The future of IEQ in green building certifications

SYNTHESIS

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ABSTRACT

Although indoor environmental quality (IEQ) and human health have been on the agenda of the green building industry, a new emphasis is being placed on building features that explicitly promote the experience of occupants. However, evidence of the performance of green-certified buildings from the occupant perspective remains inconsistent, with numerous questions on how to effectively design, assess and promote 'healthy buildings'. Focusing on the key IEQ categories of indoor air quality, thermal comfort, lighting and acoustics, this paper synthesises emerging knowledge related to IEQ and health; identifies research and practical challenges that may impede the performance of green-rated buildings; sets the foundations for researchers and green rating system developers to capture immediate and long-term opportunities; and proposes a new framework for green-certified buildings. The envisioned future of green buildings will need to be based on a thorough knowledge of the building and its users, their inter- and intra-individual variability, their spatiotemporal localisation, their activities, their history of exposures, together with a capacity of anticipation of the likelihood of future events and preparedness for them. A balanced, integrated, consideration of these factors can provide the basis for more effective green building certification systems.

PRACTICE RELEVANCE

The Covid-19 pandemic has focused attention on the importance of IEQ and highlighted the limitations of prevailing practice for promoting human experience, health and wellbeing. Most critically, the good intentions of project planning are often not reflected in real-world conditions, and established *best practices* have not kept pace with advances in research. This paper provides a critical synthesis of the literature on the effectiveness of green building ratings systems for human experience. It identifies limitations and practical opportunities for improvement in the design and application of rating tools. These observations present specific, actionable, opportunities to improve the design and operation of green building rating systems. Rating system developers and practitioners can use this information to better align design intentions with outcomes. Explicit consideration is needed for differences in individual preferences, spatial and temporal variabilities of IEQ factors, occupant exposure history, and other factors impacting IEQ.

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1. INTRODUCTION

Since the inception of the first green building certification schemes in the 1990s—*e.g.* Building Research Establishment Environmental Assessment Method (BREEAM) in the UK and Leadership in Energy and Environmental Design (LEED) in the US—most systems have shared aspirations: (1) to mitigate climate change by minimising energy, material and water use, site disturbance, and waste generation; and (2) to promote human comfort, health, wellbeing and occupant experience within the built environment. Yet, despite its foundational place in green building practice, the priority on human health and wellbeing has changed significantly over time (***Figure 1***).

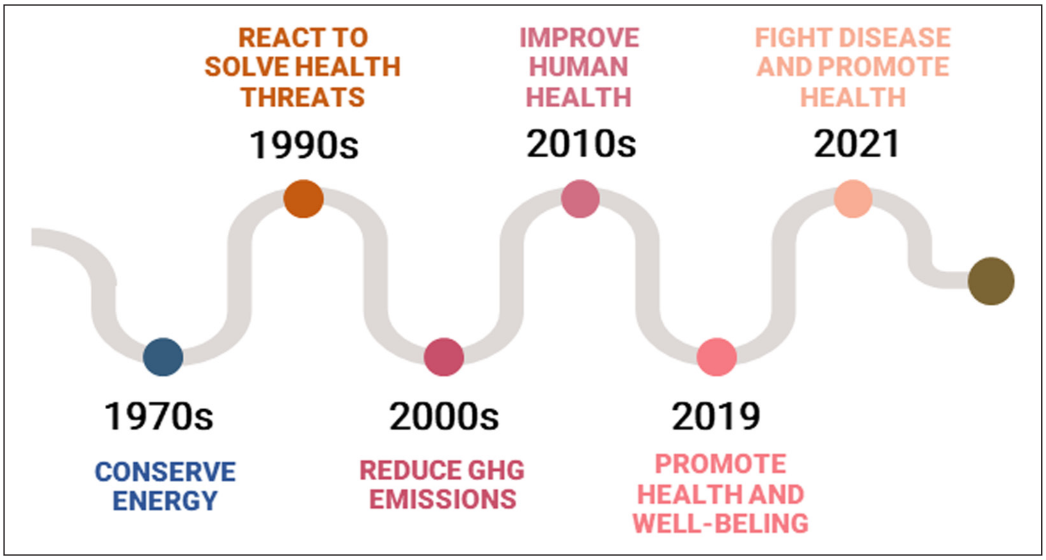

Figure 1: Historical overview of the evolution of priorities within the green building industry.

Green building rating tools emerged, in part, as a reaction to the implementation of energy efficiency measures following the energy crisis of the 1970s (left side of ***Figure 1***). An exclusive focus on energy performance in early years often resulted in undesirable secondary effects on occupants, such as reduced wellbeing and increase in sick building syndrome (SBS) symptoms and other illnesses, and this regardless of the effective energy efficiency of buildings (Mølhave 1989; Sundell *et al.* 1994; Tham *et al.* 2015; Wolkoff 2020). Studies often related the incidence of these health outcomes to inadequate ventilation as well as exposures to various physical, biological and chemical hazards (Joshi 2008). Therefore, early green certification schemes emphasised environmental health threats, notably tobacco smoke, asbestos and radon. In the late 1990s, the focus on environmental health risks was largely replaced by debates about the emissions from building materials (*e.g.* polyvinylchloride—PVC). In the early 2000s, growing awareness about the threat of global climate change again shifted priorities. This time the attention moved toward the global health consequences of greenhouse gas (GHG) emissions. In this context, a focus on indoor environmental quality (IEQ) was seen as myopic, even selfish. Over the last decade, yet another shift was observed with the emergence of the prevailing notion of 'healthy buildings'. It is important to emphasise that each 'era' in the development of green certification schemes was characterised by a concern for the connection between buildings and human health; however, attention and focus for this connection has changed dramatically over time.

The current green building paradigm is driven by the convergence of factors including:

- Demand for growth beyond traditional green building markets
- New research about the positive and negative impacts of building design and operation on health and wellbeing, but allegedly also on task performance and (potentially) overall job productivity
- Increasing awareness about gaps between design intent and real-world outcomes
- Emerging technologies for low(er) cost, ubiquitous and wearable IEQ performance measurement, which made parameters of the indoor environment and occupant outcomes more simply quantifiable and actionable

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These factors have inspired a new generation of rating tools focused on supporting occupant experience, such as WELL v2 (International WELL Building Institute 2020), Living Building Challenge 4.0 (International Living Future Institute 2021) and FitWel (FitWel, GSA 2019). Yet, despite the growing attention to these issues, there is still inconsistent evidence in the scientific literature of the ability of rating systems to achieve their intended outcomes (*e.g.* Khoshbakht *et al.* 2018; Steinemann *et al.* 2017; Licina *et al.* 2019; Lee *et al.* 2019). Evidence from field studies measuring relative improvements in occupant satisfaction with IEQ and perceived wellbeing in green-certified buildings remains ambiguous and variable across performance metrics (Gou *et al.* 2012; Altomonte & Schiavon 2013; Ravindu *et al.* 2015; Sediso & Lee 2016; Lee *et al.* 2020). Surveys in green-certified buildings have also suggested that, under some performance categories, the minimum standard requirement of an 80% occupant satisfaction rate is seldom met (Frontczak *et al.* 2012; Karmann *et al.* 2018; Pastore & Andersen 2019; Lee *et al.* 2019; Graham *et al.* 2021). These findings emphasise the need for green building certifications to critically re-evaluate current IEQ criteria, raise and fulfil expectations, and prioritise real-world IEQ and health outcomes (Colton *et al.* 2015).

1.1 SYSTEMATIC REVIEW

Several authors have provided systematic reviews of the IEQ performance in green-certified buildings (Lee & Kim 2008; Fowler *et al.* 2011; Todd *et al.* 2013; CBE 2014; Zuo & Zhao 2014; Allen *et al.* 2015; Cedeño Laurent *et al.* 2018; Khoshbakht *et al.* 2018; Geng *et al.* 2019; Allen & Macomber 2020; McArthur & Powell 2020; Worden *et al.* 2020; Ascione *et al.* 2022). However, less attention has been given to specific, actionable, guidance for the improvement of rating systems.

This paper fills this gap by synthesising research and practitioners' experience to propose a new framework for the design and operation of green building rating systems. In doing so, the research evidence here presented is based on a critical synthesis of the existing literature drawn from widely used databases such as Web of Science, Scopus and Google Scholar. The intent of the selection process was to identify relevant high-quality papers on which the authors' reflections could be grounded. This was done in two steps: by systematic bibliographic search and by supplementary literature additions. The systematic bibliographic search relied on the following keywords: *green buildings*; *sustainable buildings*; *green-certification*; *rating systems*; *indoor environment*; *IEQ assessment*; *occupant satisfaction*; and *occupant comfort*. The search included papers published between 2005 and September 2021, although a more substantial emphasis was given to papers issued in the last decade so as to address contemporary developments in green building certifications. Altogether, more than 100 papers focusing on IEQ assessment in green-certified buildings were selected and reviewed: including analyses related to physical measurements of IEQ, occupant satisfaction with IEQ, productivity, and health. Additional literature was also included in the synthesis regardless of the certification status of the buildings analysed, and the year of publication, when original aspects related to IEQ and occupant comfort and health were presented. The presented synthesis also included the comprehensive review of the rating system and IEQ credit requirements from a dozen green building certification schemes. Criteria for exclusion from the review included: papers not based on actual measured data; studies missing clear and robust methods for data collection and analyses; and papers exclusively based on results from building simulation and modelling. In the literature search, the selection was intentionally focused on IEQ aspects related to the foundational elements of thermal comfort, lighting, acoustics and indoor air quality, and to specific propositions of critical advancements within green certification schemes. However, studies were included that recognise the broader relevance of human experience in the building industry beyond the mere attainment of IEQ scores or actual green certification.

In order to give recommendations that could be relevant to building design practice, and to the potential development of green rating systems, the present authors decided to go beyond the simple synthesis of the otherwise sparse, and broadly archival, literature. Instead, the study also relied on the 'grey' literature (*e.g.* government reports, white papers, certification schemes documentation, *etc.*) and on the authors' collective long-term practical experience in the green building industry at a global level.

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1.2 OBJECTIVE

On these bases, one of the primary objectives of this paper consisted of identifying key scientific and practical insights that could help to form an integrated vision for future directions in green building certification.

The paper is structured as follows. It starts with a synthesis of the current evidence of the relationship between green building design and outcomes, including consolidated knowledge on IEQ performance and occupant satisfaction in green-certified and non-certified buildings (Section 2). A systematised approach to relevant research (Section 3) and practice-based observations and challenges are then presented that identify what hinders green buildings' performance (Section 4). Based on the literature and observations outlined in Sections 3 and 4, Section 5 sets the foundation for researchers and decision-makers to capture immediate and long-term green building opportunities. While attention is centred on rating schemes, the proposed recommendations could find application in any building development, with or without certification. Based on this, Section 6 depicts an envisioned future for green-certified buildings.

2. CURRENT EVIDENCE: WHAT WE KNOW ABOUT GREEN-CERTIFIED BUILDINGS

2.1 ELEMENTS OF GREEN BUILDING RATING SYSTEMS

A critical and constructive analysis of IEQ and green building rating systems is predicated on an understanding of the intent of these tools and prevailing representation of strategies intended to improve occupant experience. Green building rating systems integrate a specific theory of change with structural elements intended to encourage and recognise superior practices and, in some cases, performance. The theory of change is generally understood to be rooted in transparency and competitive differentiation. Rating systems provide information about practices and performance that would otherwise be invisible and undervalued by market actors. Ratings codify a set of purported *best practices* and identify specific performance levels that are understood to represent superior outcomes.

Most rating tools have a concept analogous to *systems goals*. These are programmatic aspirations such as climate protection, health promotion or biodiversity conservation. These goals are pursued with a combination of essential elements, often called *prerequisites* (or *preconditions*), and optional criteria, also known as *credits*. Goals, prerequisites and flexibility in their application are not scientific or technical questions. Fundamentally, they are an expression of the values of the community that supports the scheme.

IEQ issues provide clear examples of the importance of intent in the design of rating system criteria. For example, LEED building design and construction rating systems have credits intended to encourage access to daylight. The metrics used in current credits (USGBC 2021) are mostly based on work plane illuminance, with the goal of reducing the need for energy-dependent electric lighting. This is an important intent; however, work plane illuminance is not necessarily correlated to the perception of visual comfort, nor is it a valuable indicator for assessing the availability of biologically active luminous stimulation (Blume *et al.* 2019). The latter objective is seen as increasingly relevant to occupants' circadian wellbeing, alertness, mood, sleep quality and other factors.

The metrics used in certification tools are intimately linked to the last link in the chain: documentation and performance evaluation. Rating systems need to be cognisant of the ability to evaluate criteria at a given phase in the life-cycle of a project. For example, occupant surveys are a valuable tool to gauge satisfaction in use; however, occupants are unlikely to be present when a building is delivered. Consequently, design teams—and, in turn, rating system developers—look for proxies that can predict satisfaction before occupants are present or postpone certification until later in operation, which may be too late to provide the intended market impact (*i.e.* value for green buildings).

The description of these elements—goals, prerequisites, metrics and reviews—is needed to create the foundations for recommendations for the future development of rating system and green building practice more generally. The following sections attempt to articulate specific, actionable opportunities to improve these elements to promote better, more consistent, health IEQ outcomes.

2.2 SYNTHESIS OF THE RESEARCH EVIDENCE: GREEN CERTIFIED *VERSUS* NON-CERTIFIED

Several studies have analysed the energy performance of green-certified buildings against the general building stock (Newsham *et al.* 2009; Scofield 2009, 2013). Conversely, as illustrated in ***Figure 2*** and summarised below, fewer studies have focused on understanding the self-reported satisfaction with IEQ expressed by their occupants (*e.g.* Allen *et al.* 2015; Altomonte *et al.* 2017, 2019; Altomonte & Schiavon 2013; Schiavon & Altomonte 2014; Lee *et al.* 2019, 2020). An even smaller number of studies have measured physical IEQ parameters (*e.g.* Newsham *et al.* 2013; Liang *et al.* 2014; Tham *et al.* 2015; MacNaughton *et al.* 2017; Lee *et al.* 2019; Pastore & Andersen 2019; Licina & Langer 2021), while there is only sparse research comparing health indicators between certified and non-certified buildings (*e.g.* Thiel *et al.* 2014) (***Figure 2***).

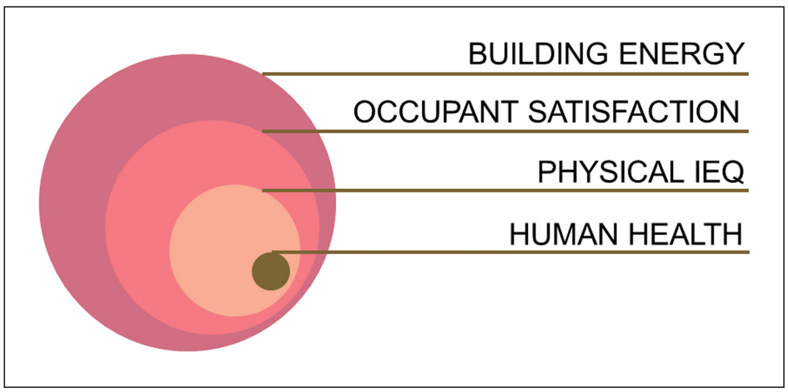

Figure 2: Qualitative illustration of the body of the existing peer-reviewed evidence on green-certified buildings.

Source: Research evidence summarised in the review by Allen *et al.* (2015).

Various studies have reported positive associations with green certification, including:

- occupant perception and satisfaction (*e.g.* Agha-Hossein *et al.* 2013; Leder *et al.* 2016; Lee *et al.* 2020; Liang *et al.* 2014; Sediso & Lee 2016)
- self-reported health symptoms (*e.g.* Allen *et al.* 2015; MacNaughton *et al.* 2016; Lee *et al.* 2019)
- cognitive performance (*e.g.* Allen *et al.* 2015; MacNaughton *et al.* 2017)

These positive effects have been seen both in new construction (Lee *et al.* 2019) and in renovations and retrofits (Lee *et al.* 2020). However, this empirical evidence has, at times, been difficult to consistently substantiate (Tham *et al.* 2015; Khoshbakht *et al.* 2018; Lee *et al.* 2019; Cheung *et al.* 2021) or to directly correlate with the intentions of green certification IEQ credits (Altomonte *et al.* 2019). Conversely, the magnitude of the effects that green rating has exerted on occupants has not consistently matched predictions based on the investments and costs incurred. For instance, some studies have reported identical, or even impaired, IEQ performance of green-certified buildings relative to the non-certified building stock (Brown & Cole 2009; Gou *et al.* 2012; Altomonte & Schiavon 2013; Ravindu *et al.* 2015; Tham *et al.* 2015; Altomonte *et al.* 2017; Sediso & Lee 2016). Even when evidence suggested higher performance in green-certified buildings, it has often not been ascertained to what extent the expectations of building occupants and the so-called 'halo' effect might have influenced perceptions. No clear mechanisms have been provided to explain the relationships between outcomes and specific actions and decisions taken in green-certified buildings.

Research has shown that IEQ performance can be improved by providing specific mandatory certification requirements (Lee *et al.* 2019) and promoting the attainment of higher certification levels such as Gold and Platinum (Pyke 2020). In some studies, measures of IEQ satisfaction have been collected before and after relocation into a green-certified building with the same occupant cohort (*e.g.* Singh *et al.* 2010; Agha-Hossein *et al.* 2013; Colton *et al.* 2014; MacNaughton *et al.* 2016; Licina & Yildirim 2021).

Only a few studies performed physical measurements in green-certified buildings of parameters characterising IEQ alone or in combination with subjective assessment (*e.g.* Newsham *et al.* 2013; Liang *et al.* 2014; Tham *et al.* 2015; MacNaughton *et al.* 2017; Lee *et al.* 2019; Pastore & Andersen 2019). While such studies are essential for alleviating research design challenges such as bias, dependent effort and misclassification, they are typically short term and focused on individual IEQ factors. Direct inter-comparability of physical measurements of IEQ and corresponding occupancy satisfaction data is rare.

In summary, the majority of data on IEQ and occupant outcomes in green-certified buildings is based on subjective ratings, with only a few cases reporting evidence on work performance (*e.g.* MacNaughton *et al.* 2017) or absenteeism (*e.g.* Sustainability Victoria Group & Kador Group 2006). Despite the studies suggesting that green-certified buildings can enhance IEQ and support human wellbeing, direct data on objective health measures are limited and inconsistent. This makes it challenging to establish quantitative relationships between green certifications and health in real-world indoor environments, also due to the fact that buildings are characterised by diverse populations, with different sensitivities, profiles and dynamic exposure requirements.

3. CHALLENGES OF THE EXISTING RESEARCH APPROACHES

3.1 RESEARCH DESIGN LIMITATIONS

The underlying causes for the inconsistent evidence of improved satisfaction, health and cognitive performance in green-certified buildings result, in part, from limitations of the prevailing research methods. A synthesis of the literature reveals substantial inconsistencies in the methods employed for data collection and analysis, and in the criteria adopted for driving inferences (***Table 1***).

Table 1: Challenges of the research approaches.

EXAMPLE OF RESEARCH DESIGN LIMITATIONS	SELECTED REFERENCES
Inconsistency between post-occupancy research hypotheses and design intents (*e.g.* evaluation for human-centric lighting *versus* design for work plane illumination)	Leder *et al.* (2016), Altomonte *et al.* (2019), Pastore & Andersen (2019)
Inconsistent and non-standardised occupant surveys	Meir *et al.* (2009), Duarte Roa *et al.* (2020)
Reliance on indirect and subjective metrics	Ucci & Godefroy (2020)
Little or no control of confounding variables, such as socio-economic, demographic or health factors	Evans & Kantrowitz (2002), Brown *et al.* (2015)
Limited or constrained efforts to establish rigorous peer or control groups for comparative studies or objective matching between green-certified and non-certified buildings	Newsham *et al.* (2013), Mac Naughton *et al.* (2017), Lee *et al.* (2019, 2020)
Limited consideration for sample size or statistical power	Brown & Cole (2009), Thatcher & Milner (2012), Agha-Hossein *et al.* (2013)

As a result, it is often difficult or impossible to aggregate data across various studies to compare and benchmark performance and to draw more general conclusions.

In terms of the collection of physical measurements to characterise IEQ and to couple them with subjective assessments (Steinemann *et al.* 2017), attention should be given to the potential divergences between what is measured at the building level and what is perceived (and valued) by occupants (*e.g.* Bluyssen *et al.* 2011; Altomonte *et al.* 2020). Such spatial and temporal discrepancies might require differentiation of approaches and priority between:

- design principles and operation strategies that can foster buildings' energy efficiency
- indoor environmental conditions that are required to perform tasks (*e.g.* working, studying, playing, *etc.*) in a state of perceived comfort

- what responds to occupants' needs, and drives their satisfaction
- the dynamic range of environmental stimuli and exposures needed to promote physical, physiological and mental health over time

A final common issue to address in study design is the inclusion and consideration of independent variables. Studies typically lack reporting information specific to rating level, categories, credits and metrics. This leads, among other impacts, to: (1) a difficulty in identifying the design features that influence building and occupant outcomes; (2) an assumption that attainment of a specific IEQ credit is directly related to improved IEQ and satisfaction; and (3) the supposition that certification level corresponds to IEQ level. While certification level could be considered an independent variable that is confounded by the inherent flexibility of various green rating systems, obtaining information at the category, credit or metric level is essential to drive the development of certification tools. Since implementation of green building practices varies by geographical location (relative to local or national requirements), building function (*e.g.* office, retail), rating system version and type, and other relevant circumstances (*e.g.* building typology, systems, *etc.*), the definition of design or operational features in green certification schemes could lead to inadequate and inconsistent independent variables.

3.2 LACK OF A COMPREHENSIVE IEQ FRAMEWORK

Despite decades of research and practice, it is clear that the green building industry lacks a common framework for IEQ design and delivery. A recent paper by Wei *et al.* (2020) summarised nearly 100 measures and methods currently used by research and practice to benchmark IEQ in buildings.

For example, Wei *et al.* (2015) reported more than 40 metrics used to describe IAQ alone. This is due to the diversity of indoor air pollutants and their myriad impacts on health and cognitive performance. Researchers have attempted to synthesise these IAQ metrics with composite indexes, such as the attempts of Wargocki *et al.* (2021) and Salis *et al.* (2017) and other methods summarised therein. Salis *et al.* (2017) proposed a method to balance indicators of short- (acute) and long-term (chronic) effects on perceived air quality and health with reference to the exposure limits and disability adjusted life years (DALYs). Yet, this work has not yet been incorporated into mainstream rating tools.

Central to the discussion on IEQ measures is the potential development of a framework for determining an overall IEQ quality rating based on the quality of its individual components (thermal, acoustic, visual and indoor air quality). Few examples of these attempts presenting thoughtful, and often novel, solutions towards IEQ assessment are shown in ***Table 2***.

Table 2: Selected efforts supporting the development of new methods for indoor environmental quality (IEQ) assessment.

EXAMPLES OF PROPOSED METHODS FOR IEQ ASSESSMENT	SELECTED REFERENCES
Rating of satisfaction with individual IEQ components with respect to the overall satisfaction with the indoor environment	Clausen *et al.* (1993), Alm *et al.* (1999), Jin *et al.* (2012)
IEQ index based on the functions describing the percentage of dissatisfied people across multiple IEQ parameters	Piasecki *et al.* (2017)
IEQ index based on five factors, including air temperature, relative humidity, CO_2 concentration, horizontal illuminance and sound pressure level	Wong *et al.* (2018), Huang *et al.* (2012)
IEQ evaluation method based on the parameters prescribed by EN 16798-1 (2020)	Danza *et al.* (2020)
IEQ asset rating method for residential buildings linking design expectations with occupant evaluations	Larsen *et al.* (2020)
Method that combines measurements of energy performance, IEQ and wellbeing indicators	Magyar *et al.* (2021)
IEQ index based on combined IEQ measurements determined with reference to EN 16798-1 (2020) and WHO (2006) air quality guidelines	Wargocki *et al.* (2021), Mujan *et al.* (2021)

Important in these proposals is the rating of the relative impact of different components of IEQ. For example, Frontczak & Wargocki (2011) summarised various studies combining indices of IEQ and concluded that, in the perception of building occupants, thermal comfort is often given slightly higher importance over indoor air quality and the acoustic environment, and much higher importance than visual comfort. However, the study also suggested that the existing evidence does not provide clear guidance on how to weigh IEQ components. The same conclusion was reported by Piasecki & Kostyrko (2018). Other studies emphasised that the relative importance of individual IEQ components can differ widely (*e.g.* within different socio-cultural and environmental contexts). These factors make it challenging to create a generally applicable unified IEQ index (Humphreys 2005). Even though some weighting methods have been proposed (*e.g.* Chiang *et al.* 2001; Buratti *et al.* 2018; Mujan *et al.* 2021), their robustness has not been widely tested. As a consequence, many rating systems default to giving equal weight to all IEQ components, assuming that they contribute equally to the overall IEQ performance. Although specific approaches vary, the present body of research suggests that a comprehensive IEQ index must include:

- a multicriteria asset rating relevant to project planning and design
- objective measures of the physical indoor environment in operation
- subjective measure of occupant experience

These core principles are a good starting point; however, there are conceptual and practical barriers to the development and application of a universally applicable IEQ benchmark.

It can also be noted there are also yet no standard modelling approaches to robustly simulate IEQ in buildings. This is also due to the complexity of the hypotheses (*e.g.* temporal scales, stochastic effects, *etc.*) that underlie such models, while the reliability of predictions might vary between different IEQ parameters.

3.3 A NEW EMERGING KNOWLEDGE

During recent years in research and practice, a new emphasis has been given to design and operation criteria that move beyond the conventional categories of energy efficiency and IEQ and shift their focus from the building to the complex and multifaceted needs and requirements of their users (*e.g.* Bluyssen 2010; McArthur & Powell 2020). To support this change in thinking, new metrics and tools are required that can consistently encompass health and wellbeing outcomes. These must be coupled with new data-collection methods that are continuous and reliable without being intrusive, yet free from experimental biases (*e.g.* fatigue and Hawthorn effects).

A series of trade-offs might often need to be resolved to respond to targets of energy efficiency and occupant requirements in terms of comfort, satisfaction and wellbeing (Altomonte *et al.* 2020). Building occupants have an awareness and express their preferences with respect to their perceived sensory environment (*e.g.* warmer, more light, lower air speed) based on their current states, transient activities and immediate expectations (Rohde *et al.* 2020). However, they might have sparse understanding of the conditions necessary to maintain a building's energy balance or the ranges and mixture of stimuli necessary to trigger their metabolic and physiological functions (*e.g.* circadian rhythms) over longer timeframes (*e.g.* on a daily, weekly or even seasonal basis), or their physical and mental health.

Substantial progress is being made by scientific research to better characterise the requirements of the various human systems, their internal connections and the variability of their responses. For example, instead of considering IEQ factors in isolation and under static conditions, recent studies have brought attention to the effect of cross-modal exposures (*e.g.* Castaldo *et al.* 2018), analysing human reactions to the synergistic or antagonistic combination of many different stimuli (*e.g.* Tang *et al.* 2020).

New metrics and tools are recently becoming available to gather building and user data, under controlled or field study conditions, in order to better identify the environmental factors—or combinations thereof—that mostly matter to the perceptions and states of building occupants (*e.g.* Duarte Roa *et al.* 2020). This will allow the definition of more robust models to predict actions and behaviours in response to changes in indoor and outdoor settings and exposures (Hong *et al.* 2017; O'Brien *et al.* 2020).

4. PRACTICAL CHALLENGES OF THE EXISTING CERTIFICATION SCHEMES

4.1 SYSTEM DESIGN CHALLENGES

IEQ is central to most widely used green building rating systems. However, current practices suffer from both the 'equal weighting' phenomena described above and the inherent flexibility available in voluntary rating tools. The BREEAM, LEED and Green Star rating schemes assign 10–20% of the rating value to IEQ criteria (Doan *et al.* 2017; Wei *et al.* 2020), and typically allow projects to select practices across multiple performance categories (*e.g.* energy, IEQ, transportation). This allows projects to achieve certification without an emphasis on IEQ, particularly for low-rated buildings (*e.g.* Silver *versus* Platinum). In practice, the implementation of IEQ practices varies significantly among green-certified projects, often lagging the adoption rate of energy-related criteria (Teichman *et al.* 2013).

Potential reasons for the predominant emphasis given to energy-related issues relative to IEQ may include the factors summarised in ***Figure 3***. As previously mentioned, some new and recently updated green certification schemes have established *prerequisites* per each category (*e.g.* WELL v2, LEED v4.1), which reduce the possible trading of IEQ for energy related credits. However, the evidence of their effectiveness in delivering improved operational IEQ is still lacking.

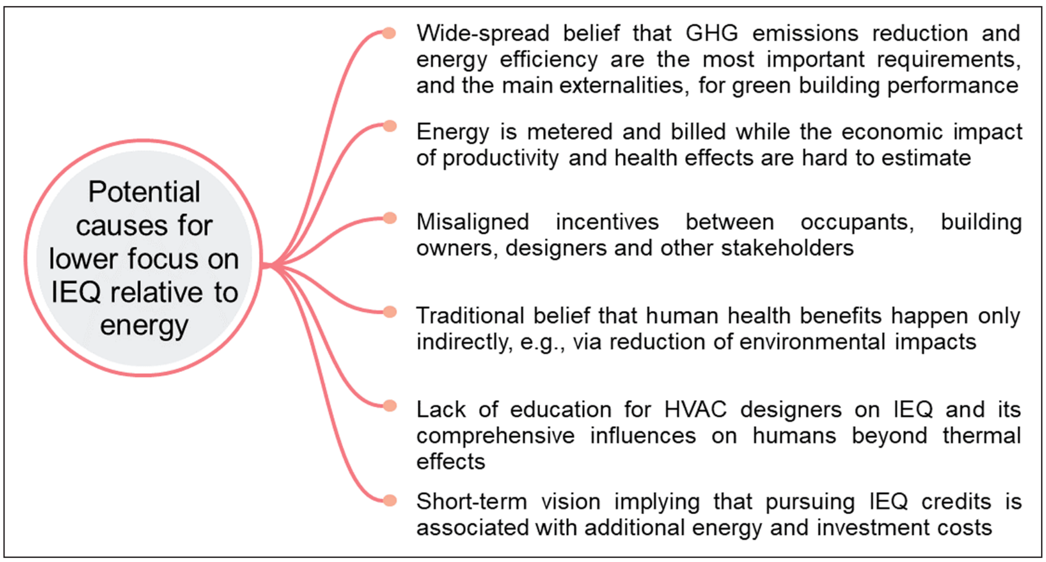

Figure 3: Potential reasons contributing to a predominant focus on energy-related issues in green rating schemes as opposed to indoor environmental quality (IEQ).

Sources: Authors' experience and, in part, through interpretation of the existing literature (*e.g.* Hamilton *et al.* 2016).

Another important system-level design challenge for international green building certification schemes is often the lack of credit and scoring customisation at a global scale. Unlike local schemes, international green rating systems seldom emphasise needs based on specific regional, cultural, climatic and building characteristics—all to be recognised by customised IEQ credit scores. The lack of customisation in scoring might result in inconsistent recognition for different levels of effort and leadership. For instance, low indoor $PM_{2.5}$ levels are equally awarded in countries with markedly different outdoor air pollution levels. A building located in an area of pristine air quality might be perceived as a global leader in a particular IEQ category, and yet a local laggard. Similarly, some green building programmes require a management plan for IEQ without giving specific directions, which can result in two buildings achieving radically different IEQ performance and yet obtaining the same certification level.

4.2 CATEGORY DESIGN CHALLENGES

Trade-offs also occur within the IEQ credit category. Most rating systems encourage projects to select from a menu of IEQ practices and performance areas. This feature is designed to provide flexibility; however, it also creates a situation where teams may focus on one or a few metrics at the expense of others. This has the potential to create situations where projects do not address IEQ elements of concern for a specific building context.

The inclusion of different IEQ metrics varies widely across green building certification schemes (Wei *et al.* 2020). For IAQ, the most frequent proxies are limited to the level of CO_2 and ventilation rate (Wei *et al.* 2015). The majority of certification schemes do not include health-relevant metrics such as secondary volatile organic compounds (SVOCs), various toxic chemicals, biological pollutants or a consideration of infectious diseases, circadian rhythms, electromagnetic fields, and personal control. The absence of many other health-relevant metrics often reflects financial and technical challenges, such as the cost of assessments or the lack of reliable reference benchmarks (Allen *et al.* 2015).

Within the IEQ category, it is also possible to have conflicts between strategies. For example, occupant-level control of thermal conditions may conflict with efforts to increase daylight penetration (Hodder & Parsons 2007; Tzempelikos *et al.* 2010). These are not necessarily defects in the intent or strategy; however, they do reflect the lack of an integrative framework to inform trade-offs. An additional challenge is the practice of 'greenwashing' through the introduction of new green building materials and products, or their unregulated alternatives, which might have not been comprehensively studied for health and safety (Dahl 2010; Steinemann *et al.* 2017).

4.3 RELATIONSHIP WITH STANDARDS AND CODES

Large global organisations for standardisation, rating and accreditations such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), European Committee for Standardization (CEN), International Organization for Standardization (ISO), American Institute of Architects (AIA) and even various green building councils operate under a set of well-defined hierarchies, systems and revenue sources. They are linked to widely adopted 'minimum' codes and point systems that are considered relatively reserved towards the adoption of novel, forward-thinking, outcomes that include primary consideration of human health.

The scientific literature reports that, among 31 green building rating systems from 30 countries worldwide, 39% rely on the ASHRAE 62.1 standard and 23% are based on the European EN 15251 and EN 13779 codes, whereas others rely on local regulations (Wei *et al.* 2015). These standards typically share features including (Persily 2015; ASHRAE 2017):

- minimum acceptability requirements, typically 80% occupant satisfaction
- objectives to minimise adverse health effects
- neglecting individual preferences and needs
- the absence of specific objectives to promote human health beyond the avoidance of adverse health outcomes

These codes and standards often function as an anchor for rating systems, which typically encourage incremental improvements relative to these baseline levels. This can make it difficult to encourage changes that researchers have shown to yield significant health and performance benefits. For example, increasing ventilation above code requirements is predicted to:

- improve cognitive performance (*e.g.* Fisk 2000; Allen *et al.* 2016; Du *et al.* 2020)
- increase economic income (*e.g.* MacNaughton *et al.* 2015; Allen & Macomber 2020)
- reduce absenteeism (*e.g.* Milton *et al.* 2000; Shendell *et al.* 2004; Mendell *et al.* 2013; Carrer *et al.* 2015)

Despite this evidence, rating systems continue to use industry-accepted codes as a prerequisite for performance.

4.4 PERFORMANCE ASSESSMENT CHALLENGES

Green building rating systems criteria are organised around the life system of buildings, including design and construction, fit out, operation, and renovation. Their criteria reflect the opportunities and limitations of these phases:

- whole-building design and construction ratings are typically awarded before occupancy
- interior design and fit-out ratings are limited to areas and systems within a tenant space

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- operations and maintenance ratings are awarded based on existing conditions with few opportunities for large-scale interventions

All three situations create IEQ performance assessment challenges.

4.5 PERFORMANCE MEASUREMENT

The constraints of project phasing and life-cycle are reflected in rating system requirements for performance measurement. Key constraints include:

- presence or absence of occupants
- completion of relevant systems
- physical access (*e.g.* tenant space)
- cost, complexity and availability of various performance tests

Rating systems have traditionally responded to these factors with flexibility, assigning these criteria to optional credits, instead of prerequisites. A few systems require demanding performance verification in operation, yet even in these cases established protocols are often sporadic (Afroz *et al.* 2020). For example, WELL v2 and BEAM Plus (Hong Kong) require occasional performance testing once every three and five years, respectively (WELL 2021).

The limitations of discontinuous measurement requirements and the emergence of new, lower cost measurement technology have encouraged the adoption of continuous, distributed approaches to IEQ monitoring. Key features of these efforts include ubiquitous data, fast and iterative feedback, and place-based solutions (Morawska *et al.* 2018). Some certification schemes award additional points for efforts to continuously monitor certain IEQ components (*e.g.* WELL v2). These requirements, however, have limitations in terms of the number of monitored parameters, frequency of measurements and spatial density of sensors.

The use of low-cost continuous sensors is, however, often unable to capture certain indicators of interest (*e.g.* air pollutants), for which laboratory-based or industrial-hygiene methods would be necessary (*e.g.* Schieweck *et al.* 2018). None of the existing green building schemes demands continuous measurements of outdoor conditions. While there are new players working on the improvement of existing approaches (*e.g.* RESET, Arc Re-Entry[1]), various scientific, technological, legal and institutional barriers remain for more effective deployment of continuous sensing.

Specifically, expectations and the ability to measure physical conditions are not sufficiently matched by the development of methods for data analysis, scoring, interpretation and communication, which can result in a lack of evidence-based guidelines for sampling/analytics and metrics for building performance. Also, methodologies on how to use this information are sparse, resulting in large, but underused, data sets (Zanella *et al.* 2014). New players on the market increasingly create their own monitoring programmes and select elements that suit them best. This creates discrepancies in protocols and data infrastructure requirements across rating systems that limit comparability (Afroz *et al.* 2020) and the creation of benchmarks.

4.6 PROFESSIONAL QUALIFICATIONS

Rating systems are more than the sum of prerequisites and credits. They are implemented by professionals sharing a common understanding of the goals and a technical vocabulary. However, expectations for these professionals vary widely. Zhang *et al.* (2019) found that only 18 of 49 rating systems require an accredited team member. Specific to the issues in the present paper, it is also notable that IEQ is only a small fraction of training material and there is no requirement for prior experience or education. This means that rating system training is not likely to be a reliable predictor of IEQ expertise. Loose requirements for acquiring accreditations stem from the concern that posing stricter conditions might hinder the adoption of a certification scheme. Some rating system developers are filling this gap with specialised training, such as the WELL Accredited Professional and FitWel Ambassador credentials.

5. RECOMMENDATIONS

Since their inception, green building certification systems have had a profound influence on the construction industry globally, guiding building practitioners, owners and managers to shape the qualities of built spaces. This paper has explored the opportunities and challenges facing the green building industry seeking to improve the promotion of health and human experience. From the evidence-based research challenges summarised in Section 3, and the practical observations outlined in Section 4, two sets of complementary recommendations are now offered for researchers and rating system developers.

5.1 RECOMMENDATIONS FOR RESEARCHERS

Advances in IEQ will require targeted investment in critical knowledge gaps and technical capabilities. ***Table 3*** summarises the key recommendations for researchers that could help overcome the current challenges of research development in green-certified buildings summarised in Section 3.

Table 3: Summary of current research and key proposed recommendations for researchers.

CURRENT STATE	PROPOSED RESEARCH RECOMMENDATIONS
Inconsistency in methods leading to difficulties in robust benchmarking (see Section 3.1)	• Standardise methods of data collection and post-occupancy evaluation • Implement studies that use control groups, representative samples and same cohorts of occupants (*e.g.* before/after moving to a green building)
Lack of reporting of independent variables (see Section 3.1)	• Obtain comprehensive information at the category, credit and metric levels from green-certified buildings in order to provide statistical control over relevant, potentially confounding, variables
Lack of a clear consolidated framework for IEQ performance measurements (see Section 3.2)	• Develop new metrics and tools to gather data that support a benchmarking of indoor environmental quality (IEQ) • Systematise IEQ metrics (including subjective, objective and health-based measures) into simpler indicators based on standardised criteria, identifying proxies that are optimised for human experiences and which can inform building users and control systems
Limited capacity of current modelling approaches to reliably predict IEQ and occupant outcomes in buildings (see Section 3.2)	• Develop improved capabilities of modelling software with possibility to integrate IEQ and occupant behaviour at an early design stage of a building's life-cycle
Investigation of human responses to IEQ that are currently over-regulated within narrow and static ranges (targeting neutrality and average acceptability) (see Section 3.3)	• Move beyond 'dose–response' and static relationships by studying complex and dynamic interactions and feedbacks between occupants and their settings at an instantaneous level and over time (Bluyssen *et al.* 2011; Altomonte *et al.* 2020) • Shift from a 'generic occupancy' approach to one that embraces inter-individual (between people) and intra-individual (within a person) variabilities (*e.g.* Castaldo *et al.* 2018; McArthur & Powell 2020) • Explore the benefits of personal control and adjustments while supporting opportunities for individual preferences and needs (Brager *et al.* 2015; Miura & Ikaga 2016) • Identify new and energy-efficient ways to allow IEQ conditions to float over wider ranges of settings (Hoyt *et al.* 2015; Wargocki & Wyon 2017)
Investigation of monotonic human responses to environmental stimuli (see Section 3.3)	• Improve the understanding of potential interactions among IEQ parameters and consider metrics capturing the effects of dynamic indoor exposures • Characterise the requirements of the various human systems, their internal connections and the variability of their responses with studies focusing on cross-modal exposures in complex real environments, enabling the measurement and analysis of human physical and physio-psychological responses to the synergistic (or antagonistic) combination of different stimuli (van Marken Lichtenbelt *et al.* 2017; Parkinson & de Dear 2015; Schweiker *et al.* 2020; Houser & Esposito 2021)
Lack of collaboration across disciplines	• Adopt a holistic approach that stimulates collaboration across all IEQ disciplines (lighting, acoustics, air quality, thermal comfort), but also goes beyond IEQ silos and interlinks building sciences, health sciences, environmental sciences and social sciences

5.2 RECOMMENDATIONS FOR RATING SYSTEM DEVELOPERS

Rating systems turn scientific research and technical capabilities into practical market transformation tools. Section 4 above shows that they can be more effective in promoting human health and experience in buildings. ***Table 4*** summarises key proposed recommendations for rating system developers that could help overcome existing limitations.

CURRENT STATE	PROPOSED RECOMMENDATIONS
Relative priority on environmental/energy performance over health and experience. Variable adoption of indoor environmental quality (IEQ)-related credits (see Section 4.1)	• Establish more evenly balanced goals for environmental/energy performance and IEQ (Teichman *et al.* 2013; Doan *et al.* 2017; Wei *et al.* 2020). This requires rebalancing priorities within prevailing rating systems or perhaps reconsidering prioritisation schemes entirely
Lack of customisation in IEQ scoring at a global scale (see Section 4.1)	• Adopt customised credit scores that promote and award IEQ-related actions addressing regional priorities and which are not bound to consistencies across global portfolios • Provide local, regional and global contexts to measure effective performance through *alternative compliance paths* to projects around the world. A good example is offered by Green Star Australia that explicitly recognises national and global leadership (GBCA 2014) • Explore the utility of weighting coefficients (Lee 2013). Some developments on this front have been initiated by WELL, linking the population-based health data from the Global Burden of Disease database with specific credits from green building certification schemes • Adopt new tools and approaches to provide globally consistent benchmarks while simultaneously addressing regional and local conditions. This can be done through complementary assets and operational performance measurements
Pursuing IEQ credits that are not of primary concern for a specific building context (see Section 4.2)	• Establish a minimum performance for each IEQ category while maintaining flexibility. Account for cross- and inter-category interplays
Focus on conventional categories of IEQ and exclusion of many health-relevant metrics (see Section 4.2)	• Effectively transfer to building practice the results of ongoing studies on the complex and multifaceted needs and requirements of building users (McArthur & Powell 2020) • Adopt new metrics and tools that more easily allow one to monitor and evaluate occupants' health and wellbeing outcomes (*e.g.* Danza *et al.* 2020; Wargocki *et al.* 2021)
Insufficient transparency in requirements and measured outcomes. Practice of 'greenwashing' (see Section 4.2)	• Balance clear statements about the IEQ credits of projects and consistent measurements of real-world performance • Adopt a full transparency approach and pursue truly green products with known emission factors and effects on IEQ, health and safety (Dahl 2010; Steinemann *et al.* 2017)
Heavy reliance on base requirements from conventional IEQ standards (see Section 4.3)	• Recognise current disconnections between the intent of actions and real-world outcomes (*e.g.* Karmann *et al.* 2018; Graham *et al.* 2021) • Identify the weaker links in the design, delivery and operational processes and address them through continuous improvement • Prioritise the development of new health-based thresholds for indoor environments, new data schemes, *etc.* • Adopt and award with additional points more stringent credit requirements that transcend the demands of conventional standards. Shift of attitude from 'nice to have' to 'must have'
Loose and sporadic requirements for occasional IEQ performance verification (see Section 4.5)	• Establish frequent and robust IEQ performance testing before and during building occupancy to also capture seasonal variations of IEQ
Absence of requirements for continuous monitoring that make IEQ performance based on design and not actual conditions (see Section 4.5)	• Broaden performance verification in order to enhance diagnosis and response times through continuous monitoring and assessment indoors and, when needed, outdoors • When needed, combine these practices with occasional in-depth assessment by trained experts
Underdeveloped methods for sampling, data analysis, scoring, interpretation and communication (see Section 4.5)	• Develop evidence-based guidelines for sampling, analytics and metrics for building performance • Standardise protocols, data infrastructure and communication requirements across green rating systems
Loose and insufficient requirements to acquiring professional accreditation (see Section 4.6)	• Adopt requirements for professional accreditation to demonstrate education in the relevant field and partner with experts (*e.g.* industrial hygienists) in order to establish frameworks and rules for IEQ performance assessment
Lack of flexibility to encompass future occupant needs and adverse events	• Make rating systems more flexible and adaptable to the needs and preferences of occupants (*e.g.* health, physiology, *etc.*) as well as more resilient to events (unpredictable) related to the occurrence of new diseases and weather extremes

Table 4: Current state of green rating systems and key recommendations.

6. THE FUTURE OF GREEN-CERTIFIED BUILDINGS

Green building certifications are powerful market transformation tools. Health and human experience have been central to these systems since their inception. Today, knowledge and expectations are rising, and it is important for rating systems to raise the bar for recognition. Imagining a graphical representation of building performance, the pyramid presented in ***Figure 4*** proposes a potential progression towards what could be the 'future of green' (Tier 4).

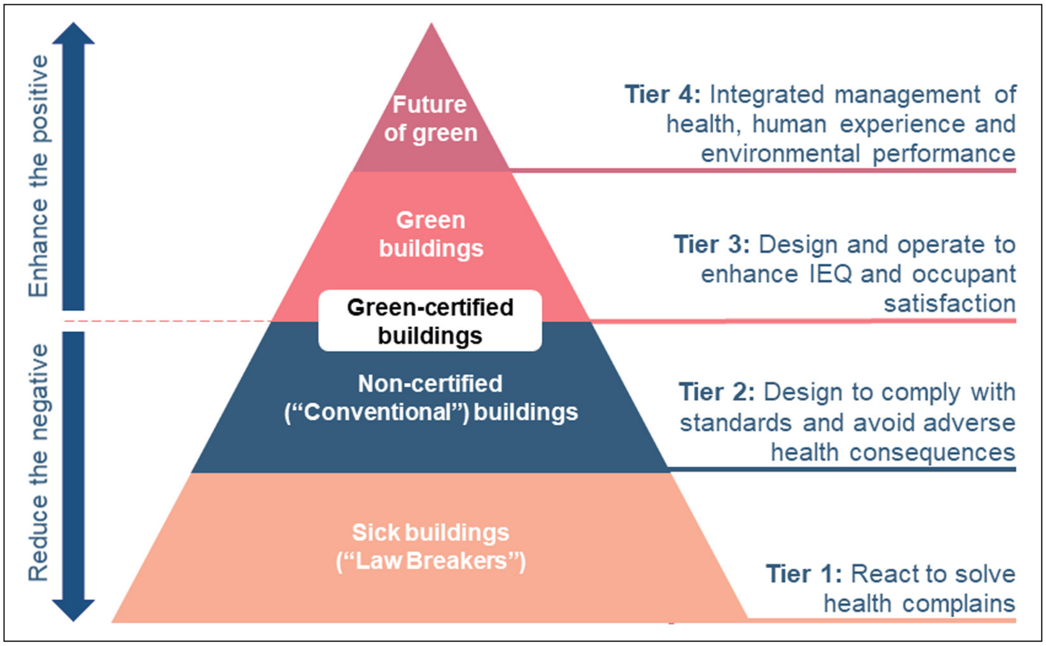

Figure 4: Four-tier building performance model with progression from sick buildings (Tier 1) to envisioned future green buildings (Tier 4).

The envisioned future of green buildings ('Tier 4') will define leadership in the green real-estate industry by directing efforts towards integrated management of human (subjective and objective IEQ, health and human experience) and environmental objectives (circularity, resources and energy use). These goals are intertwined. Provision of healthy IEQ should not compromise ecological integrity, globally and locally, or responsibility for the planet and its people. The 'future of green' implies a change of approach from the avoidance of poor performance to the multiplication of the physical, social and mental opportunities that can support people's flourishing and thriving. This emerging knowledge needs to be effectively translated into new design opportunities, enhancing rather than restraining creativity, offering an inspiration rather than a verification, the promotion rather than the constraint of ingenuity and imagination, and perhaps also with a focus given primarily to adaptive and adjustable measurement methods rather than the use of absolute and prescriptive metrics. These Tier 4 buildings will need to recognise and encourage practices that drive positive behavioural change that also extend beyond the time of being present in these buildings.

It is time to critically examine the priorities reflected in long-standing rating systems. Recent events, such as the global threat of Covid-19, have launched a new set of values and priorities, while redefining the way human health is thought about. This is accompanied by a greater sense of urgency related to climate action and supply chain impacts. The Tier 4 buildings will need to reflect such new needs with novel science and technologies, negotiating between trade-offs and prioritising over the potential occurrence of conflicting requirements.

NOTE

1 For RESET, see *https://www.reset.build/standard/air*; and for Arc Re-Entry, see *https://arcskoru.com/sites/default/files/Arc%20Guide%20to%20Re%20Entry%20v1.2.pdf/*.

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COMPETING 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.

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