents the weight of the objective performance in the IEQ factor and (Geng et al., 2020) considered it equal to 0.5 for all IEQ factors. While this method gives a comprehensive evaluation of indoor environment, It is more time consuming and the result is dependent on the number of occupant responds.

To normalize the building energy consumption in **Eq. 5**, the delivered energy is divided by an energy constraint value which is reliant on the building category in China. it was selected as 85 kWh/m^2 and 110 kWh/m^2 for type A and B in hot summer cold winter zone of China.

1.4. NABERS Energy and IE ratings

As an initiative of the Council of Australian Governments (COAG), the Commercial Building Disclosure (CBD) program requires the building's NABERS Energy star rating to be included in any advertising material for the sale, lease or sublease of commercial office space of 1,000 m^2 or more (CBD, 2010), intending to improve the energy efficiency of Australia's large office buildings and to ensure an informed market. In contrast, other aspects of building performance, such as indoor environmental quality (IEQ), is less concerned by the government, despite a wealth of research demonstrating significant correlations between IEQ and occupant health, comfort and productivity (e.g., Newsham et al.(Newsham et al., 2008); Al horr et al.(Al horr et al., 2016); Wang et al.(Wang et al., 2021)).

The NABERS ratings (ranging from 1–6 stars) evaluate energy, water, waste, and indoor environment (NABERS, 2015a). By considering both building performance and user preferences, NABERS provides a comprehensive environmental assessment (Fay et al., 2004). NABERS has three different rating scopes to reflect the split of responsibilities of different stakeholders: base building (building owners and managers), whole building (building owners, managers and tenants) and tenancy (tenants).

The NABERS Energy tool benchmarks the energy usage performance of buildings in Australia. Based on the Investment Property Database, best-performance office buildings have a greater return on investment compared to conventional lower quality buildings (Lee et al., 2017). As a certification tool, NABERS Energy is calibrated considering various operational correction factors such as climate, service hours and net lettable floor, all of which are considered in base building schemes (Bannister, 2012).

The NABERS IE scheme measures indoor environmental conditions in office buildings. NABERS IE considers five key indoor environmental factors (thermal services, indoor air quality, acoustic comfort, lighting and office layout). Factors are evaluated separately to identify areas that need improvement, and their weighting in the total score is based on their impact on occupants (NABERS, 2015b).

NABERS IE rating combines on-site measurement (quantitative) as well as occupants' satisfaction surveys (qualitative). The NABERS IE satisfaction surveys quantify occupants' satisfaction levels with many aspects of the indoor environment. Depending on the specific rating scope, NABERS IE requires different types of data and their weighting is different, shown in Table 2 (Residovic, 2017). The final score received for each IEQ factor represents the ranking of that specific building compared with the NABERS IE benchmark (NABERS, 2015c).

Table 2. Data required for NABERS IE rating for different rating scopes (Residovic, 2017)

	Base building	Tenancy	Whole building

	Data	Weighting	Data	Weighting	Data	Weighting
Thermal services	M	40%	-	-	M, S	30%
Indoor air quality	M	40%	M, S	40%	M, S	30%
Acoustic comfort	M	20%	M, S	25%	M, S	15%
Lighting	-	-	M, S	25%	M, S	15%
Office layout	-	-	S	10%	S	10%

(M denotes on-site measurement; S represents Occupant survey; - represents no measurements.)

For more detailed information regarding the NABERS IE scheme (Base building rating) refer to Appendix 1.

1.5. Aims of the current research

The gaps which have been found by conducting literature review are:

- The absence of an appropriate energy normalization method for Australian buildings to compare energy consumption across different climate zones;
- The lack of investigation on the relationship between energy consumption in buildings and the NABERS IE certificate(Geng et al., 2020; Gui and Gou, 2020; Liu et al., 2018);
- The need for a more comprehensive Building Energy Efficiency Certificate (BEEC) incorporating both energy and indoor environmental quality in Australia's Commercial Building Disclosure (CBD) program.

The above-mentioned gaps evident in the existing literature inspired the current study, which focuses on the following three core objectives:

1) Adapt Geng et al. (2020)'s method to Australian context for normalizing energy use intensity in NABERS buildings located in different climatic zones; 2) Explore the statistical correlations between normalized EUI, IEQ score, NABERS IE rating stars, and NABERS Energy rating stars; 3) Develop an Energy and Indoor Environment Index to benchmark the energy and IEQ performance of Australian office buildings certified by NABERS Energy and IE.

This paper is arranged into five sections. Section 2 details the materials and methods in this research, Section 3 outlines the results of the analysis, Section 4 discusses the findings and compares them with the results of previous studies, and Section 5 provides the main conclusions and future research directions.

2. Materials and methods

2.1. Building data source

The database used in this research is publicly available on NABERS website, which is updated continuously throughout the year and offers information about buildings which have valid NABERS certification(NABERS, 2015a). Information in the dataset includes building geographical information (latitude, longitude, premise number, street name, city and state), NABERS rating type (energy, water, IEQ or waste), rating scope (base building, tenancy, or whole building), Energy rating information (energy rating score, annual energy consumption, CO_2 emission, energy use intensity), IEQ rating information (IEQ rating score, thermal comfort score, air quality score, acoustic comfort score, lighting score, office layout score), water rating information and waste rating information. In this study, only NABERS Energy and IE ratings are of interest, and solely building with base buildings certificate are selected for analysis due to their large sample sizes in the database.

As presented in **Table 2**, thermal comfort, IAQ and acoustic comfort represent 40%, 40% and 20% of the total base building IEQ score (IEQS), respectively. Based on the NABERS online database (accessed October 2020), 1,089 and 112 buildings were certified by NABERS Energy and NABERS IE, respectively (NABERS, 2015a). In addition, annual energy consumption (MWh) and EUI (MWh/m^2) of certified buildings are presented as energy performance indicators. Given that most certified buildings are in the six capital cities of Australia, namely, Adelaide, Brisbane, Canberra, Melbourne, Perth and Sydney, only buildings in these 6 cities have been selected for further analysis.

2.2. Energy normalization method

The evaluated office buildings were constructed in different years, have variate HVAC systems and are located in six different cities. A significant part of total building energy consumption is related to HVAC systems. A typical HVAC system in a mechanically ventilated building is responsible for nearly 40% of total building energy consumption and 70% of base building energy consumption (Department of the Environment and Energy, 2013; Ma et al., 2015). Therefore, it is imperative to carry out normalization of HVAC energy use in buildings across different Australian cities. To accurately compare energy use in these buildings, we tried to eliminate the impact of buildings' geographical location and climates on buildings' energy consumption as much as possible.

Based on the Köppen-Geiger climate classification, Australia has 15 different climate divisions (Every et al., 2020). While the northern part of the continent has a tropical savanna climate, the southern part is generally warm and oceanic. The western side of Australia has a hot, semi-arid and Mediterranean climate, and the eastern side is mostly humid with a subtropical climate (Beck et al., 2018).

According to the Bureau of Meteorology of Australia, the comfort level values are considered as 18 ̊C and 24 ̊C for heating and cooling, respectively (Bureau of Meteorology, 2020). The 30-year average HDD and CDD of 6 major Australian cities were adopted as a baseline value for the weather normalization process. Therefore, **Eq. 2** climate normalization factor (NF) was localized to standardize energy use intensity in buildings from different climate zones of Australia.

$$NF = W_h . \frac{HDD_{18,base}}{HDD_{18,ac}} + W_c . \frac{CDD_{24,base}}{CDD_{24,ac}} \quad (6)$$

There are two differences between **Eq. 2** and **Eq.6.** First, the CDD setpoint is changed to 24 ̊C according to the Bureau of Meteorology of Australia (Bureau of Meteorology, 2020). Second, the constant weighting for cooling and heating purposes (W_h=3/7 and W_c=4/7) for cities investigated by (Geng et al., 2020) is modified based on climatic condition of each Australian city. For this purpose, an actual office building in Australia was simulated in each of 6 cities and weights (W_h and W_c) were determined by ratio of months heating and cooling is needed in each city. The simulation was conducted using SketchUp and TRNSYS software (**Fig. 1**). The simulated building has four floors, with a total floor area of 2717.2 m^2 and useful office area of 2177.9 m^2 (**Fig. 2**).

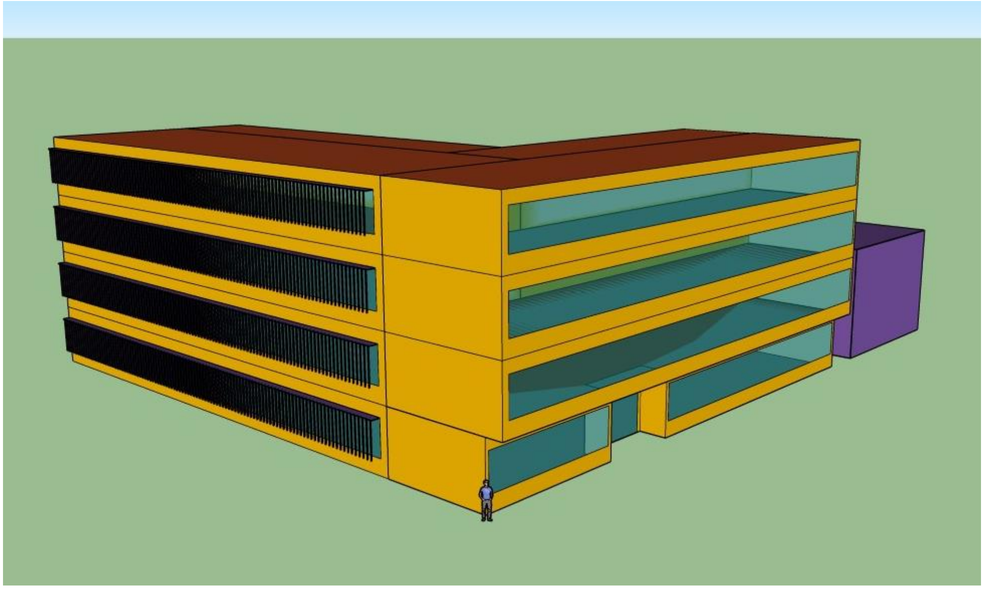

Figure 1. South-western view of the simulated office building model

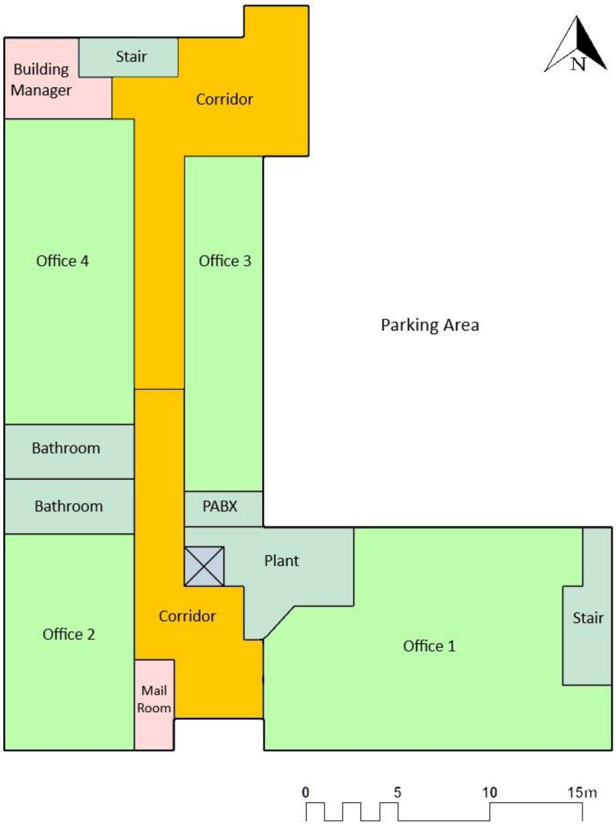

Figure 2. Floor plan of the simulated office building model

The details of simulated office building are presented in **Table 3.**

Table 3. Key information of the simulated building

Gross floor area	2717.2 m^2
Useful area	2177.9 m^2
Building height	21 m
Occupancy schedule	7:30 am – 6 pm (Monday to Friday)
Occupancy rate	1 person per 25m^2
HVAC system	Reverse cycle air-cooled systems and air handling units
Cooling setpoint	23.9 ̊C
Heating setpoint	21.0 ̊C
Equipment load	16.1 W/m^2
Lighting load	12 W/m^2
External walls (R-Value)	Brick + Airspace + Brick (0.55 m^2.K/W)
External roof (R-Value)	Finish +light concrete + Plaster (0.5 m^2.K/W)
Windows (U-Value)	double-glazed (1.37 W /m^2.K)
Window to wall ratio	0.4

The 30-year average CDD and HDD values of the Australian cities were obtained from the Bureau of Meteorology of Australia website and are presented in **Table 4**.

Table 4. Climate characteristics and Weather normalization factor in studied cities(BizEE)

City, state	Dominant load	Climate	HDD	CDD	NF	η
Canberra, ACT	Heating load	Cold	1,984	58	1.42	1.29
Adelaide, SA	Mixed load	Mixed	918	185	0.75	0.82
Melbourne, VIC	Heating load	Cold	1,206	67	1.38	1.27
Perth, WA	Mixed load	Hot	663	192	0.70	0.79
Brisbane, QLD	Cooling load	Hot/humid	269	136	0.90	0.93
Sydney, NSW	Mixed load	Mixed	503	94	1.35	1.24

Heating load = Annual conditioning load >67% heating
Cooling load = Annual conditioning load >67% cooling
Mixed load = Annual heating load 33-66%

HVAC systems are responsible for roughly 70% of the base energy consumption in office buildings (Department of the Environment and Energy, 2013). Therefore, Energy normalizing factor (η) can be calculated using **Eq. 7.**

$$\eta = \frac{(0.3\ \times total\ energy\ consumption) + (0.7\ \times\ total\ energy\ consumption\ \times NF)}{total\ energy\ consumption} = 0.3 + 0.7 \times NF \quad (7)$$

It is noteworthy to mention that the high humidity is another factor influencing the building energy consumption in office buildings located in tropical and subtropical climates. Most commercial buildings in Australia do not have independent humidity control. In order to quantify the impact of dehumidification on building energy use, as a worst-case scenario, we have assumed that the above case study building, located in Brisbane, has an independent humidity control and have simulated the building energy consumption spent on dehumidifying the indoor air to 60% relative humidity. Based on the simulation result, the energy used for dehumidification accounts for less than 9.5% of the total building energy use. Therefore, this influence of relative humidity is neglected for all Australian office buildings in the energy normalization process. Detailed explanation of weather normalization method and humidity influences is presented in Appendix 2.

2.3. Building sample descriptive statistics

Nighty-seven office buildings that have both NABERS Energy and IE certifications were studied to evaluate the relation between energy consumption and IEQ (**Fig. 3)**. While the NEUI of mentioned buildings is 98.3 kWh/m^2 and its distribution is positively skewed, the mean IEQS is 81.1% and its distribution is almost normal. The key NEUI and IEQS statistics of different buildings considered in this research are presented in **Table 5**.

Table 5. Key statistics of NABERS-rated buildings

	Annual NEUI (kWh/m^2)	IEQ score (%)
Mean	98.3	81.1
Max	264.6	96.7
Min	31.2	61.3
Median	92.7	81.3
Standard deviation	36.2	9.2

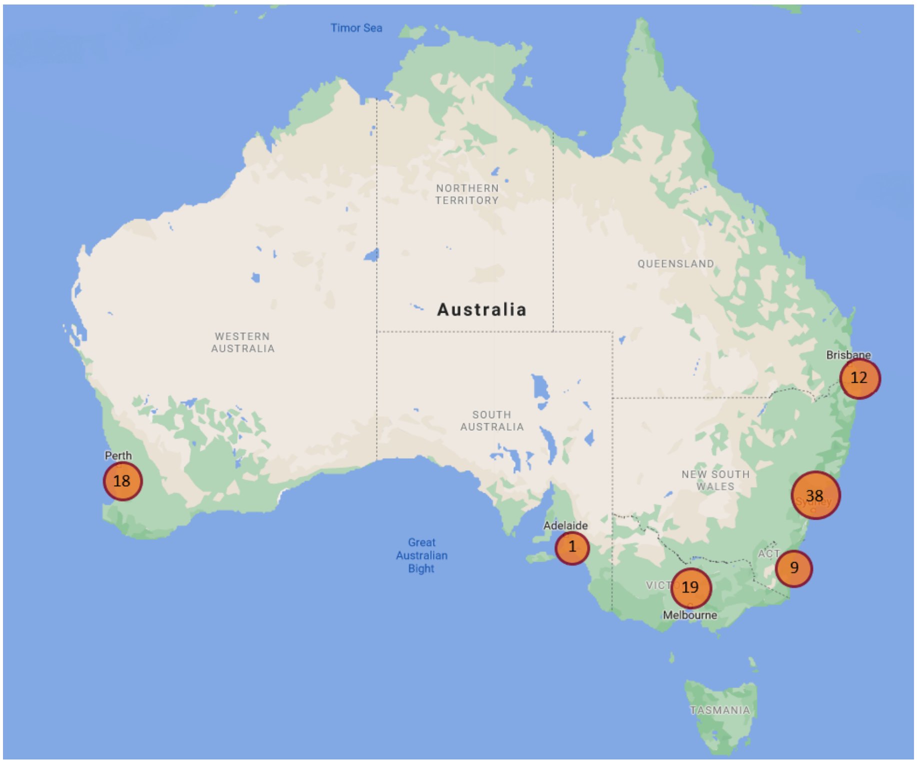

Figure 3. Distribution of buildings with both NABERS Energy and IE certifications

2.4. Analytical techniques

The correlation between NABERS Energy and NABERS IE with their indicator (Energy consumption and IEQS) have been investigated by Gui and Gou(Gui and Gou, 2020). In this study, the possible relationship between the NEUI and NABERS IE will be investigated. Also, in the promising relation between IEQS and NABERS Energy rating would be evaluated in this stage.

The analysis of variance (ANOVA) and Kruskal-Wallis tests investigate the significance of the differences between variables. Where the normal distribution of samples is a preliminary assumption for ANOVA, the Kruskal-Wallis test still functions even when data is not distributed normally (Gui et al., 2020). The statistical analysis of ANOVA and the Kruskal-Wallis test were performed to determine whether there was a significant difference in NEUI and IEQS values for the various NABERS levels.

Since a sufficiently large sample in a statistical test usually demonstrates a significant difference result (i.e. $p < 0.05$), “Effect size” should be calculated as a secondary assessment. Effect size (η^2) is referred as standardized measures of effect to the raw difference between groups (Sullivan and Feinn, 2012). Based on (Schagen and Elliot, 2004), effect sizes could be categorized as small ($\eta^2 \geqslant 0.2$), medium ($\eta^2 \geqslant 0.5$), and large ($\eta^2 \geqslant 0.8$). Therefore, the effect size of NABERS IE on NEUI and NABERS Energy on IEQS was calculated.

In this section, linear regression models were analysed to evaluate the variation of NEUI with NABERS IE levels and the dependency of IEQS to NABERS Energy rating. The level of NABERS certification (Energy and IE) served as the independent variable in the regression models, while NEUI and IEQS served as the dependent variables. The regression model is presented in **Eq. 7**.

$$Y = \alpha x + \beta + \varepsilon \qquad (7)$$

Where *Y* is the dependent variable (NEUI and IEQS) and *x* the related NABERS rating (Energy and IE).

In **Eq. 7**, α is known as the regression coefficient, which means the amount of dependency of the dependent variable fluctuation by a single unit increase in the independent variable. Moreover, β, or the ‘Intercept’, is the value of the dependant variable when the independent variable is zero, and ε is standard error (the amount of information that the model fails to explain).

ANOVA and Kruskal-Wallis tests were conducted to investigate the relationship between Energy and IEQ. Additionally, effect sizes were calculated to evaluate the impact of NABERS IE rating on NEUI(R_1) and NABERS Energy rating on IEQS (R_2). Then, a linear regression was conducted (**Fig. 4**).

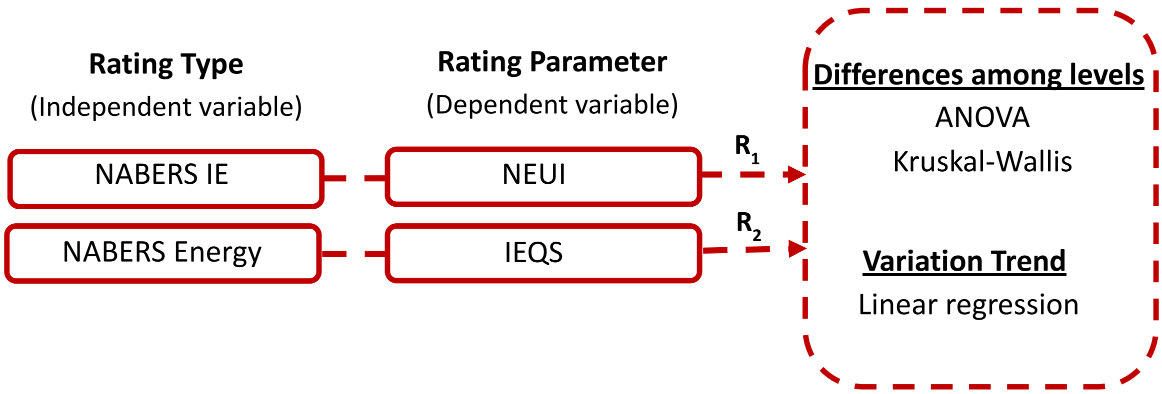

Figure 4. Secondary rating parameters analysis over NABERS certifications

The combined effect of NABERS certificates on NEUI was also explored to investigate the effect size of different certificates on NEUI. Firstly, assumptions of linearity, normality, and absence of multicollinearity, were examined. Linearity means that the predictor variables in the regression have a straight-line relationship with the outcome variable. The Variance inflation factor (VIF) method was selected to check the absence of multicollinearity.

2.5. Development of Energy and Indoor Environment index (EIEI)

To benchmark the energy and IEQ performance of office buildings in Australia, we introduce a new *Energy and Indoor Environment Index (EIEI)*, which is a ratio between the IEQ scores awarded by NABERS IE (NABERS, 2015c), and the building energy performance (**Eq. 8**). This index can be used for both 'base building' and 'whole building' rating scopes. The 'whole building' rating scope refers to rating for organisations that both manage and occupy their office space, or in some cases where a single tenant occupies the entirety of a building.

The EIEI index has two main advantages compared with the previous indexes. Firstly, the normalized EUI is considered in the calculation of building energy performance which results in more accurate results. Secondly, this index is based on NABERS IE ratings, and IEQS can be obtained once the NABERS IE rating is available.

$$EIEI = \frac{IEQS}{Building\ energy\ performance} \tag{8}$$

IEQS in **Eq. 9** is the accumulative impact of IEQ factors and it is revealed by NABERS database for each NABERS IE certified building (NABERS, 2015a). For the calculation of IEQS, $IEQ_{i,m}$ denotes the physical performance and $IEQ_{i,s}$ is the result of subjective surveys of IEQ factor *i*. Also, α_i and β_i represent the weight of each IEQ factor and weight of the physical measurement in the IEQ factor, respectively. Based on the building rating categories, n, α and β are presented in **Table 6**(NABERS, 2015a).

$$IEQS = \sum_{i=1}^{n} \alpha_i \cdot [\beta_i \cdot IEQ_{i,m} + (1-\beta_i) \cdot IEQ_{i,s}] \tag{9}$$

Table 6. Coefficients used in IEQS calculation(NABERS, 2015a)

IEQ factor	Base building		Whole building	
	n=3		n=5	
	α	β	α	β
Thermal services	0.4	1	0.3	0.5
IAQ	0.4	1	0.3	0.5
Acoustic comfort	0.2	1	0.15	0.5
Lighting comfort	-	-	0.15	0.5
Office layout	-	-	0.1	1

The building energy performance is calculated by the building's normalized energy use intensity divided by the baseline energy consumption in Australian commercial buildings (COAG, 2012) (**Eq. 10**), in which η represents the weather normalization factor, which can be obtained from **Table 4**. Also, based on the different building ownership type and rating categories, the '*energy constraint value*' can be selected from **Table 7**.

$$Building\ Energy\ Performance = \frac{\eta \times EUI}{Energy\ constraint\ value} \tag{10}$$

Table 7. The energy constraint value based on the building ownership and category (COAG, 2012)

Ownership type	Category	Energy constraint value ($kWh/m^2.a$)
Government	Base building	132.6
	Whole building	204.8
Private	Base building	156.5
	Whole building	262.9

3. Data analysis and results

3.1. Relationship between Energy and IEQ (R_1 and R_2)

By investigating NABERS certified buildings, it becomes evident that there is a possible relationship between the NABERS IE rating and NEUI (**Fig. 5**). The number of buildings with NABERS IE certificate is presented at the top of each group. Based on the NABERS IE rating category boxplots, it can be deduced that the highest-quality NABERS IE buildings consume less energy while providing a better IE for occupants. In other words, thermal comfort and IAQ (which are the main criteria to reach a high NABERS IE rating) can be provided with low energy requirements.

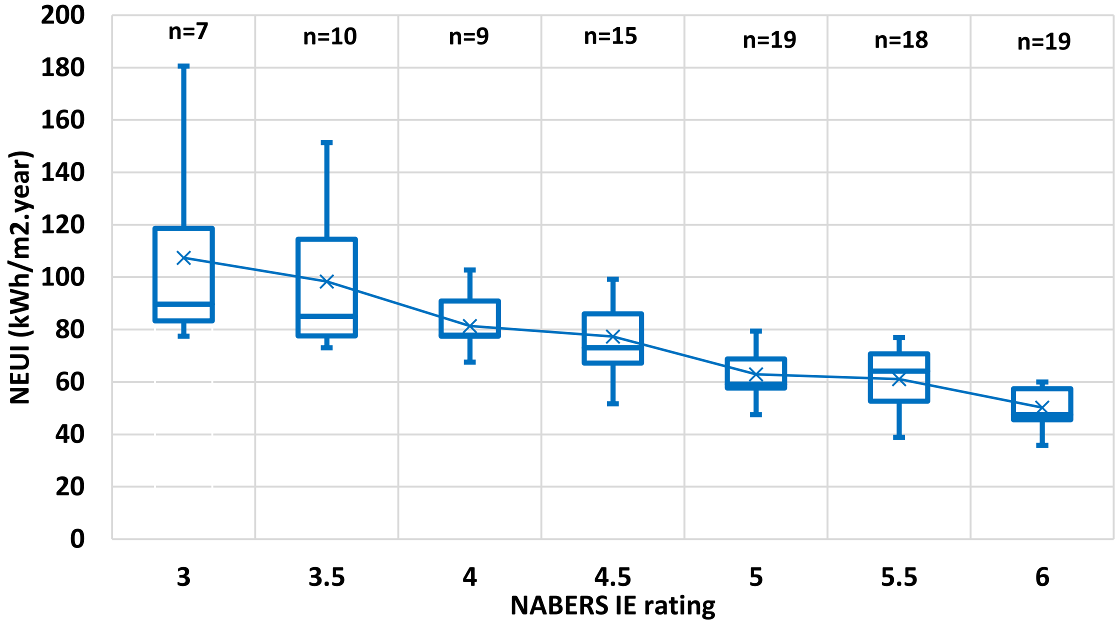

Figure 5. Normalized EUI comparison of sample buildings

The results of the ANOVA and Kruskal–Wallis tests for sample buildings are presented in **Table 8**. The outcome indicates that there is a significant difference ($p<0.001$) between the average normalized EUI of buildings with different levels of NABERS IE ratings and this represents a large-size effect ($\eta^2 = 0.51$). The NABERS Energy ratings do not have any significant impact ($p=0.195$) on the buildings' IEQ scores.

Table 8. ANOVA and Kruskal-Wallis results for secondary relationships (R_1 and R_2)

	Independent variable	NABERS IE	NABERS Energy
	Dependent variable	NEUI	IEQS
ANOVA	DF	6	8
	SS	354,430	931
	MS	5,905	116
	F value	14.626	1.43
	P-value	<0.001	0.195
	η^2	0.51	0.11
Kruskal-Wallis	Chi-squared	57.5	9.954
	DF	6	8
	P-value	<0.001	0.268

To evaluate the impact of NABERS IE certificate on NEUI, regression analysis was performed. Table 9 demonstrates the estimates of the regression model. It can be seen that about 45% of the variance in the NEUI is predictable from the NABERS IE rating. A single unit increase in NABERS IE certification can reduce NEUI by 19.79 kWh/m^2 annually (**Table 9**).

Table 9. Regression analysis between NABERS IE and NEUI (R_1)

Dependent variable	Independent variable	Estimate α	Intercept β	Standard error ε	R^2	Adjusted R^2	Sig.
NEUI	NABERS IE	-19.79	167.55	20.30	0.455	0.449	<0.001

Therefore, it is rational to evaluate the combined impact of NABERS Energy and IE certificates on prediction of energy use in buildings.

3.2. The combined impact of NABERS IE and Energy on NEUI

Based on the result of previous section and study by Gui and Gou (Gui and Gou, 2020), it is evident that both NABERS Energy and IE can be used to predict the NEUI in certified buildings. In this section, their combined effect on energy use in office buildings was investigated.

The normal predicted probability analysis showed that the residuals are normally distributed, and preliminary assumptions of linearity and normality were met. Also, the analysis demonstrated the absence of multicollinearity (VIF=1.22) **(Table 10)**. The results of multiple linear regression are shown in **Table 10.** The result indicates that NABERS Energy has a more influential contribution to NEUI than NABERS IE. The *p*-value is less than 0.001 and adjusted R^2 is 0.920, indicating that 92% of the variance in NEUI can be explained by the building's NABERS IE and Energy ratings, with the latter having a greater impact. Therefore, for the Australian sample analysed, it is evident that a building's NEUI can be accurately predicted by its NABERS Energy and IE certifications (**Eq. 11**).

Table 10. Multivariate regression analysis between NABERS IE, NABERS Energy and NEUI

Dependent variable	Independent variable	Estimate α	Intercept β	Standard error ε	R^2	Adjusted R^2	Sig.	VIF
NEUI	NABERS IE NABERS Energy	-9.88 -21.98	228.12	6.847	0.922	0.920	<0.001	1.22

$$NEUI = 228.12 - 21.98 \times NABERS\ Energy - 9.88 \times NABERS\ IE \quad (11)$$

3.3. EIEI in NABERS buildings

To further compare energy and IEQ performance within 97 NABERS buildings with both Energy and IE certifications, they were categorised into high-performance NABERS buildings (HNBs) and low-performance NABERS buildings (LNBs). The rationale behind this separation is based on the NABERS database showing the average Energy and IE rating for offices is 4.5 Stars. Therefore, HNBs refers to buildings that have an excellent performance in both energy rating (i.e., 5-6 stars) and IE rating (5-6 stars)(NABERS, 2015a).

A total of 49 market-leading buildings were considered as HNBs (**Fig. 6**). Another 48 buildings were deemed as LNBs, which were categorised into three groups. High Energy NABERS (N=24) had a high NABERS Energy rating (i.e., 5-6 stars) but a relatively low NABERS IE rating (i.e., 3-5 stars). Likewise, 7 high IE NABERS buildings had an excellent IE rating but poor energy rating. The rest 17 buildings performed moderately or poorly in both energy and indoor environment aspects.

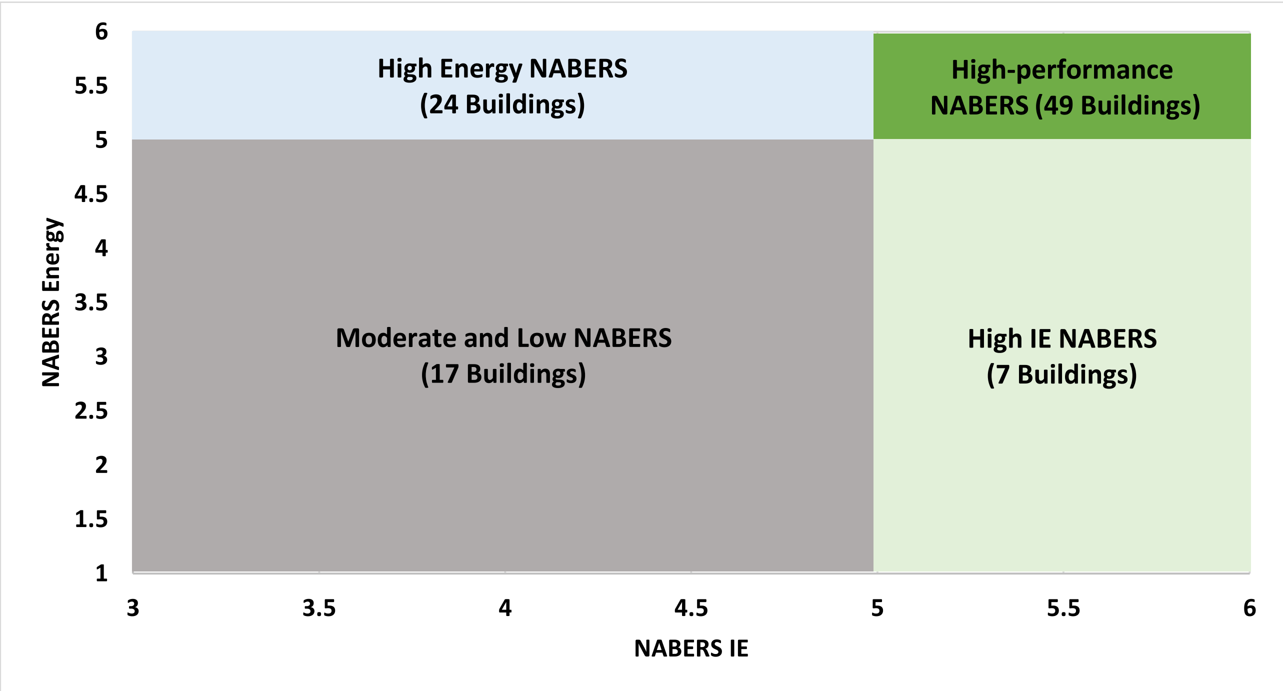

Figure 6. The categorisation of NABERS buildings based on Energy and IE certifications

As is presented in **Table 11**, HNBs consume 55.5 kWh/m^2 of energy per annum, which is 35.9% less than the normalized EUI of LNBs, 86.7 kWh/ m^2. The standard deviation of NEUI in high-performance NABERS buildings and low-performance NABERS buildings are 8.9 kWh/m^2.a and 23.7 kWh/m^2.a, respectively. The lower standard deviation of HNBs means that the data are closely clustered around the mean. Also, the average IEQS in HNBs is 87.3%, which is 12.6% higher than their counterpart (74.7% for LNBs).

Table 11. Key descriptive statistics for sample buildings

Parameter	NEUI (kWh/m^2.a)		IEQS (%)	
	HNBs	LNBs	HNBs	LNBs
Number of buildings	49	48	49	48
Mean	55.5	86.7	87.3	74.7
Max	69.7	180.6	96.7	91.7
Min	35.8	51.7	76.8	61.3
Median	57.2	78.5	86.1	75.1
Standard deviation	8.9	23.7	5.4	7.8

Fig. 7 illustrates different levels of energy and IEQ performance in sample buildings. The vertical and horizontal axis in **Fig. 7** represent IEQS (**Eq. 9**), and building energy performance (**Eq. 10**), respectively. Thresholds in this figure are based on the method introduced by (Geng et al., 2020). Moreover, horizontal thresholds were added to illustrate the importance of indoor environment in buildings. Hence, when a building is located on the left side of the graph, it indicates the building consumes a small amount of energy per square meter. Also, points which are in the top of **Fig. 7** represents buildings that provide excellent indoor environment. The thresholds divide the graph into 5 distinct zones where A and E zones represent the best and worst building performance, respectively.

Fig. 7 demonstrates that most of the HNBs are within Zone A in EIEI, meaning that they can provide the best indoor environment with reasonable energy consumption. A few LNBs located inside zone A, as well. All HNBs which failed to achieve grade A had EIEI value lower than 2. In other words, while they perform well in providing indoor environment (IEQS > 80%), they consume excessive energy to provide such an environment. The majority of LNBs were within Zone B and C in EIEI, with only a few in Zone D. There is just one building in Perth that has a building energy performance (**Eq. 10**) of more than 1. This building's NABERS Energy and IE are 1 and 3, respectively. This NABERS building is a good example of a rated building that uses excessive energy to provide an adequate indoor environment quality. Scenarios like this and issues pertaining to excessive energy consumption to provide indoor environment satisfaction are discussed in the following section.

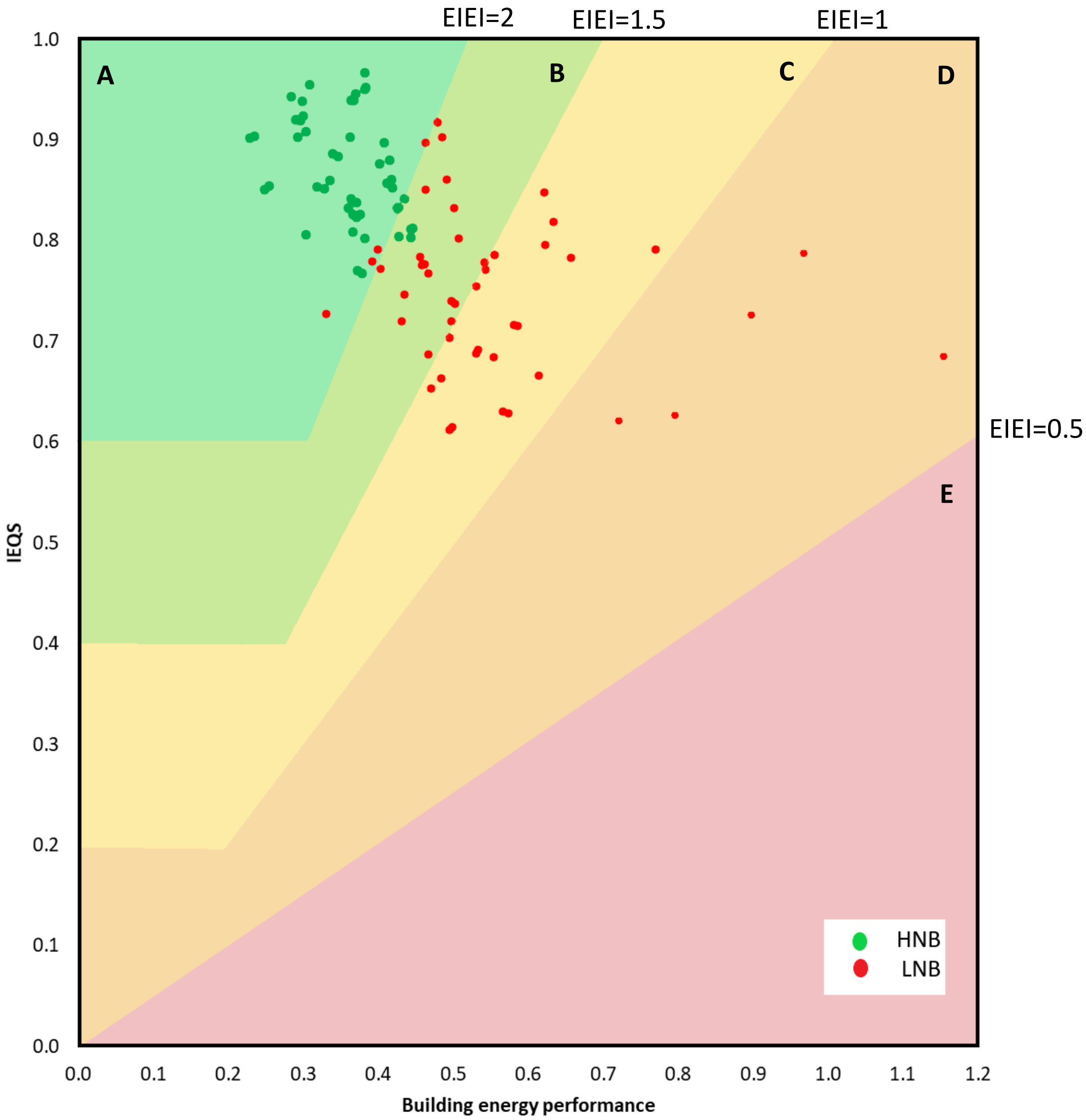

Figure 7. Energy and indoor environment index for HNBs and LNBs

4. Discussion

4.1. Comparison with previous studies

The current research evaluates Energy and IEQ in buildings rated by NABERS which is not a widely discussed rating scheme in previous studies. This study further advances the research by Gui and Gou (Gui and Gou, 2020). The use of energy normalization factors enables the comparison of building energy use between different climate zones and facilitates the exploration of more accurate relationships between normalized building energy and NABERS certifications. It is found that NABERS IE and NEUI are inversely correlated. In contrast, the study does not identify any significant relationship between NABERS Energy and IEQ score. Finally, a strong multivariate correlation is found between NEUI and both NABERS IE and Energy certificates, with the latter being a more significant contributor; this relationship has not previously been investigated.

The study also reveals that HNBs consume less energy than LNBs, which was also confirmed by (Almeida, Laura et al., 2020). Moreover, the mean IEQS in high-performance NABERS buildings is 12.6% higher than that in low-performance NABERS buildings. This resonates with the previous finding that buildings with high energy performance can provide a better indoor environment than low quality non-green ones (Lee, J.Y. et al., 2020; Sediso and Lee, 2016).

4.2. Implications for policy and practice

Inspired by Geng et al. (Geng et al., 2020), The Energy and Indoor Environment index was designed to comprehensively evaluate building performance. This comprehensive index would normalize IEQ and EUI factors for buildings and rank them accordingly. Many low-performance NABERS buildings needed to consume more electricity than best-practice buildings due to a range of factors including poor building design, construction, or operational management (see: buildings graded D in **Fig. 7)**. On the other hand, due to the Commercial Building Disclosure (CBD) program of Australia, sellers and lessors of office space of 1,000m^2 or more have to obtain a Building Energy Efficiency Certificate (BEEC) before the building goes on the market for sale, lease or sublease (CBD, 2010). This biased rule motivates some building managers to focus efforts purely on energy efficiency to obtain a high NABERS Energy rating at the expense of indoor environment quality and occupants' health, satisfaction, and wellbeing (see: buildings in the bottom of grade C in **Fig. 7)**. This issue is not exclusive to the Australian context, but also identified in other countries with other rating systems (Ncube, 2012). Therefore, there is a modification needed in BEEC to require office buildings to have both NABERS Energy and IE certificates. In this way, building performance can be evaluated in a more comprehensive way.

The analysis not only proves that there is a relationship between NABERS ratings (Energy and IE) with NEUI but also confirms a linear relationship between them. Importantly, the developed prediction model helps building managers compare their delivered energy consumption with the NABERS benchmarks. In this way, facility managers would discover if excessive energy were being consumed to provide an adequate indoor environment quality, and they could subsequently adjust the indoor conditions to achieve more reasonable levels of energy consumption.

4.3. Study limitations

Although NEUI had a negative linear relationship with the NABERS Energy and IE certificates, the lack of buildings with both certificates could have biased the results. Most building managers preferred to acquire the NABERS Energy certification, and only 97 buildings had both Energy and IEQ certifications. It is notable that this study only considered NABERS 'Base building certificates' to make the buildings comparable. There are not enough buildings with NABERS 'Whole building' and 'Tenancy' certificates in the database. This issue resulted in other important IEQ factors (i.e., lighting and layout) being neglected, along with occupant satisfaction. These factors should be evaluated in future studies when more buildings have the NABERS IE certificates. Moreover, future studies should evaluate whether the impacts of energy and IEQ on total EUI differ from various climatic conditions. In addition, post-occupancy evaluation of building occupants' satisfaction and physical measurements of IEQ and energy should be conducted and correlated with the NEUI.

5. Conclusion

This study has developed a method to normalize energy use intensity in NABERS buildings located in different climatic zones in Australia. It also explored the statistical correlations between normalized EUI, IEQ score, NABERS IE rating stars, and NABERS Energy rating stars. Also, a new benchmarking method was presented to evaluate and compare buildings in Australia.

The major findings of the study can be summarised as follows:

1. Analysis of sample buildings revealed a moderate correlation between NEUI and NABERS IE rating (R^2=0.455, p<0.001).
2. A multivariate regression between NEUI and NABERS certificates (Energy and IE) demonstrated that, on average, a one-level rise in the NABERS Energy and IE reduced NEUI in Australian office buildings by 21.98 kWh/m^2 and 9.88 kWh/m^2, respectively (R^2=0.922, p<0.001).
3. Moreover, this study compared high-performance NABERS buildings with low-performance ones. The result revealed that, on average, high-quality buildings can deliver 12.6% better IEQ with 35.9% less energy consumption in comparison with low-performance ones.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: