The Innovation Hub

for Affordable Heating and Cooling

Report #LLHC1-3

Living Labs Healthcare Sector: Examination of the potential to align health and energy co-benefits

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QUEENSLAND UNIVERSITY OF TECHNOLOGY

About i-Hub

The Innovation Hub for Affordable Heating and Cooling (i-Hub) is an initiative led by the Australian Institute of Refrigeration, Air Conditioning and Heating (AIRAH) in conjunction with CSIRO, Queensland University of Technology (QUT), the University of Melbourne and the University of Wollongong and supported by Australian Renewable Energy Agency (ARENA) to facilitate the heating, ventilation, air conditioning and refrigeration (HVAC&R) industry's transition to a low emissions future, stimulate jobs growth, and showcase HVAC&R innovation in buildings.

The objective of i-Hub is to support the broader HVAC&R industry with knowledge dissemination, skills-development and capacity-building. By facilitating a collaborative approach to innovation, i-Hub brings together leading universities, researchers, consultants, building owners and equipment manufacturers to create a connected research and development community in Australia.

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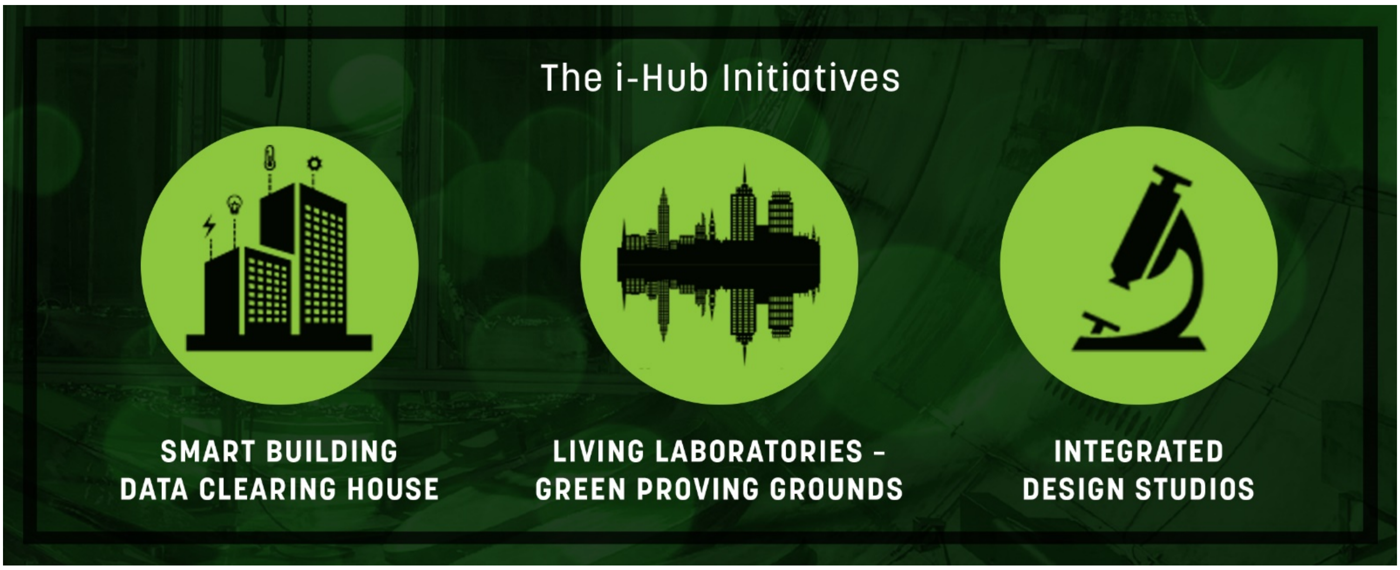

i-Hub Healthcare Living Laboratories Sector-wide engagement and impact

The Healthcare Living Laboratories Sector Engagement project will quantify healthcare sector energy consumption, identify the potential for renewable energy technologies to reduce sector energy consumption and cost for HVAC in particular, and propose requirements for optimal integration of renewable energy technologies.

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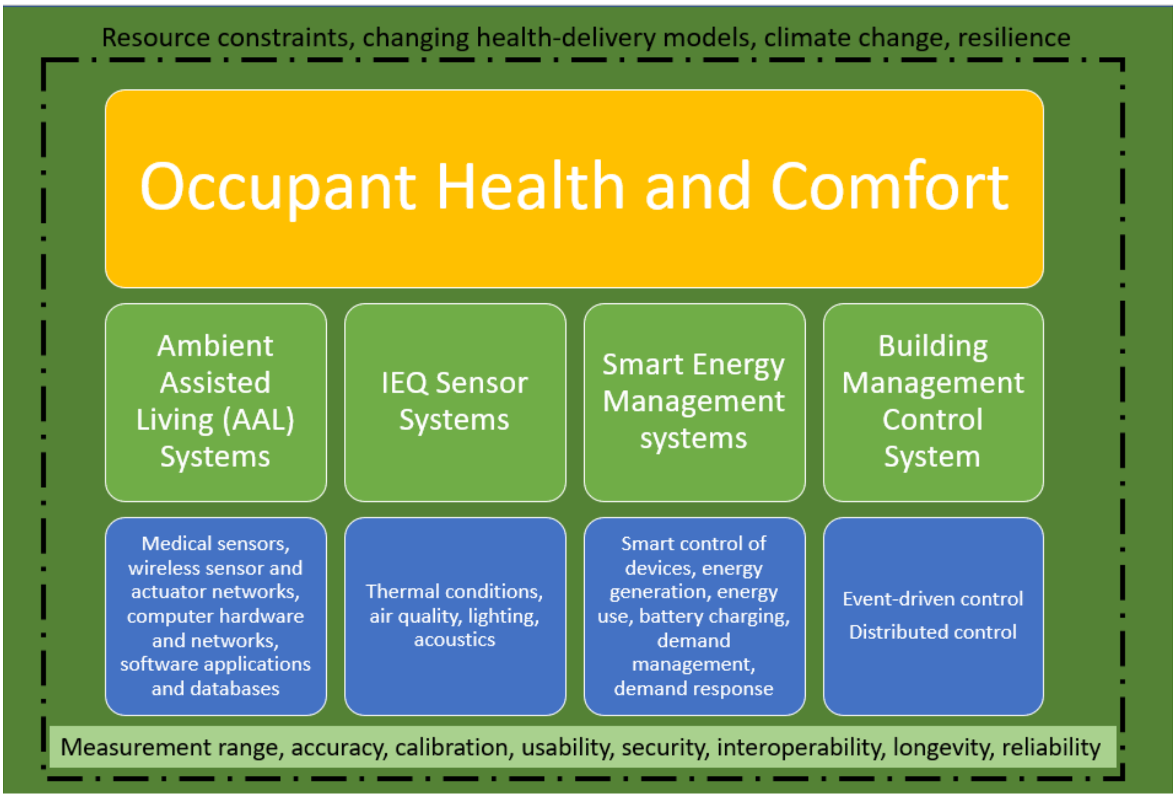
1 EXECUTIVE SUMMARY

The iHUB's Living Laboratory Healthcare Sector Wide project aims to enable Healthcare Facilities (HCFs) to address multiple energy challenges: high energy use, peak demand, renewable energy utilisation, energy costs and the environmental impact of energy sources. As the largest portion of HCF energy use is attributed to indoor climate control and air quality, this report examines key performance indicators (KPIs) and metrics for indoor environment quality from the perspectives of health, building services, resilience and smart technologies. It is hoped that a broader set of KPIs, beyond typical normalised annual energy use intensity metrics (e.g., kWh/m^2/year), can help build a sound business case for energy efficiency and renewable energy projects in HCFs, and add value to the core service of health care. This integrated systems approach is consistent with an EU Directive that requires energy efficiency improvements in buildings in the EU (addressing energy, climate change mitigation and adaptation objectives) to consider additional benefits for health and wellbeing, productivity and building value.

While the primary function of HCFs is patient/occupant care, the health and well-being of hospital users (patients, residents, staff and visitors) is affected by the quality of the indoor environment, impacting on their physical and psychological health. The main building quality / building services that are considered to contribute to indoor environment quality (IEQ) are thermal comfort, acoustic comfort, visual comfort, and indoor air quality. Some performance requirements for individual IEQ parameters are typically included in codes, standards and design guides. These building services are seen as supporting healthcare services but are also subject to scrutiny on cost and environmental impacts. This report highlights a vision of an integrated health and energy approach within the context of resource constraints, health-delivery models, climate change and resilience.



Eight key messages emerge from this report:

1. Different user groups and individuals will have different indoor environment requirements and therefore different 'best' solutions.
2. IEQ solutions can positively and negatively impact on each other and on energy consumption / demand.
3. Green rating tools typically allocate around 20% of total points to IEQ criterion, even though the vast $ of energy use in HCFs is for delivery of IEQ.
4. There is a need for an integrated design approach from the very beginning of the process of conceiving a healthcare facility (new or major retrofit).
5. There is a need for robust and evidence-based integration of engineering, sustainability, and environmental factors and measurement strategies with users at the focal point.
6. Building systems need to be commissioned and continuously monitored not only for energy impacts (e.g., consumption, demand, load factor, greenhouse gas emissions etc) but also for impact for building occupants.
7. The methodologies used for determining cost effectiveness by medical and engineering fraternities are fundamentally opposed, and approaches need to be more closely aligned and focused on the achievement of health and societal value and co-benefits.
8. Overheating and power outage risks due to climate change need to be specifically factored into design and operation, increasing the resilience of HCFs and their ability to protect the health of occupants and the well-being of society as a whole.

As such, all stakeholders in healthcare facilities need to consider monitoring and reporting on a range of key performance indicators that embrace

- Whole of building | site | campus energy use, impact on greenhouse gas emissions, network impact, load flexibility / demand response capacity, and progress toward net-zero carbon goals
- Energy use and outcomes/impact metrics at a building services level, for each of the indoor environment quality criterion (thermal comfort, acoustic comfort, lighting comfort and indoor air quality)
- Resilience metrics that account for the risks of overheating and power outages
- Health metrics that can be used to quantify and qualify additional value (or loss of value) resulting from energy-focused actions.

A suite of metrics is presented in Table 4-3 for consideration by administrative, facilities management and clinical staff of healthcare facilities and their respective clientele.

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2 INTRODUCTION

2.1 Aim and purpose of this report

The overall aim of the Living Laboratory Healthcare Sector Wide project is to enable Healthcare Facilities (HCFs) to address multiple energy challenges: high energy use, peak demand, renewable energy utilisation, energy costs and the environmental impact of energy sources. The specific aim of this report is to move towards the (potential) development of new key performance indicators (KPIs) and metrics that link building services and energy performance (especially peak demand, renewable energy and resilience) to core health services (i.e., healthcare plans for occupants/patients). This report collates existing literature on the role of indoor environmental control in the health and well-being (and hence care plan) for occupants of HCFs and extrapolates the implications for energy demand and resilience of HCFs. It proposes health-outcomes related KPIs for energy projects in the healthcare sector, using a systems-thinking approach for the evaluation of energy efficiency, demand management and renewable energy projects. It is hoped that a broader set of KPIs can help build a sound business case for energy efficiency and renewable energy projects in HCFs. This integrated systems approach is consistent with EU Directive 2018/844 (Article 2a.1) that requires energy efficiency improvements in buildings in the EU (for climate change mitigation and adaptation) to consider additional benefits for health and wellbeing, productivity and building value. This EU approach is demonstrated, for example, in the Alliance for Deep RENovation in Buildings (ALDREN, www.aldren.eu) that seeks to link building rating approaches (energy, sustainability, indoor environment quality) with financing instruments and building passports, demonstrating a co-benefits approach.

2.2 Energy Indicators

A previous iHUB report, Healthcare Sector Energy Baseline, examined a range of existing energy KPIs and data for the healthcare sector domestically and internationally, to better understand (and hence manage) energy use and greenhouse gas emissions. The report reviewed published literature (e.g., government and sector reports, industry papers and academic publications), collating and evaluating healthcare sector related KPIs. Energy use intensity (EUI) was (and is) the predominant way of reporting energy use in HCFs, and published literature revealed that HCF EUI varies considerably, depending on the climate, the types of facilities, occupancy rates, equipment etc. Commonly used energy KPIs for EUI in hospitals are energy per floor area per annum, energy per bed day per annum, energy per bed per annum, or energy per separation per annum. In residential aged care, additional KPIs indicating EUI include energy per resident per annum, and heating (or cooling) energy per floor area per annum.

The existing KPIs were evaluated in terms of their effectiveness in enabling renewable energy or energy storage; improving energy efficiency or productivity; reducing peak demand; and managing energy demand. Recommendations of how to select KPIs were provided. The existing KPIs are being used as a reference for i-Hub Living Lab comparisons. The effectiveness of those current sector energy KPIs are being evaluated for innovative energy technologies in reducing peak demand, energy use or operation expense, enabling renewable energy or energy storage.

Literature clearly indicates that existing KPIs (at building or equipment level) are inadequate for diagnosing challenges and opportunities for building performance improvements [1, 2]. The Healthcare Sector Baseline Report proposed purpose oriented KPIs for assessing the impacts of energy performance improvement projects (Table 2-1). These KPIs are organised based on different aspects of the whole healthcare energy system. Two of these (highlighted in blue) relate to assessing possible health and safety benefits of energy improvement projects. This report delves further into the interconnections between energy and health.

Table 2-1 Purpose oriented KPIs for Healthcare Facilities

Purpose	Possible KPIs	Data inputs examples
- **Site Peak Demand Reduction** - **Reduce demand charge**	Highest kW (or kVA) in every month (or billing period)	Half hourly kW (or kVA) demand profile over at least 12 months' time
- **Enabling renewable energy, e.g., rooftop PV** - **Reduce energy charge**	Monthly energy consumption	Monthly kWh over at least 12 months' time
- **Testing building envelope energy performance improvement technologies e.g., louvre, paint, glazing**	- Locational thermal comfort - Locational cooling or heating delivered - Locational energy consumption - Locational peak demand	- Outdoor dry bulb temperature - Indoor dry bulb temperature - cooling/heating during the testing period (air volume and temperature) - kWh over the testing period - interval kW (or kVA) over the testing period
- **Testing new HVAC energy efficiency technologies e.g., coolant or water improvement**	- Equipment specific cooling or heating output - Equipment specific energy input - Equipment specific	- Outdoor dry bulb temperature - cooling/heating during the testing period (incoming and outgoing water volume and temperature) - kWh over the testing period - interval kW (or kVA) over the testing period

- **Assessing environmental impact of energy performance improvement projects**	- Greenhouse gas emissions
	- Waste
	  o Non-radioactive
	  o Radioactive
	- Water and sewage
	- Avoided GHG emissions
	- Avoided air pollution
	- VOC level
		- Ratio of onsite renewable energy generation to total consumption
		- Ration of total renewable energy consumption to total consumption
		- Ratio of Renewable generation power to peak demand
		- Waste category and weights
		- Water consumption and sewage amounts
		- Avoided tCO_2-e and $
		- Avoided *PM_{10}, NO_x, and SO_2*

- **Assessing health impact of energy performance improvement projects**	- Average length of stay (ALOS) - Less onsite infection rates	- Health survey - Medical records
- **Assessing safety impact of energy performance improvement projects**	- Less safety incidents	- Post-occupancy comfort survey
- **Assessing network benefits**	- Wholesale cost of peak 30-min electricity demand - Total self-consumption rate - Rate of PV used for HVAC self-consumption - Net facility load factor	- Reduced potential cost if on electricity wholesale market - locally generated renewable and local total power demand and HVAC demand

2.3 Scope and methodology

For the purposes of this report, HCFs include hospitals, aged care facilities (residential aged care, care homes, nursing homes, retirement living, independent living units, supported living units), and day surgeries, medical services, clinics, and general medical practices in stand-alone buildings (e.g., not inside office buildings or shopping centres). The facilities that were NOT considered in this review include senior living communities (not aged care); pathology/testing laboratories that are separate from other health services buildings; health research facilities; pharmacies; pharmaceutical production and warehouse facilities; allied health services such as dentistry, podiatry, optometry (when not part of broader medical/health facilities mentioned previously).

Given the complexity of issues relating to HCFs, this report used an integrative literature review process [3] that involved identification and evaluation of diverse sources, including both academic and grey literature. Search terms included:

- Hospitals, residential aged care, nursing homes, care homes, healthcare facilities
- Health, wellbeing, staff, patients, residents
- Energy, energy demand, net zero carbon, net zero energy
- Indoor air quality, indoor environment quality, thermal comfort, acoustic comfort, noise, acoustic comfort, visual comfort, daylighting, air quality, ventilation, HVAC (heating, ventilation and air conditioning)
- Resilience, sustainability
- KPI, indicators, metrics

Only papers and reports in English were reviewed. Higher priority was given to review papers (that summarise knowledge of a particular field up to a certain point in time) and to papers published in the last decade (since 2010). The focus was on identification of health benefits (as opposed to disease or illness prevention) and metrics other than energy use intensity. The vast majority of identified literature related to hospitals and residential aged care facilities.

3 INDOOR ENVIRONMENT QUALITY OF HEALTHCARE FACILITIES

By their very nature, HCFs exist to take care of vulnerable members of our community, accentuating the need for these buildings to consider how the buildings and their services enhance or hinder the wellbeing of occupants and assist with, or detract from, the health-related tasks being performed in the facility. While the primary function of HCFs is patient/occupant care, the health and well-being of hospital patients and aged-care residents is affected by the quality of the indoor environment, impacting on their physical and psychological health [4-9]. The main building quality / building services factors that are considered to contribute to indoor environment quality (IEQ) are thermal comfort, acoustic comfort, visual comfort, and indoor air quality [10-14]. Minimum performance requirements for these individual parameters are frequently included in building codes and standards, and in healthcare facility design and operation guides. These building services are often taken for granted as supporting the provision of healthcare services (i.e., patient and staff hygiene and safety), whilst trying to reduce the energy costs and environmental impacts of providing these services. An alternative growing field of research considers how these building service factors may play a more active role in healthcare, by enhancing patient health as well as staff satisfaction and efficiency [15-18]. Other research points to significant knowledge gaps in the understanding of the interactions between these factors (each of the building services and building occupants), calling for a transdisciplinary and holistic approach that acknowledges that the indoor environment is a dynamic and complex system [19].

The following sections present health (Section 3.1), engineering (Section 3.2), resilience (Section 3.3) and smart devices (Section 3.4) aspects of IEQ. The concurrent consideration of IEQ and energy is particularly important in the context of HCFs that typically operate continuously (24 hours/day); have a high energy intensity due to the nature of their services [20]; have a high occupancy rate; and cater for two distinct types of occupants: vulnerable occupants who are continuously exposed to the indoor environment and are often quite sedentary, and staff who work varying length shifts and have varying levels of activity. The purpose of this section is to create a foundation for the possibility of identifying or developing KPIs that explicitly link the energy and health benefits, creating a dual benefit for HCFs.

3.1 Health and Indoor Environment Quality

Health, in this section, is viewed as continuum between illness and wellness that incorporates the bio-psycho-social (BPS) model of complex causal factors and subjective experiences [19]. This section highlights literature relating to each of the previously mentioned IEQ factors, focusing on the impact of the factor on occupant and staff health.

3.1.1 Thermal comfort

Thermal conditions can have serious effects on health. It can lead to multiple chronic diseases including cardiovascular problems, respiratory conditions; impact on mental health; and result in mortality in some cases [21-24]. The study by Yenneti et al [24] shows evidence of correlation between heat waves and increased mortality and morbidity, as well as emergency hospitalisation rates of heart-disease patients. The most vulnerable groups to health risks resulting from exposure to extreme weather conditions are the elderly, infants/children, low socio-economic demographics, and people with pre-existing health issues [22-26].

The 'thermal comfort' criterion is an attempt to determine occupant satisfaction with a building's indoor thermal conditions. Note that the focus is on occupant satisfaction, not occupant health. Physiological, psychological and environmental factors influence occupants' thermal comfort over the course of a day and over time [27] and the thermal environment of HCFs is thought to affect the healing process of patients and the productivity of staff [28].

Given that the occupants of HCFs are vulnerable, in the first instance, there is perhaps a need to re-consider the limitations of the concept of 'thermal comfort'. In the context of heat (or absence of heat) as a potential health hazard, an individual's protective factor is the capacity of their body to respond to heat. Acclimatisation and thermoregulation determine human heat tolerance and vulnerability to heat stress, requiring consideration of a range of factors and conditions, as summarised in Table 3-1 (an extract from [29]).

A 2016 review of the impact of HCF thermal environments on occupants [28] reported that

- Thermal discomfort affects sleep quality and quantity:
    - Cold conditions impact on
        - The ability to fall asleep and stay asleep
        - Increase shivering, inattentiveness, and muscular and joint tension
    - Warm conditions impact on increased wakefulness (reduced REM and non-REM sleep)
- Thermal conditions (comfort or discomfort) during surgery impacts on patients' overall satisfaction with surgical care

Thermal conditions within operating theatres also have an impact on the health and safety of staff because the staff have limited options for managing their thermal sensation (i.e., little control over the physical environment; requirement for activity levels related to their tasks; and requirement of specific clothing related to the context) [30].

Relative humidity is considered in thermal comfort studies as it plays a role in thermoregulation. However, it also impacts on other health aspects. One the one hand, very low humidity (i.e., very dry air) dries out mucous membranes and the skin. On the other hand, high humidity can potentially create an environment that supports mould or dust mites that can trigger asthma and allergies. High humidity settings are often used in burns wards to aid in recovery, and recent medical evidence suggests that increasing ambient humidity (e.g., RH50%, compared to RH20%) may assist in reducing flu symptoms and promoting more rapid recovery [31]. This suggests that altering indoor RH levels may be a treatment method for flu.

Table 3-1 Factors and conditions affecting individual responses to the thermal environment

Factors	Key conditions
Thermoregulation - physiological	Range is very narrow (core body temperature 36.8 °C +/- 0.5; heat stroke occurs at 40 °C) and varies between individuals The upper range of heat exposure that humans can tolerate has not been defined, and may not be definable Heat sensitivity is affected by factors such as obesity, age, illness, medication, aerobic fitness, gender, and acclimatisation, with individual influencing factors of sweat capacity, cardio capacity and blood volume
Thermoregulation - behavioural	Relies on individual's perception of body temperature and an individual's ability to modify the environment to reduce body temperature Older people have less ability to perceive temperature Relies on personal actions: adjusting clothing (type and level), reducing activity, moving to a cooler space, hydrating, wetting the skin Relies on actions within buildings: operating windows, shades, or fans to reduce heat or increase air movement to enhance evaporation from skin The evaporative effect can be enhanced or restricted by clothing: not just the insulation level (clo), but also by fabric breathability and garment fit
Acclimatisation	Heat tolerance can be improved due to physiological adaptation to a new climate Sudden or extreme heat events can impact on typically acclimated residents New arrivals to a region can be unacclimated People experiencing predominantly air-conditioned environments can be unacclimated
Vulnerability	Physiological and behavioural factors are closely linked, and the impairment of either of these reduces thermal tolerance and increases sensitivity to heat Older people are particularly vulnerable to heat-related morbidity and mortality Physical and social vulnerability can limit adaptive capacity and increase exposure

Within the context of HCFs, it is worth remembering the three broad user groups within the facilities: staff, patients/residents, and visitors. Individual factors such as clothing thermal resistance and metabolic rate impact on thermal sensation. The three main user groups, by their very nature, have different levels of activity (impacting on their metabolic rate) and different clothing types (impacting on thermal resistance). Within each group there will also be multiple variations due to the individual differences in physiology, health status, acclimatisation etc. Meeting the thermal comfort/health needs of such a heterogenous group of people is very challenging.

3.1.2 Indoor air quality

The air quality inside buildings is impacted by polluted outside air that enters by infiltration, natural openings or mechanical ventilation systems, and by pollutants from within the building. The indoor air quality (IAQ) can be affected by gases, volatile organic compounds, particulate matter, fibres, organic and inorganic contaminates and biological particles chemicals. The groups most vulnerable to poor IAQ are children, young adults, the elderly, and those suffering chronic respiratory and/or cardiovascular diseases [32]. The reported benefits of improvements in air quality, in general, include reduced infections and reduced staff absences due to illness [33].

The chronic and acute health impacts of potential air pollutants are typically presented as long-term and short-term Exposure Limit Values (ELV), derived from epidemiological studies and animal experiments (refer to Figure 3-1). This figure shows some of the international and national guidelines for indoor environments and work environments, and the work being undertaken to characterise building materials to avoid introducing air pollutants in indoor environments (based on Lowest Concentration of Interest LCI). This will evolve into an indoor materials emissions labelling scheme. Note that exposure duration and population sensitivity are factors for consideration.

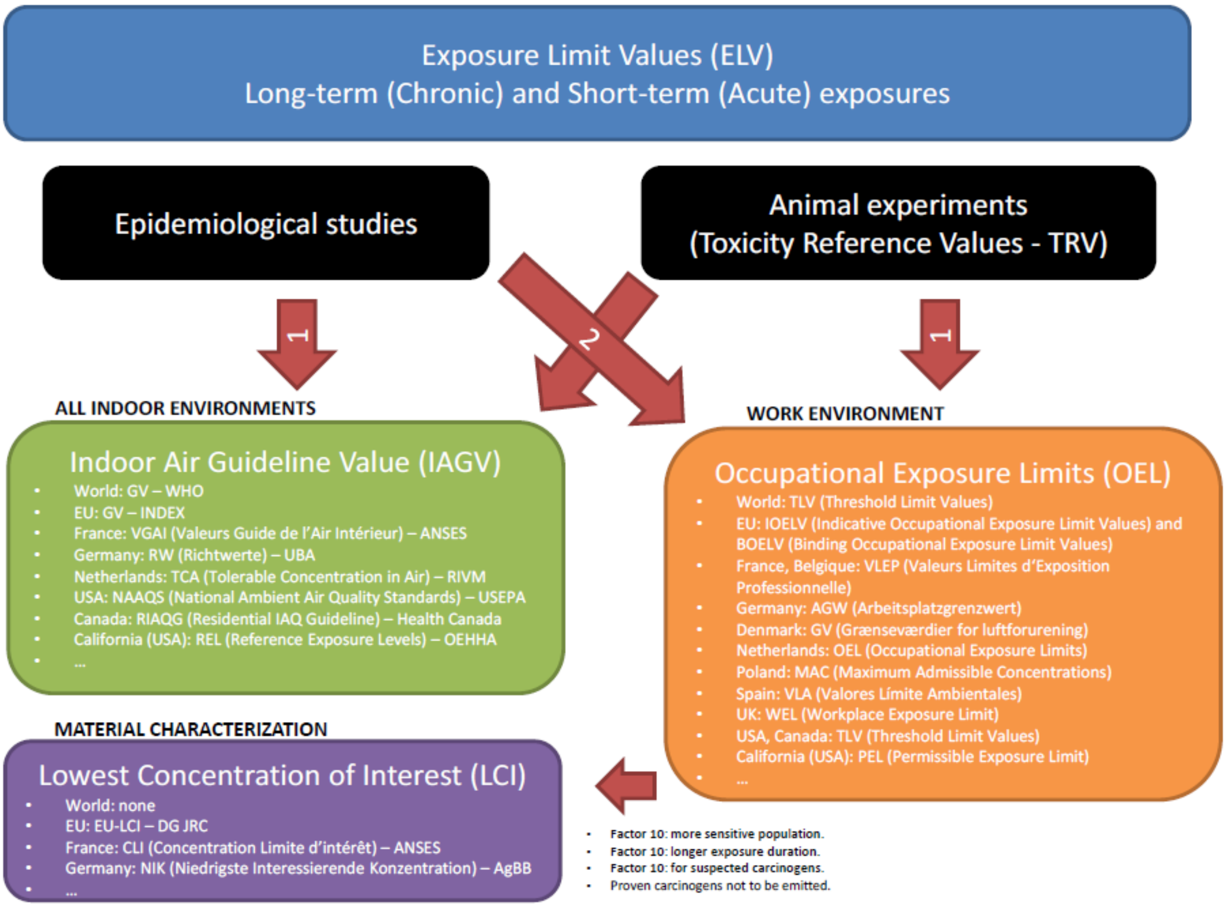


Figure 3-1 Exposure Limit Values and applications (Source: [34])

Common pollutants, their source, and their impact (as relevant to HCFs), are summarised in Table 3-2 (derived from US Environment Protection Agency (www.epa.gov) and [35, 36]). Note that some of these pollutants are moderated by temperature and relative humidity. The source of pollutants have been categorised also by the carrier (indoor or outdoor air), as this relates to ventilation strategies in buildings.

Table 3-2 Indoor air pollutants, sources and impacts in HCFs

Pollutant	Carrier / Source	Negative impact on health
Bio-aerosols	*Indoor air* (Building occupants and users)	Infection spread
Carbon monoxide (CO)	*Outdoor air* (e.g., vehicle and industrial emissions; generators) *Indoor air* (unvented or poorly maintained combustion such as heaters, stoves)	Sick building symptoms (e.g., fatigue, impaired vision, reduced brain function, nausea, headaches) Changes in blood pressure and heart rate
Carbon Dioxide (CO_2)	NOTE: not a pollutant, but concentration levels >1000 ppm impact on occupant health, and CO_2 is used as a proxy for occupancy and hence ventilation rates	Acute: reduced cognitive performance (tiredness, concentration) Chronic: kidney calcification, bone demineralisation [37] Decrease in decision-making performance [38]
Formaldehyde (HCHO)	*Indoor air* (e.g., medical treatments; formaldehyde solutions; building products, finishings and furnishings; clothing and fabrics; cleaning products and disinfectants; cosmetics)	Low level: Irritation of eyes, nose, throat High level: Coughing, wheezing, chest pains, bronchitis Long term exposure: cancer
Fungal pollutants	*Outdoor air* (e.g., fungal sources) *Indoor air* (e.g., air conduits)	Allergic rhinitis, asthma
Nitrogen Dioxide (NO_2) (subset of NO_x)	*Outdoor air* (vehicle and power plant emissions)	Asthmatic symptoms; respiratory tract irritation
Particulate Matter (PM_{10} and $PM_{2.5}$)	*Outdoor air* (e.g., dust, smoke, chemical reactions)	Lung function Blood stream?
Ozone (O3) (terrestrial)	*Outdoor air* (vehicle and industrial emissions in reaction to sunlight)	Irritation / inflammation of eyes, nose, respiratory system Reduced lung function Exacerbation of chronic respiratory diseases
Volatile Organic Compounds (VOC or TVOC)	*Outdoor air* (vehicle and industry emissions) *Indoor air* (organic chemicals in building products and finishes; office equipment; aerosol spray; cleaning products; disinfectants; air fresheners)	Irritation of eyes, nose, throat Headaches, nausea Liver, kidney and central nervous system damage Cancer

3.1.3 Visual comfort

The health impacts of visual comfort in healthcare settings are reported in two broad categories: the impact of daylight / natural light, and the impact of access to views.

Research suggests that daylighting can (may)

- Reduce depression [39]
- Reduce pain medication intake [40, 41]
- Reduce stress for patients and caregivers [33]
- Enhance recovery from surgery [42]
- Reduce length of stay in hospital for some patients [43, 44].

Some studies provided nuanced results, such as:

- The effect of the seasonality and diurnal variation of daylight on heart attacks [45]
- The impact of sunlit rooms in reducing length of stay for bipolar depression [46] and severe and refractory depression [47]
- Reduced agitation in elderly dementia patients [48]
- Improved circadian rhythms such as sleep-wake and activity-rest cycles, and reduced duration of stay of patients with seasonal affective disorders (SAD) [49]
- Light therapy can improve sleep and reduce depression and agitation in persons with Alzheimer's disease [50].

A 2015 review of the evidence of links between daylight and health [51] indicates a range of benefits, such as:

- Improved vision and reduction in eye strain, myopia and headaches
- Improved sleep quality
- Reduced ADHD prevalence
- Prevention of obesity

A number of studies also report on the positive impact of daylight on healthcare workers, such as reduced stress, decreased errors, higher satisfaction, reduced absenteeism, and enhanced morale [12, 15, 52, 53]. For the elderly, additional benefits of addressing lighting (both daylighting and artificial lighting) include reduced falls and anxiety levels, and improved social contact, appetite, mood and self-confidence: contributing to a higher level of confidence and independence [12]. Despite these multiple benefits reported for patients, residents and staff in healthcare settings, Salonen highlights that there is a need to recognize that the lighting needs (amount and timing of different qualities of light) is not homogenous across all user groups [12].

Some research also points to a correlation between patients' exposure to natural or pleasant views and decreases in duration of stay, pain, post-surgical complications and mortality rate [17, 42]. Natural views in general were found to have a positive psychological effect on patients, even when that natural view may be artwork. Artwork depicting nature was shown to help reduce stress and pain of patients, compared to abstract artwork [15, 54].

This would perhaps point to the need to carefully consider the location of windows, to maximise the combined benefit of natural lighting, sunlight and pleasant views.

3.1.4 Acoustic comfort

Noise can be a health risk, contributing to increasing stress, blood pressure, and hypertension, and potentially contributing to cardiovascular disease [55]. Studies suggest a correlation between living near noisy urban areas and the chance of heart attack and obesity [17, 55]. High noise in the workplace was also found to increase fatigue, irritation, headaches and feeling sick [17].

Environmental noise measurements in hospitals show day time values of 37 – 88.6 dB(A) and night time values of 38.7 – 68.8 dB(A) [56]. The sources of noise in HCFs can include people's interactions (e.g., speech and movements), therapeutic equipment and procedures, building services (e.g., air conditioning ducts) and outdoor environment. The literature shows that high levels of noise in HCFs:

- Are correlated with increased stress and longer patients' recovery periods [15, 57, 58]
- Result in poor levels of comfort and high levels of annoyance for patients [55]
- Disturb patient sleep cycles (and hence recovery time) [15]
- Slow patient recovery, increase occurrence of medical errors, and increase incidence of rehospitalisation [56]

A long list of patient benefits attributed to reducing noise levels is provided in the review by [12]:

> *"improve sleep, reduce annoyance, improve satisfaction, reduce both pain and the use of pain medications, decrease psychological and physiological stress, reduce emotional exhaustion, reduce headaches, promote better communication between patients and family members, enhance patient privacy and confidentiality, improve safety, decrease heart and respiratory rates, decrease blood pressure, increase oxygen saturation, decrease confusion an disorientation, shorten recovery time and hospital stays, and reduce re-hospitalization."*

High levels of noise in healthcare environments can also indirectly affect patients through impact on staff stress levels, tension headaches, fatigue, and irritation, which consequently can result in reducing their empathy to patients and increase the likelihood of errors [15, 17]. Salonen's review includes other staff benefits of reducing noise: increased satisfaction, effectiveness and productivity; improved communication; and reduced medical errors [12].

> "There is a growing body of clinical research that shows that better acoustics leads to improved health outcomes. Well-designed, high quality spaces have been shown to facilitate a reduction in the use of analgesics, improved patient recovery times, increased staff efficiency and reduced staff turnover. Further, poor acoustic design of clinical, theatre and consultation areas can negatively impact the performance, communication and concentration levels of staff."
>
> NSW Health Infrastructure Engineering Services Guideline 2016
> https://healthfacilityguidelines.com.au/news/new-reference-nsw-health-infrastructure-engineering-services-guideline

3.2 Engineering and Indoor Environment Quality

This section examines some key design and operation guidelines and standards as they relate to the building services that contribute to IEQ in healthcare settings.

3.2.1 Thermal comfort

Six primary factors are considered to contribute to thermal comfort: the air temperature, radiant temperature, air speed and relative humidity of the occupied space, and the metabolic rate and clothing insulation level of the occupants.

Many buildings use the ASHRAE Standard 55 and Predicted Mean Vote (PMV) or Percentage Persons Dissatisfied (PDD) for designing the indoor thermal conditions. This and similar standards are rooted in research highly reliant on healthy, young adult (male) subjects (awake) in office type environments [59] and the concept that thermal comfort means thermal neutrality in a uniform steady-state environment. The PMV model, first developed 51 years ago, remains the most widely used approach to assessing indoor thermal comfort around the world [60].

Numerous research questions the applicability of PMV. In broad terms, the key problem associated with this model is that it does not differentiate thermal comfort based on age, gender, ethnicity, cultural preferences and norms, climatic variations, different types of occupants in the same space, or sleeping occupants [61]. The World Health Organisation (WHO), for example, identified the standard internal temperature in rooms for the elderly to be 2-3°C higher than 'comfort' temperatures for young adults [22], and Australian research suggests that the elderly can feel comfortable in a wider range of temperatures when compared to young adults (although ageing, dementia and pharmacological interventions can decrease their sensitivity to thermal changes) [62]. Several other studies show that the thermal preferences for older adults are different from ASHRAE standards, however the magnitude and direction of preferred conditions (above or below the PMV) for older adults when compared to younger adults was not consistent in all studies [22, 59].

Other studies demonstrate that PMV underestimates the thermal sensation of pregnant women [63] and that the thermal sensation of hospital staff varies depending on location, tasks being undertaken, and the associated clothing worn for those tasks, e.g., nurses, anaesthetists and surgeons in operating theatres [64]. Thermal preferences in hospitals have also been studied. A study in two hospitals in Bangkok's tropical climate showed the differences in acceptable temperature range for patients (21.8 -27.9°C), visitors (22.0 - 27.1°C) and medical staff (24.1 - 25.6°C), all of which were warmer than the Thai Standard for Environmental Sanitation and Safety in Hospital (20.0 – 25.0°C at 50 - 70% RH, for waiting rooms in outpatient department) [65]. A study in two hospitals in Saudi Arabia, where hospital wards have fixed set point temperature range (21 - 24°C), revealed significant thermal preferences for patients in different types of wards: cardiology (20.1 - 21.8°C); surgical (22.2 - 23.9°C); medical (24.8 - 25.3°C); oncology (25.3 - 26.8°C) [66]. A 2020 review of thermal comfort in hospital environments reports that 10 out of 12 studies that compared PMV with occupants' thermal sensation vote (TSV) concluded that PMV over- or under-estimated thermal comfort in hospital settings [67].

A 2016 review of the thermal environment in healthcare facilities [28] reiterates that international standards for thermal comfort are drafted for healthy people, and highlights that, within hospitals:

- Codes and standards focus on hygiene and safety parameters, not the thermal environment per se
- Temperature and humidity settings focus on controlling infection
- Thermal comfort standards are based on
  - Building occupants being awake (not sleeping)
  - Steady state conditions
- Patient groups and healthcare personnel may occupy the same space at the same time (but have different activity and clothing levels, and hence thermal needs)
- Operating rooms present additional challenges, with a range of activity levels and clothing types by staff, different patient requirements, and varying heat loads (e.g., from people, lighting and medical equipment)

The review highlighted the need to "reconcile the different thermal comfort requirements of different types of occupants"; better understand "the thermal environment conditions required by different spaces"; and find solutions to enhance patient and staff health outcomes. These needs are similar to those highlighted in a 2012 review of thermal comfort in hospitals [68].

This collective evidence calls into question the limitations and potential problems of HCFs relying on these approaches to establishing temperature set points, and for designing and operating HVAC systems to deliver these conditions [22].

So what options might there be to the PMV model? According to Lomas and Giridharan [69], BSEN15251 is a better fit for hospitals (compared with ASHRAE and CIBSE standards) because:

- It is "an adaptive thermal comfort standard based on limiting the deviation of operative temperature outside a defined envelope"
- It can be used at both the design stage (prediction) and operation stage (in use)
- It discriminates between spaces used for different purposes
- It allows for health providers to define the applicability of category boundaries (Cat I, II and III) and allowable deviations from these boundaries

Although both ASHRAE and the European Standard can incorporate the adaptive comfort model, the USA system is based on average monthly mean temperature (T_{mm}) whereas the EN standard uses a weighted running mean (T_{rm}) (equation shown in Figure 3-2). A comparison of the resultant temperature ranges for hospitals is shown in Table 3-3 (including Australian guidelines) and visualised in Figure 3-3. Note that the ASHRAE Adaptive Comfort standards are for non-conditioned buildings, and that in free-floating buildings (buildings without mechanical heating and cooling), neutral temperatures (in the context of occupant thermal comfort) are more closely linked to external temperatures.

$$T_{rm} = (1 - \alpha_{rm}) [T_{e(d-1)} + \alpha_{rm} T_{e(d-2)} + \alpha_{rm}^2 T_{e(d-3)} \ldots]$$

where α_{rm} is a constant between 0 and 1 which defines the speed at which the running mean responds to outdoor temperature, $T_{e(d-1)}$ is the daily mean outdoor temperature (°C) for the previous day, $T_{e(d-2)}$ is the daily mean outdoor temperature (°C) for the day before that, and so on.

Figure 3-2 Calculation of Running Mean Outdoor Temperature

Table 3-3 Thermal comfort standards (indoor operative temperature) in hospital settings

Zone	Temperature range and exceedance	Source
Single and general wards with supply only ventilation	18 – 28°C (dry bulb), with maximum of 50h/yr exceedance	UK Department of Health Technical Memorandum HTM03-01
Buildings with no mechanical heating/cooling	0.31°Tmm+15.3 to 0.31°Tmm+20.3	ASHRAE 55 Adaptive Comfort mode
Cat I: hospital wards Cat II: staff areas, consultation and administrative offices Cat III: public and circulation spaces	Cat I: 0.33°Trm+16.8 to 0.33Trm+20.8 Cat II: 0.33°Trm+15.8 to 0.33°Trm+21.8 Cat III: Max. exceedance of 3-5% of annual hours	Recommendation by [69] based on BSEN15251 (for hybrid buildings)
Patient Room Consult Rooms Laboratories Operating theatre	21-24°C (design temperature) 24°C (design temperature) 24°C (design temperature) 16-27°C (design temperature)	NSW Health Infrastructure Engineering Services Guidelines 2016
Class 9a and 9c buildings	PMV -1 to +1 =/> 95% of the floor area of all occupied zones for not less than 98% of the annual hours of operation of the building. PMV is to be calculated in accordance with ASHRAE Standard 55	NCC 2019 Volume 1 Amendment 1

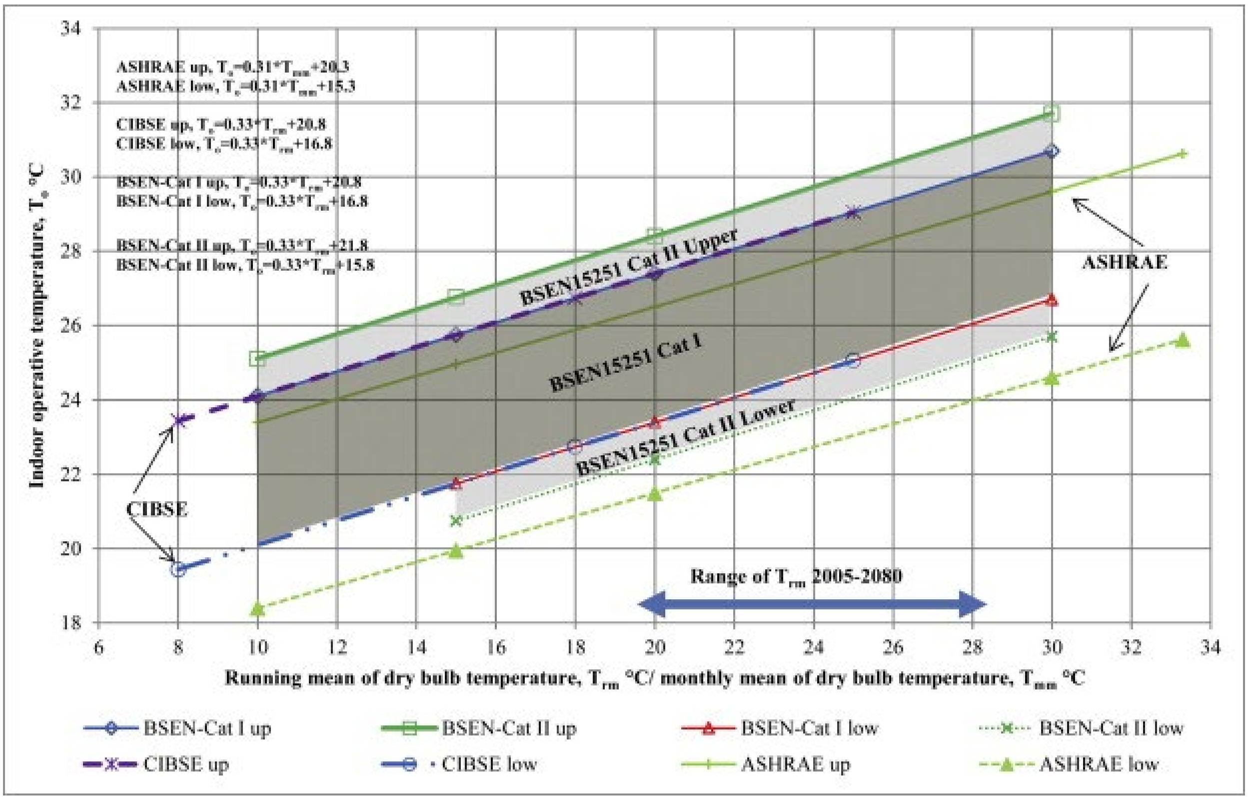


Figure 3-3 Comparison of ASHRAE, CIBSE and BSEN indoor operative temperatures [69]

3.2.2 Indoor air quality

A browse through the history of ventilation research and regulation reveals intriguing changes to 'recommended' ventilation rates ranging from 15L/s per person in 1890s to a low of 2.5 L/s in 1981, then an increase to current levels. Such variations could be attributed to the relative importance and state of understanding of drivers such as the contaminant of focus (body odour initially, then other contaminants), the concentration limits of various pollutants; building typology; and energy efficiency requirements [70]. The initial focus on odour extended to research on sensory pollution loads (olf/m^2 floor) and the development of an evaluation method: perceived IAQ (PIAQ). The limitations of this approach, as reported by Persily, included:

- Some contaminants are odourless
- Individuals can adapt to some odours over time (losing their sensitivity to the odour)
- Adaptation may not occur for other odours, and irritation responses may increase over time
- The sensory loads are averaged over a large number of individuals, and the derived ventilation rates are applied to the whole building (or building section)

The PIAQ was the basis for the ventilation rates (10 L/s per person) in ASHRAE Standard 62 – 2004a and CEN 1998: Indoor Environment Design Criteria. This ventilation rate was somewhat 'validated' by some research in office buildings that found that mechanically ventilated buildings were more likely to have sick building syndrome at ventilation rates < 10 L/s per person. Over time, ventilation research and resultant standards or regulations have considered the contaminant source (e.g., external or internal), floor area, air distribution effectiveness, and energy efficiency. The current four key functions of ventilation are illustrated in Figure 3-4. Each of these functions of ventilation requires different air flow rates, distribution and control (including control of infiltration), creating potential conflicts and trade-offs between the different functions.

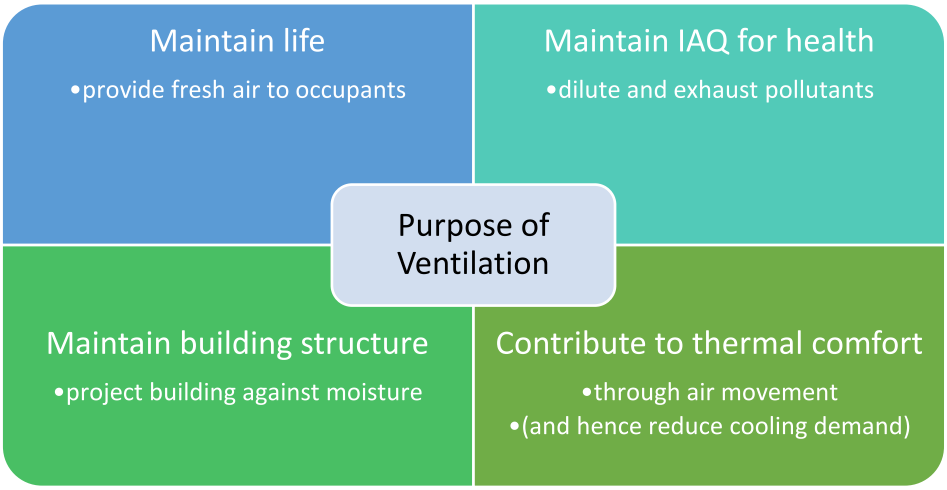


Figure 3-4 Four key functions of building ventilation

3.2.2.1 Outdoor air

Outdoor air is mixed with indoor air to achieve the functions shown in Figure 3-4. The two key challenges associated with introducing outdoor air into indoor environments are outdoor contaminants (particularly PM2.5 and tropospheric ozone) and moisture (relative humidity). The former presents health risks to occupants, and the latter presents risks to both the occupants and the building. Ventilation systems, regardless of whether natural, mechanical or hybrid, need to take into account the relevant characteristics of the outdoor air that directly impinge on achieving its functions. This means that attention must be paid to outdoor air, in particular the pollutant concentration, moisture content, temperature and movement of the outside air. Strategies that are responsive to these characteristics need to be implemented to ensure that the introduction of outdoor air does not make indoor environmental conditions worse. The key factors that contribute to ventilation parameters are visualised in Figure 3-5. Filter efficiency is communicated through Minimum Efficiency Reporting Values (MERV) rating from 1-16. The higher the rating, the better the filter is at trapping specific types of particles (0.3 – 10 microns). HEPA filters are high efficiency particulate air filters that remove at least 99.97% of particles of 0.3 microns (e.g., dust, pollen, mould, bacteria). These filters need period cleaning and replacement in order to perform their function of removing pollutants to protect human health.

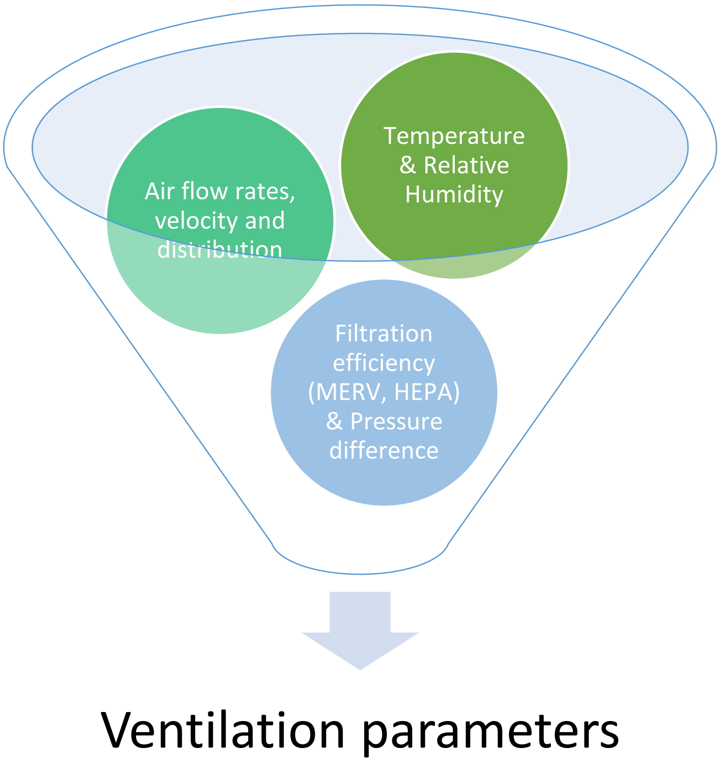


Figure 3-5 Integration of ventilation parameters

Working through the IEA's Annex 5 (Air Infiltration and Ventilation Centre AIVC), Borsboom et al provide an overview and prioritisation of pollutants, identification of potential health effects and control strategies to reduce negative health effects [71]. In highlighting the need to have better insight into outdoor sources of pollutants and pollutant behaviour indoors, it details specific polluting compounds that can have an outdoor source, including Acetaldehyde, Acrolein, Alpha-Pinene, Benzene, CO, CO_2, Ethylbenzene, Formaldehyde, NOx, Ozone, Phthalates, PM2.5 / PM10, Polycyclic aromatic hydrocarbons (PAHs), SO_2, Toluene and Ultra fine particles (UFPs). This report was important in highlighting the lack of a universal approach to addressing the potential hazards posed by a diverse range of compounds from a diverse set of sources nor a method for quantifying the benefits of reducing concentrations to non-hazardous levels. It reveals that ventilation research is now focused on indoor air quality and health, requiring a better understanding of pollutant exposure, emission rates, dispersion processes and loss mechanisms such as chemical losses or deposition. It elaborates the role of ventilation in managing health risks, and the need for the development of methods to quantify the benefits and limitations of ventilation for this purpose.

AIVC ventilation research continues to examine the link between ventilation, pollutant control and health. In particular this IEA work is examining the role of ventilation in low energy buildings and changing global challenges. Some questions to be addressed in the coming decade include:

- Will the nature and distribution of outdoor air pollutants change as our stationary energy and transport systems are increasingly electrified? In particular, how will electrification of these systems impact on the prevalence of PM2.5 and tropospheric ozone? How could this impact on ventilation options?
- Can the world afford for mechanical systems to be installed in all buildings globally (arguably the systems providing greatest control of outdoor pollution), or should we be proactively examining hybrid ventilation options that can make greatest use of ambient conditions when the outdoor air is of high quality (in terms of pollution, temperature and humidity)?
- Have we adequately defined indoor environment conditions that protect the health and wellbeing of occupants, are low energy, and yet account for different climates, cultures, building types, and occupant demographics?
- Ventilation and heating and cooling technologies to date have focused on average weather conditions. What new technologies and design strategies are needed for managing extreme events? How do extreme weather conditions impact on outdoor air pollutants and humidity?

The NCC does not specify how buildings should be ventilated, but it requires ventilation to be ‘sufficient’ to ensure that contaminant limits are not exceeded (Table 3-4). It is assumed by the writers of this report that this short list of pollutants is a ‘starting point’ for the construction industry, not an exhaustive list of all pollutants of concern.

Table 3-4 Maximum contaminant limits for indoor air quality (NCC 2019 Vol. 1 Table FV4.1)

Pollutant	Averaging time	Maximum air quality value
Carbon dioxide CO_2	8 hours	850 ppm
Carbon monoxide CO	15 minutes | 30 minutes | 1 hour | 8 hours	90 | 50 | 25 | 10 ppm
Formaldehyde CH_2O	30 minutes	0.1 mg/m^3
Nitrogen dioxide NO_2	1 year | 1 hour	0.0197 | 0.0987 ppm
Ozone O_3	8 hour, daily maximum	0.0473 ppm
Particulate matter $PM_{2.5}$	1 year | 24 hour (99th percentile)	10 μg/m^3 | 25 μg/m^3
Particulate matter PM_{10}	1 year | 24 hour (99th percentile)	20 μg/m^3 | 50 μg/m^3
Total Volatile Organic Compounds TVOC	1 hour	500 μg/m^3

Indoor pollutants considered relevant in the context of low-energy residential buildings (e.g., of likely relevance to residential aged care) are shown in Table 3-5 [72].

Table 3-5 Pollutant relevant to low-energy residential buildings

Pollutant	Long-term exposures		Short-term exposures	
	ELV	Averaging Period	ELV	Averaging Period
Acetaldehyde	48	1 yr	-	-
Acrolein	0.35	1 yr	6.9	1 hr
Alpha-Pinene	200	1 yr	-	-
Benzene	0.2	Whole life (carcinogenic risk level 10^{-6})	-	-
Carbon dioxide	-	-	1000	8 hr
Formaldehyde (CH_2O or HCHO)	9	1 yr	123	1 hr
Naphthalene	2	1 yr	-	-
Nitrogen dioxide	20	1 yr	470	1 hr
PM10	20	1 yr	50	24 hr
PM2.5	10	1 yr	25	24 hr
Radon	200	1 yr	400	8 hr
Styrene	30	1 yr	-	-
Toluene	250	1 yr	-	-
Trichloroethylene	2	Whole life (Carcinogenic risk level 10^{-6})	-	-
TVOC	-	-	400	8 hr
Mould	200	1 yr	-	-
Concentration is given in ug/m^3 except for carbon dioxide which is in ppm, radon which is in Bq/m^3, and mould given in CFU/m^3.				

The limitations of this data, as reported by Adabie [34], include:

- There is limited data regarding pollutant levels in modern low energy buildings
- Data often only includes aggregated pollutant concentrations, without details of specific pollutants or the ventilation context
- Pollutant concentration data often doesn't correspond to the long-term and short-term exposure periods
- Some pollutant measurements are not measured continuously but are taken immediately after building completion (which may result in higher concentration levels than 'normal')
- Real-time measurement of some pollutants (e.g., VOCs) is currently quite expensive
- It is difficult to simulate IAQ in building modelling, due to challenges in finding relevant input data

Another limitation, as reported by [73], is that most ventilation studies have been undertaken in temperate climates, resulting in most guidelines being published in countries with temperate climates. There is, therefore, a substantial knowledge gap in relation to pollutants and ventilation strategies relevant for the tropics.

3.2.2.2 IAQ in HCFs

(NOTE: this section excludes recent (2020-21) publications relating to COVID-19 and ventilation.)

A very recent review of IAQ (chemical pollution) in patient wards [74] highlights that hospital IAQ microclimate parameters typically include temperature (T), humidity (RH), carbon monoxide (CO), carbon dioxide (CO_2), total volatile organic compounds (TVOCs), particulate matter (PM) and bacteria. T and RH are frequently measured, and to some extent CO_2, however there is little understanding of, and accounting for, the complex interactions between parameters, for example the relationship between

- T and RH and microorganism growth and VOC emissions
- Direct sunlight and daylight and infection suppression
- Window openings and PM concentrations
- Cleaning solutions (for infection control) and TVOCs
- Ventilation rates / air distribution effectiveness and TVOCs or infection control
- Inadequate maintenance of HVAC systems and microbial growth
- Door motion and indoor air fluxes
- Building fit-out materials and VOCs
- Occupants, occupant movement, shedding of particles, and resuspension of microbial materials
- Medical activities, equipment and anaesthetic gases, and indoor pollutants

The type of ventilation system also impacts on health outcome. An IAQ study of different departments in 37 Taiwanese hospitals [35] reported:

- Higher CO concentrations in wards
- Higher TVOC levels in wards (ICU and dialysis) and pharmacy departments
- Filtration systems in central air conditioning plant effectively removed aerosol pollutants (PM and fungi) from outdoor air
- CO levels higher in hospitals with centralised mechanical air conditioning, regardless of whether the system was air handling units (AHU), fan coil units (FCU) or mixed type (AHU/FCU).
- Environments with window type or single-split air conditioners had higher levels of PM2.5, PM10 and fungi, but lower levels of CO.

Another Taiwanese study [6] proposed an IAQ monitoring system for healthcare environments using CO_2 sensors connected to a Zigbee wireless network that would then activate ventilation or air purification devices. This was at the time of early ‘big data’ and ‘smart’ systems.

A very recent South Korean IAQ study [36] focused on facilities with occupants susceptible to air contaminants: hospitals, specialised hospital, aged care facilities and postnatal care facilities. It compared IAQ concentrations (CO_2, NO_2, O3) of these facilities with those in general facilities (e.g., department store, museum, movie theatre etc). Key findings include:

- Average concentrations of these pollutants did not exceed Korean IAQ standards, but CO_2 and NO_2 concentrations were higher, and O_3 concentrations were lower, in the ‘susceptible’ facilities compared to general facilities

- There were significant correlations between CO_2 and NO_2, and between NO_2 and O_3
- Concentrations were affected by the climate: CO_2 concentrations were correlated with temperature; NO_2 concentrations were negatively correlated with relative humidity; and O_3 concentrations were correlated with both temperature and relative humidity (water molecules play an important role in the formation of ozone)
- Mean concentrations of the three pollutants varied by season, with CO_2 and NO_2 highest in spring, and O_3 highest in summer.

A study of aerosol infection risk in an Australian major hospital [75] assessed the impact of ventilation rates on infection risk from three airborne pathogens: influenza, tuberculosis and rhinovirus. It found that the risk of patients getting infected (from a previous patient with influenza) in an outpatient consultation room ranged from 3.6 – 20.7%, depending on the duration each person occupied the room. Some interesting findings include:

- The outpatient consultation rooms had much lower proportion of outdoor air (compare to the lung function laboratory and emergency department isolation room)
- Outdoor air ratios did not vary with season
- Air exchange rates were affected by open / closed doors, and seemed to be affected by location of doors with respect to location of return air vents

A German study [76] found that a unidirectional displacement airflow (UDF) system reduced the airborne bacteria burden in operating theatres by 90%. According to the authors, the standard for operating theatres to date has been turbulent mixing ventilation systems (TMV) that stream high velocity sterile filtered air into the surgical field. This creates turbulence, however, that makes bacteria airborne and creates discomfort for surgical staff. It is also dependent on the room volume and focuses on reducing bacterial burden, not replacing contaminated air. In contrast, the UDF system, similar to laminar airflow (LAF) systems used in clean rooms, discharges sterile filtered air from the ceiling into the surgical zones, replacing contaminated air and minimising turbulence.

These six studies suggest that it is important to measure different pollutants (indoor and outdoor concentrations), understand the source of the pollutants (indoors or outdoors) and the impact of environmental conditions, and use that information to inform ventilation strategies that improve IAQ. An integrated approach to IAQ was presented in [5], proposing a “decalogue” of “best practices” that included consideration of the location of hospital rooms (in relation to outside air pollutants and indoor layout); room layout; microclimatic parameters (T, RH, CO_2, TVOCs, PM_{10}, $PM_{2.5}$, bacteria, air change rate, surface area of furnishings); ventilation system (dilution, filtration and air purification parameters); materials and finishings (limiting VOCs); furniture and equipment (limiting VOCs); cleaning activities and products (limiting VOCs); maintenance activities (active and passive sampling); and users (the role of patients, visitors and clinical and non-clinical staff). (Refer to Figure 3-6.)

Figure 3-6 Decalogue of IAQ practices in patient rooms (Based on [5])

> "An air quality metric should identify when the quality of indoor air is unacceptable and should be based on its effects on human health and comfort, acknowledging that they may not be immediate."
> B. Jones. AIVC VIP36 Metrics of Health Risks from Indoor Air

3.2.3 Visual comfort

Lighting (and ventilation) is included in Australia's National Construction Code (NCC) Part F (2019 Amendment One Edition 1). The objective of this part (F04) is to safeguard occupants (from injury, illness or loss of amenity due to isolation from natural light and lack of adequate artificial lighting; and illness or loss of amenity due to lack of air freshness). The NCC requires natural light to be provided to all sleeping spaces in hospitals and residential aged care buildings (Class 9a and 9c buildings). The Average Daylight Factor is calculated for each window and needs to be not less than 2%. This metric and other additional visual comfort metrics are briefly described in Table 3-6.

Table 3-6 Visual comfort metrics

Metric	Explanation
Average Daylight Factor (Required by NCC)	The average illuminance (from daylight) on a horizontal plane in a room (compared to the amount of unobstructed outside daylight under overcast conditions)
Continuous Daylight Autonomy	Fraction of occupied hours met by daylight
Useful Daylight Illuminance (UDI)	The % of occupied hours when a target illuminance range is met by daylight
Daylight Glare Index (DGI)	Predicts discomfort or reduction in visibility from daylight
Luminance contrast ratio (relates to daylight)	The contrast between glazing and surrounding surfaces
Unified Glare Rating (UGR)	Predicts level of discomfort produced by light sources
Colour Rendering Index (CRI)	Accurate representation of colours under artificial light (i.e., as they would appear under natural light)
Correlated Colour Temperature (CCT)	The hue of light output compared to a black body radiator emitting an equivalent hue. Denoted in degrees kelvin (K)

Visual comfort (access to daylight and natural views) is affected by window size, position and type, the geometry and finishes of the interior space, and by glare. The potential challenges associated with increasing window area to provide visual comfort can include increased construction costs, increased space heating / cooling requirements (because glass has a lower thermal resistance the opaque walls); how to control for glare; and how to optimise window to wall ratio [77]. These challenges can be met, to varying degrees, by careful selection of the glazing, and the use of fixed and/or dynamic window shadings. The selection of appropriate control mechanisms requires careful evaluation of limitations (e.g., seasonal effectiveness of fixed external shading; reliance on occupant action for operating internal shading) and cost implications (e.g., construction costs versus building control complexity versus whole of life maintenance and operation costs). The importance of using multiple metrics was highlighted in [78] who found that while daylight factor, illuminance and luminance levels can be better than requirements indicated in regulations, occupant visual discomfort can still occur (e.g., if glare is not considered).

The NCC 2019 does not provide recommendations of illuminance levels (these are in AS/NZS 1680.2.5), other than a minimum illuminance of not less than 20 lux, appropriate to the function of the building / part of building, to enable safe movement. It does, however, specify energy efficiency performance benchmarks, as shown in Table 3-7. Note that these power densities are significantly less (i.e., more energy efficient) than those contained in current healthcare facility guidelines (e.g., the NSW Health Infrastructure Engineering Services Guidelines 2016).

Table 3-7 Maximum illumination power density (NCC 2019 Vol 1 Table J6.2a)

Space	Maximum illumination power density (W/m^2)
Health-care – infants' and children's ward and emergency department	4
Health-care – examination room	4.5
Health-care – examination room in intensive care and high dependency ward	6
Health-care – all other patient care areas including wards and corridors	2.5
Kitchen and food preparation area	4
Laboratory – artificially lit to an ambient level of 400 lx or more	6

The NSW Health Infrastructure Engineering Services Guideline 2016, in contrast to the NCC, does require lighting systems to deliver user comfort, comfort control, a healthy environment, task visibility and good visual performance (in addition to the energy efficiency). It promotes the use of qualitative assessment of visual comfort rather than quantitative assessment such as illuminance levels. It also requires consideration of CRI, CCT and glare. Consistent with the NCC, it acknowledges the importance of natural light for patient care areas and requires consideration of daylighting as a means of reducing electric power (but only with careful consideration of daylight control).

3.2.4 Acoustic comfort

Achieving acoustic comfort can be challenging because of potential conflicts with other indoor environment conditions, sometimes requiring occupants to choose between thermal comfort and a quiet indoor environment [77], for example:

- Natural ventilation (e.g., open windows and open concept design can allow unwanted noise intrusions)
- Daylighting (e.g., glazing and open concept design can enable noise transmission)
- Exposed thermal mass for enhancing thermal comfort (hard smooth surfaces are poor sound absorbers)

The three main approaches to acoustic solutions are

1. Absorbing noise (i.e., reducing sound reflectance)
2. Blocking noise (i.e., isolating the source of the sound)
3. Covering noise (e.g., white noise generators)

In addition to the beneficial effects of noise reducing finished for patients and staff [12], using sound absorbing materials reduces sound reverberation time and has been shown to result in improved speech intelligibility which in turn reduces the risks of conflicts and errors [57]. Speech intelligibility is conceivably of very high value in hospitals (with high levels of ambient noise, and the importance of clear communication between staff, and between healthcare workers and patients), and in aged care facilities (with a resident population with a high likelihood of diminished hearing acuity and/or diminished vocalisation).

Part F5 of the NCC contains the specifications for sound transmission and insulation, but only relates to residential buildings (class 2, class 3 and class 9c residential aged care). The objective is to safeguard occupants from illness or loss of amenity due to ‘undue sound transmission’ between adjoining single occupancy units, and between single occupancy units and common areas. This includes meeting performance requirements for sound transmission through floors, walls, service penetrations and doors.

Some metrics used in Acoustic Comfort are explained in Table 3-8.

The NSW Health Infrastructure Engineering Services Guideline again demonstrates a more wholistic approach to acoustic comfort, specifying different acoustic requirements for clinical areas, public areas and back-of-house areas, including

- dB limits for continuous and intermittent noise levels
- speech privacy requirements for different areas within hospitals
- wall and floor impact sound isolation
- room reverberation time

The Guideline also attempts to address key sources or carriers of noise by incorporating considerations of environmental noise, architecture acoustics and building services noise and vibration. While mechanical ventilation systems can be a means of covering noise, they can also be a source of unwanted noise. Neither the NCC nor the Health Infrastructure Engineering Services Guideline appear to consider speech intelligibility.

Table 3-8 Metrics used in Acoustic Comfort

Metric	**Explanation**
Sound Transmission Class (STC)	A surface's ability to block sound from being transmitted
Noise Reduction Coefficient (NRC)	The fraction of sound that is absorbed by a material upon hitting it; determined at octave bands.
Weighted Sound Reduction Index (Rw)	The sound insulation property of walls, floors, windows, doors. Expressed in decibels (dB). The higher the figure, the better sound isolation.
Spectrum adaption term (Ctr)	Used to modify the Rw to account for noise sources with a large low-frequency component (e.g traffic, music)
Speech Intelligibility Index	The % of words clearly comprehended by listeners in a room
Ambient Noise Level (dB)	The magnitude of background noise Continuous | intermittent
Room reverberation time (RT)	The time it takes for a sound in a room to decrease by 60dB after a source stops generating sound (measured in seconds)
Impact sound isolation	The sound generated through building surfaces when one objects hits another

3.3 Resilience and Indoor Environment Quality

One of the key concerns of building and indoor environment researchers is the impact of climate change on buildings and their occupants, in particular the concern about overheating risk. Possible contributors to overheating risk, as discussed in the literature, include:

1. *Energy efficiency strategies* implemented to reduce greenhouse gas emissions
    a. Increased thermal performance requirements have often resulted in higher insulation levels that, in some climates and building contexts, 'trap' heat in the building
    b. More airtight buildings (i.e., reduced air leakage / infiltration)
    c. Use of high performance glazing and windows, leading to higher glazed area (resulting in limiting heat loss during cold seasons, but potential to increase heat gain in hot seasons)
2. *Increase in external ambient temperature* due to the changing climate and to the urban heat island effect (note that neither are typically included in design considerations or modelling software used for regulatory and design purposes)
3. *Changes in internal heat gains* during operation (i.e., factors not considered at the design stage e.g., due to poor communication of performance objectives and lack of integrated design process).

While overheating risk is starting to appear in some building regulations, a review of the development of overheating criteria [79] revealed some significant limitations, as summarised and commented on in Table 3-9.

Table 3-9 Limitations of current overheating criteria in buildings

Limitations of current overheating criteria	Comment
Buildings are allowed to exceed a certain upper temperature limit for a small number of occupied hours annually	No indication of what occupants are meant to do on those occasions. Exceedance allowance is based on annual hours, not exposure limits for occupants
Process requires prediction of performance (overheating potential) in design, not in use	No requirements to report on actual overheating
Criteria apply to the whole building, and only to occupied hours not total hours	No consideration of different requirements for different zones (e.g., sleeping zones) No consideration of buildings that are occupied 24/7
Compliance (with overheating requirements) is modelled using historical typical (average) weather data (TRY or TMY)	Future weather files are not used to model how buildings may perform in the climate in which they will operate during their expected life

These issues are a focus of current international collaboration through IEA Annex 80 that focuses on resilient cooling. A 2021 publication presents a conceptual model of a resilient cooling system that is centred on people, and the buildings, technologies and the energy infrastructure on which they rely to provide a safe indoor environment [29]. This framework (shown in Figure 3-8) combines features of Disaster Risk Management (DRM), Natural Hazards management, and properties of socio-economic and engineered systems. It presents a view that resilience is a property of functions and systems; that resilience is both a process and an outcome; and that strategies to improve resilience can provide co-benefits (the ‘resilience dividend’).

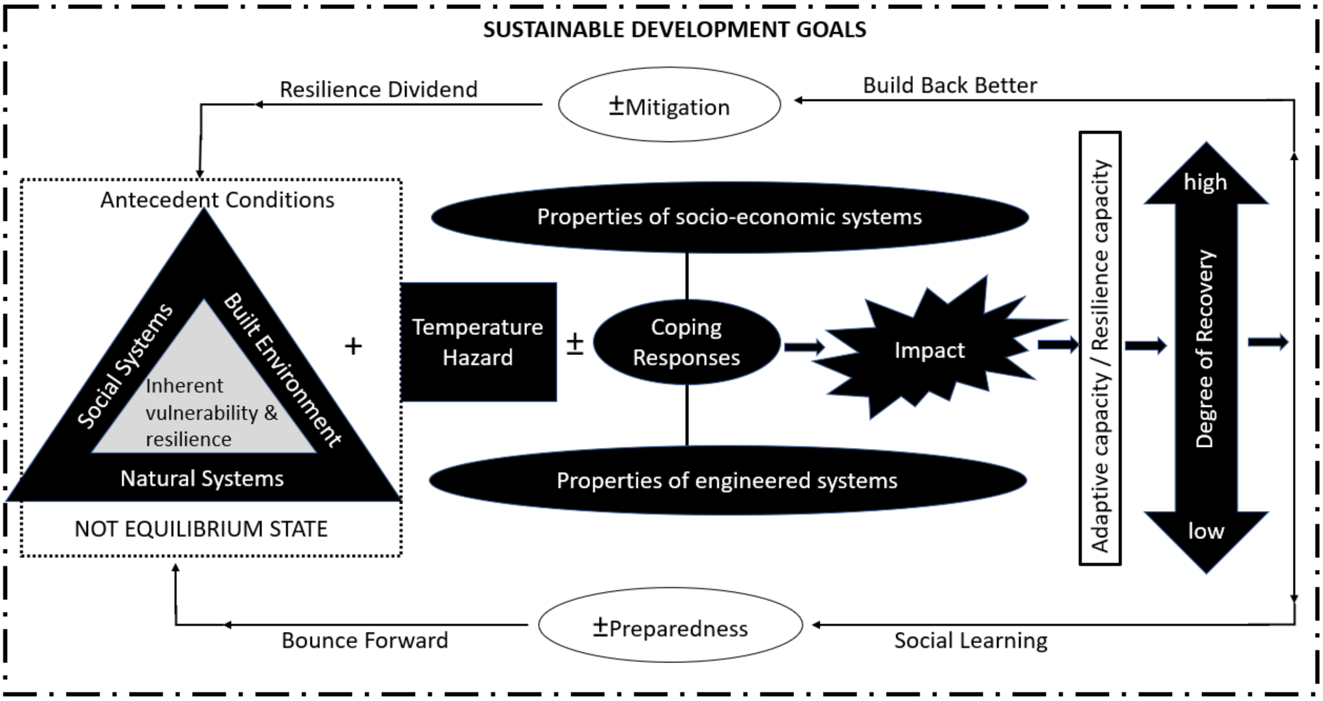


Figure 3-7 Conceptual model of resilient cooling

Annex 80 work is continuing, bring together researchers from 20 countries to:

- Provide a framework for evaluating cooling technologies in the context of heat waves and power outages [80]
- Review resilient cooling strategies [81]
- Develop future climate files (globally) for use in simulations of active and passive cooling strategies
- Collate and develop key performance indicators for evaluating and comparing solutions
- Evaluate Standards and policies to support implementation.

A preliminary broad set of KPIs has been proposed and is summarised in Table 3-10.

In addition to this set of work, a number of papers from other researchers have investigated resilience in healthcare facilities specifically, with a particular focus on overheating and energy risks. Key findings from each of these papers is summarised in Table 3-11.

Table 3-10 IEA Annex 80 Resilient Cooling proposed KPIs (May 2021)

Building quality metrics relating to indoor thermal conditions	
Indoor Overheating Degree (IOD)	A measure of the overheating of an indoor space. Summation of positive values of the difference between zonal indoor operative temperature and the zonal comfort limit temperature, averaged over the sum of zonal occupied hours. Corresponds to weighted unmet hours (EN TR 16789-2:2019) and weighted exceedance hours (ASHRAE 55 2020)
Ambient Warmness Degree (AWD)	The measure of the heat stress of an outdoor environment. The summation of positive values of the difference between the outdoor air temperature and a fixed base temperature (to be defined).
Overheating Escalation Factor (OEF)	The proportion of IOD and AWD
Unmet Hours	Number of hours of occupation outside a zonal comfort criterion within a given time of zone occupation. Annex 80 will use unweighted unmet hours (% outside a given range), expressed for every month
Passive Survivability	The ability to maintain safe indoor thermal conditions in the absence of active cooling
Thermal Autonomy	The fraction of time a building can passively maintain comfort conditions without active systems. Expressed as % of hours.
Recovery time	Time required to recover from a failure to the designed thermal condition. Expressed in hours.
Energy metrics	
Annual energy demand intensity	Annual cooling / heating load per conditioned floor area Annual cooling / heating source energy per conditioned floor area Expressed in kWh/(m^2.a)
Annual cooling source energy saving intensity	Annual reduction of source energy for cooling, per conditioned floor area, that can be achieved by a specific (resilient) cooling measure, against a conventional cooling solution without this specific (resilient) cooling measure. Expressed in kWh/(m^2.a)
HVAC and Grid Metrics	
Seasonal Energy Efficiency Ratio (SEER); Seasonal Coefficient of Performance (SCOP)	The seasonal efficiency (ratio between useful heating or cooling output and power input) of heating and cooling technologies. Power input to include all auxiliary energy inputs required by the system (e.g., compressor, fans, circuit pumps, actuators, controls)
Reduction in peak source power demand density	The annual reduction of source peak power demand, relative to floor area, that can be achieved by a specific (resilient) cooling measure, against a conventional cooling solution without this specific (resilient) cooling measure. Expressed in W/m^2. May be extended to include number of annual hours that grid power demand exceeds grid power supply.

Table 3-11 Selected papers discussing overheating and energy risks in HCFs

General Topic	Key points	Title / Reference
Threat of overheating in buildings	Climate change increases threat of human heat stress inside buildings. Proposes a heat-safety metric for design and building regulation.	*Overheating and passive habitability: indoor health and heat indices* [82]
Current and future risk of overheating in residential care and extra-care homes	Aged care facilities need to be future-proofed against climate change and overheating. Little awareness by designers of overheating risk and long-term adaptation options (passive, semi-active and active). Design needs to focus on long-term planning rather than near future.	*Care provision fit for a warming climate [83]*
Review of hospital disaster resilience indicators	Indicators fall into 3 domains: constructive, infrastructural and administrative resilience. Subdomains of infrastructural resilience include power and HVAC (and fuel) NOTE: Maintenance of IEQ not included in subdomains	*Towards developing a model for the evaluation of hospital disaster resilience: a systematic review [84]*
Climate change risks and opportunities for Australian hospitals	Four identified objectives (to ensure continuity of service) relate to physical integrity, essential building services, inter-agency communications and access (transport routes). Design and Facilities Management need adaptation strategies to mitigate risks and maximise significant social, economic and health opportunities.	*Climate change risks and opportunities in hospital adaptation* [85]
Overheating risks, health impacts and power failures	Passive survivability is impacted by power failure during extreme heat conditions. The impact of different energy efficiency strategies to improve heatwave resilience, depends on specific building characteristics and climate (and hence makes national guidelines less useful). There is a need for a clear definition of thermal resiliency metrics	*Synergies and trade-offs between energy efficiency and resiliency to extreme heat – a case study* [86]
Power outages in healthcare facilities	Short and longer-term power outages can have severe impacts on HCFs. Outpatient medical care, residential aged care and at-home care are affected by short-term power outages, indirectly impacting hospitals. All healthcare facilities, including hospitals, are likely impacted if outages > 24 hours. Some services that are essential for the proper functioning of healthcare facilities may not be	*Scenario-based impact analysis of a power outage on healthcare facilities in Germany* [87]

	included in emergency power system design (e.g., HVAC).	
Overheating risk and older people	In UK, building design is focused on keeping occupants warm, with no consideration of needing to keep them cool Older people's thermal comfort needs are highly diverse, having implications for building design, building services and energy demand	*Designing for an imagined user: Provision of thermal comfort in energy-efficient extra-care housing [88]*
Health and heat indices	Literature on indoor heat-health thresholds in non-industrial settings is limited. Only two existing heat indices address all six thermoregulation variables, have a heat stress threshold, and are included in existing occupational standards for heat stress measurement and monitoring: Wet-bulb globe temperature (WBGT) Predicted heat strain (PHS)	*Overheating and passive habitability: indoor health and heat indices [82]*

3.4 Smart Devices and Indoor Environment Quality

Smart phones, smart devices, smart homes, smart cars: are there commonalities?

An Ambient Assisted Living (AAL) system is an Internet-of-Things (IOT) ecosystem of wearable and non-wearable sensors, devices, hardware, wireless connectivity and software applications. AAL systems, enabled by advancements in electronics and computing, have been developing particularly in the last decade as a response to ageing populations (and associated healthcare costs), moves towards personalised health care, and changes in society expectations regarding where and how health care should be delivered [89-91]. Such systems could include:

- Health status sensors in wearable devices and medical devices (e.g., cardiovascular, body temperature, hydration, body motion)
- Activity status sensors (e.g., exercise levels, Activities of Daily Living (ADL))
- Mental and social-well being status (e.g., engagement with exergame and immersive environments)
- Indoor environment quality (e.g., temperature, humidity, air quality, light, noise)
- Appliance control (in integrated systems, control of appliances such as fans or air-conditioners in response to sensor feedback)
- User interfaces ('resident' and primary care giver).

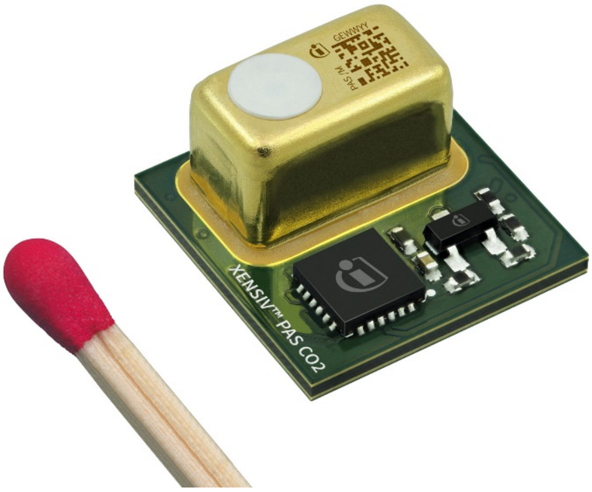
Key challenges within the AAL context, as reported by the research, include:

- Low levels of standardisation (of sensors and associated IT) and modularity, that inhibit interoperability and expansion capability
- The large amount of data (how to manage it, and make sense of it)
- Non-active involvement of users (not engagement in the design process; limited feedback to system designers; unappealing or non-verified user-interfaces)

- The need to consider the energy efficiency of the system
- Limited approaches to full integration, functionality and automation (e.g., with smart home technologies and indoor environment control).

These challenges are similar to those faced by smart homes (e.g., home automation and home energy management systems), smart phones, and smart cars.

The automotive industry has addressed some of these challenges already, as they have moved from mechanical systems to electronic systems to improve the physical and environmental performance of vehicles. Significant advances in micro-electronics have made this possible. Modern vehicles have multiple sensors (estimated to be in the range of 60 – 100) that are used in numerous systems, such as user comfort and control, chassis stability, safety mechanisms, power train, user interfaces (infotainment systems), etc. This industry has a standard specification (AEC-Q100) for packaged integrated circuits (ICs) that measures strength, safety, reliability and overall viability, under different conditions and to different performance level requirements. The specification of components that meet this standard underpins interoperability and long-term functional reliability (e.g., consumers expected to keep cars for over 10 years). The data from these sensors is processed onboard in real time, to enable continuous control and optimisation. While it is predicted that automotive electronics may account for a third of the costs of future vehicles, they enable new features such as autonomous driving, high power EVs, and high-speed and secure communications and infotainment [92].



This Photo by Unknown Author is licensed under CC BY-SA

So what might this mean for the potential to integrate health and energy considerations in healthcare facilities? Figure 3-8 presents a view of what such a ‘system framework’ might look like and Section 4 discusses some of the aspects of integration that would need to be considered and proposes a suite of metrics for consideration by healthcare facilities.

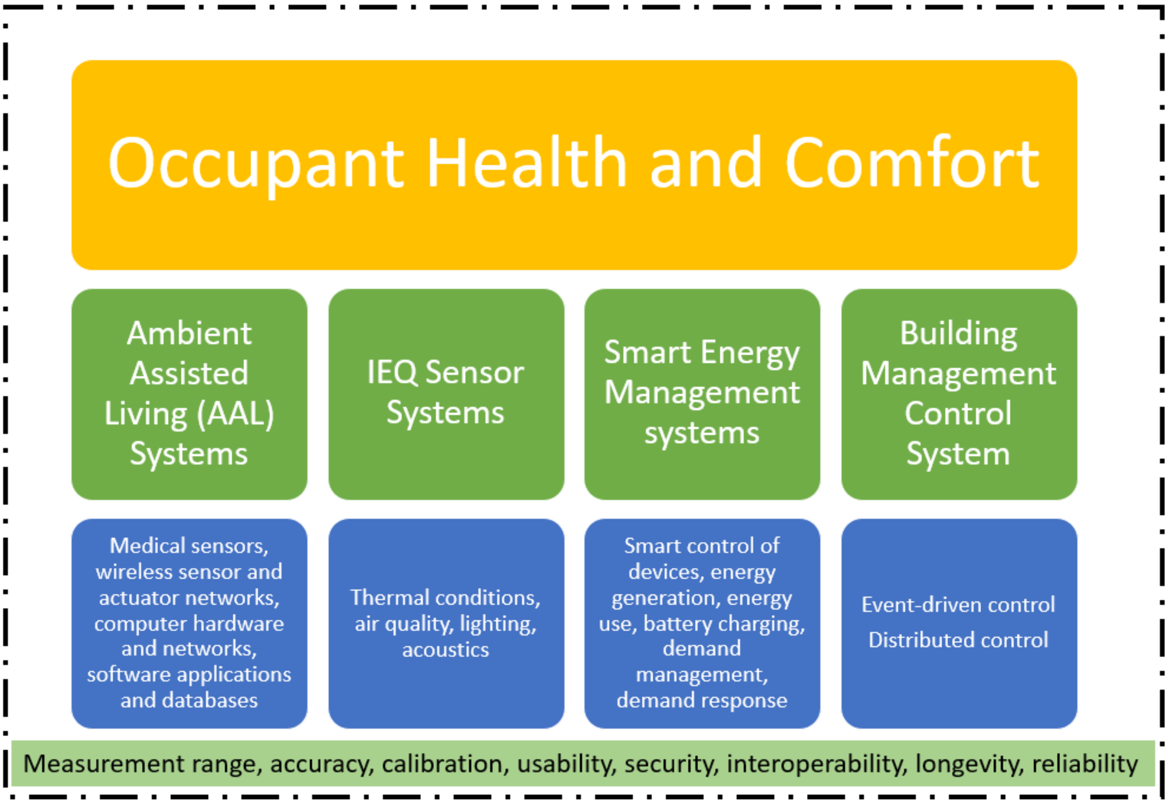


Figure 3-8 Vision of integrated health and energy systems

4 IS INTEGRATION OF ENERGY AND HEALTH POSSIBLE?

This section considers the implications of the evidence presented in the previous section, in terms of HCF energy use and demand, and the potential opportunities for bridging the gap between healthcare KPIs and building operation KPIs.

4.1 Interactions between IEQ and energy systems

Energy is needed to condition the outdoor air (heat, cool, humidify, dehumidify) regardless of whether this outdoor air is via a ventilation system or via infiltration (leakiness or openings), and to power systems like fans and air cleaning devices (e.g., electrostatic precipitation, ionisation, plasma or photocatalytic oxidation) that contribute to indoor air quality [34]. Obviously, energy is also used to power lighting. The interactions between the four IEQ parameters and energy is quite complex, but an attempt to visualise the relationships is shown in Figure 4-1 (incorporating the work of [77]). The figure highlights the interconnectedness between all parameters, pointing to the need for considering wholistic solutions that result in co-benefits.

Such an integrated approach is not obvious in Australia's NCC that has an energy objective (to reduce greenhouse gas emissions) that is not explicitly connected with the health and amenity objectives (to safeguard occupants from injury, illness or loss of amenity).

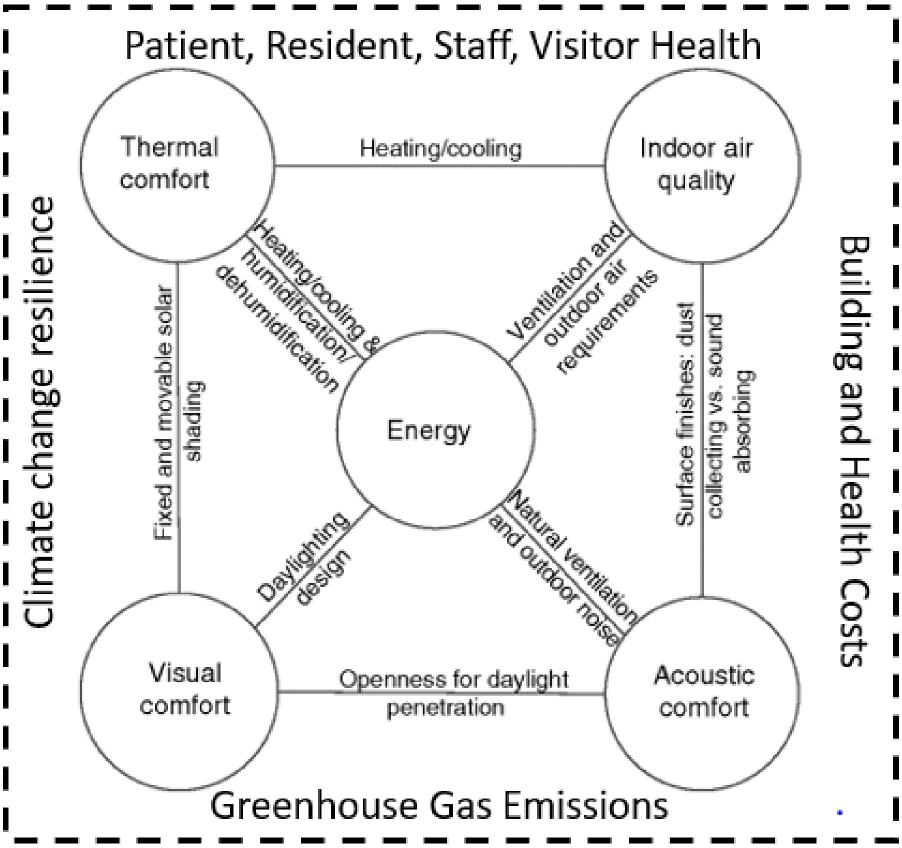


Figure 4-1 Interactions between IEQ, Energy, Cost and Climate Change

Some aspects of integration emerged from a 2015 Review of IEQ (totality of the four aspects) [4], including:

- There is a need for the validation of IEQ parameters of measurement as a basis for the development of an integrated IEQ performance evaluation model
- The relationship between subjective occupant surveys and objective physical measurements as assessment methods of IEQ in buildings needs to be established
- There is a need to determine IEQ comfort levels acceptable to all the occupants / uses
- A model indicative of the performance of IEQ in buildings should be inclusive and centred on the occupants' satisfaction with the IEQ

Integrated IEQ performance that is centred on occupant health, not just satisfaction, will also need an evaluation framework that

- Validates IEQ parameters and assessment methods (both qualitative and quantitative)
- Enables HCFs to achieve environmental sustainability objectives as well as improve patient health outcomes, and staff well-being and productivity [93]
- Addresses the different perspectives of staff and facilities managers regarding if and how IEQ performance requirements are being achieved [94]

Some of the challenges associated with developing such a framework, as identified by [95] as part of IEA Annex 5 (AIVC), are that (i) some IAQ standards use non-health-based metrics; (ii) threshold values don't provide sufficient information to inform decisions and strategies; and (iii) CO_2 concentrations [typically used in buildings as a default IAQ measure] are limited in their usefulness. Jones argues that as the well-being of individuals considers both mortality and morbidity, Health Adjusted Life Years (used for population health indicators) could be an avenue worth pursuing.

Some of benefits and limitations of metrics typically used in IAQ assessments are shown in Table 4-1.

Building on research that highlighted the need for a holistic approach to health indoor environments [19], and the past and continuing work of IEA Annex 5, an EU project – Alliance for Deep RENovation in buildings (www.aldren.eu) – seeks to simultaneously address IEQ and energy. The ALDREN project aims to

- Include IEQ in the scope of deep energy renovations to promote solutions supporting comfort and health and to ensure that renovations to meet zero carbon goals are not detrimental to indoor environmental conditions
- Link building rating tools (e.g., energy, sustainability, IEQ) with financing instruments to emphasise enhanced building value and create strong incentives for investment
- Develop a building passport that documents improvements in energy efficiency and IEQ.

It is important to note that EU regulations require an "evidence-based estimate of expected energy savings and wider benefits, such as those related to health, safety and air quality" (EU Directive 2018/844, Article 2a.1(g)).

An IEQ rating scheme has been proposed as part of this work (illustrated in Figure 4-2) to work in concert with existing EU energy performance directives [96]. Note that in its attempt to be relatively simple, this initial proposal does not include the multiple metrics that would be required to adequately qualify and quantify occupant health in each of the four areas. It is proposed that such a new metric could have three or four categories, similar to EN15251 for thermal comfort, to account for different occupant types. For example, Cat I could indicate the IEQ metrics for spaces occupied by sensitive and fragile people (e.g., hospitals and aged care facilities).

Table 4-1 IAQ Metrics and Limitations

Metric	Explanation / Benefit	Limitation
Perceived Indoor Air Quality (PIAQ)	Occupants' personal assessment of IAQ. Keeps the focus on building occupants.	Subjective; Inability for nose to small all harmful contaminants; High dependence on T and RH; People can adapt to malodours after only a few minutes
Measurement	Direct measurement of range of contaminants.	Individual concentrations incomparable because of different health impacts, time scales, and units; Complexity of number and type of indoor spaces; number of contaminants to monitor; data collection and utilisation for dynamic control
Exposure Limit Values (ELV)	Ratio of maximum concentrations (for each pollutant) to their respective ELV concentrations. Developed for occupational environments to give a quick indication of risk.	Not clear how a change (e.g.,by 10%) would affect occupant health and comfort; An indication of the relationship between exposure and health consequences is required; limited data from different building types and from low energy buildings; no accounting for 'cocktail effect' of multiple chemicals/exposures, or for the context (e.g., ventilation); different values between countries and over time
Disability Adjusted Life Year (DALY)	Years of healthy life lost due to early mortality and/or disability/disease	Both are a means of evaluating public health interventions to reduce population disease burden (DALY) or increase population quality of life (QALY). Neither captures wider effects of interventions. Both incorporate subjective factors and weightings. QALY is used widely for assessing cost-effectiveness of population health interventions (e.g., medicines).
Quality-Adjusted Life Year (QALY)	Years of perfect health gained by an intervention	
Burden of Disease	The difference between current health status of a population and an ideal situation where they all live into old age, free of disease and disability	Requires social/ethical considerations at a population scale, such as the relative 'value' of population groups (young, disabled, old) and what is considered 'disability'.

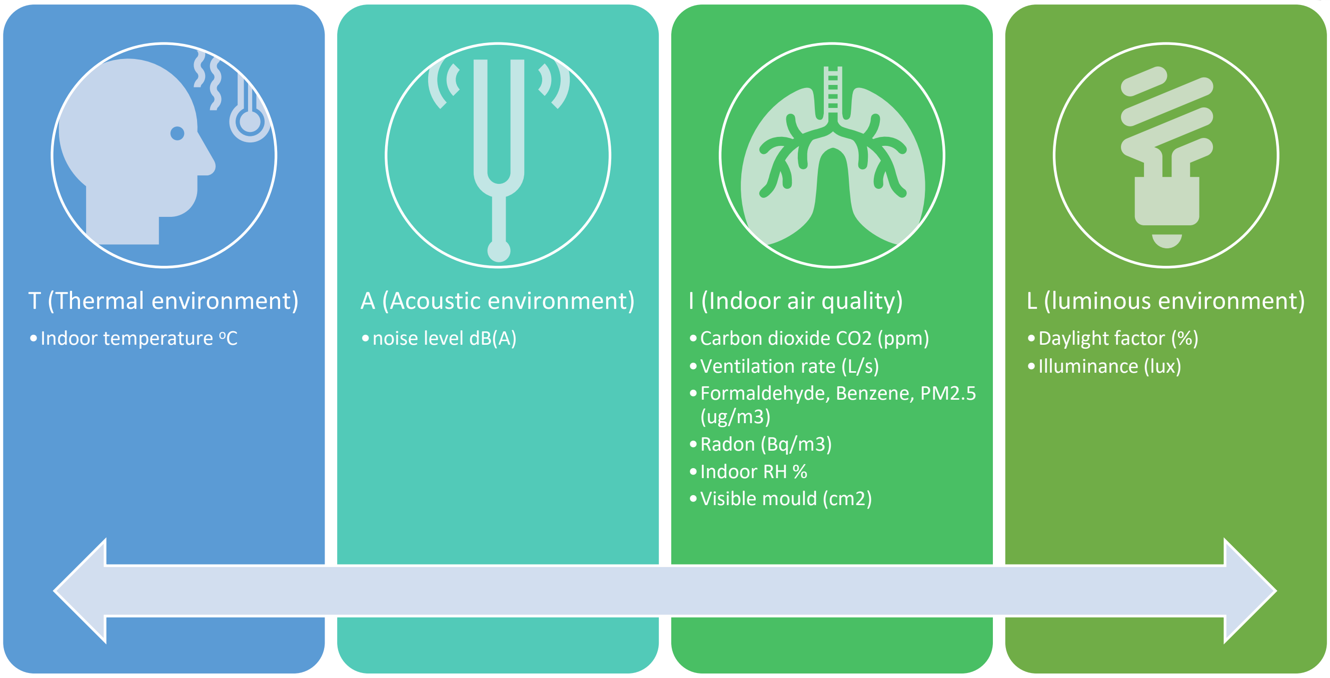


Figure 4-2 Proposed IEQ rating scheme - TAIL

The TAIL IEQ proposal raises the question of what instrument/s could or should be used for determining cost effectiveness.

Table 4-2 describes some of the methods used to evaluate the cost effectiveness of healthcare treatments or energy efficiency measures. While both health and engineering tend to incorporate benefit-cost analyses, the methods actually utilised are quite different. On the one hand, health economics evaluates the benefits of therapies against their cost, and the specific methods used by Australia's Pharmaceutical Benefits Scheme (PBS) are described first. Another health economic measure compares the accounting and opportunity cost approaches to the metric of a hospital bed day (or alternatively the average length of stay ALOS). On the other hand, building or engineering cost-effectiveness evaluation methods tend to focus on return on capital investment (relating to the benefits of energy improvements), including pay-back period, internal rate of return etc. Note that there has been a broad change of terminology internationally from "cost-benefit analysis" to "benefit-cost analysis", reflecting a change of initial focus to identifying benefits, before calculating costs. The Australian Government, including the Australian Building Codes Board, continue to use the older "cost-benefit analysis" terminology, reinforcing focus on costs ahead of benefits and value.

> "In a world with scarce resources where choice must be made between competing alternatives, opportunity cost is the value of the best alternative forgone"
>
> *Economic Evaluation of Medicines*, 2017

Some newer and currently less used but very useful methods are also described. Regardless of the method used, it is essential that the scope, assumptions, and judgements utilised in the method are clearly communicated and transparent. Moves to integrating health and energy performance KPIs will also need to consider how to better align cost effectiveness methodologies.

Table 4-2 Methods for evaluating cost-effectiveness

Medical treatment cost-effectiveness evaluation methods	
Cost-minimisation **[97]**	Used by PBS when the treatment option being considered (e.g., a drug) is considered non-inferior to the treatment it would most likely replace, in terms of health outcomes. The outcome is a cost comparison. No benefit is measured.
Cost-utility **[97]**	Used by PBS when the treatment option being considered (e.g., a drug) is considered superior to a treatment it would most likely replace, in terms of health outcomes. The outcome is a cost comparison (incremental cost per QALY gained). Benefits are measured in QALY; Costs measured in $/QALY)
Incremental Cost Effectiveness Ratio (ICER) **[97]**	A statistic used to summarise the cost-effectiveness of a new drug relative to the comparator. It is reported as $/QALY gained. $ICER = \frac{\text{Cost A} - \text{Cost B}}{\text{Effect A} - \text{Effect B}}$ No threshold, but Tayler reports (in 2017) that a new drug worth a cost < $50,000 per QALY gained is more likely to be recommended for funding by the PBS.
Contingent Valuation (Willingness to Pay; Hospital Bed Day) **[98]**	Cost of a hospital bed day: (a) Accounting cost (how much a bed costs a hospital to run i.e., total costs divided by number of beds) (b) Economic/opportunity cost (the value of a bed in terms of patient outcomes (reduced stay); waiting lists etc.) Ties in with Average Length of Stay (ALOS)
Building and energy cost-effectiveness evaluation methods	
Regulatory Impact Assessment (cost-benefit analysis) **[99]**	All regulatory changes are required to undertake a Cost-Benefit Analysis (CBA). The broad steps are shown on the following page. Some specific terms used in this process include: Value of a statistical life (VSL) – assumed to be the life of a young adult with at least 40 years of life ahead Value of a statistical life year (VLY) – estimate of the value society places on a year of life; estimate how much society is willing to pay to reduce the risk of mortality. NOTE: the PBS does not generally accept cost-benefit analysis (without an accompanying cost-utility analysis). The PBS also uses QALY not VLY or VSL.
Benefit-Cost Analysis (return on investment; pay-back period)	Health Infrastructure NSW requires "*optimum energy improvement return for capital investment*". It also offers financial support for projects that can achieve a 15% performance benefit above the minimum NCC Section J (energy) requirements with a payback period of <7 years.
Whole of Life Costing / Total cost of ownership / Life-cycle costing	The total cost of ownership over the life of an asset. Includes upfront capital costs, operational costs to ensure service continuity, and disposal / replacement costs. Example: application of this process to evaluate the cost effectiveness of particle filters to a building's air supply intake [100]

	Life-cycle cost = (cost of filter + labour + filter disposal) + (additional fan power required to overcome pressure drop x operating hours x electricity price) Life-cycle benefits = impact on morbidity and mortality + reduction in building cleaning + positive impact on productivity
Multi-dimension objective-oriented clustering-based method (MOC) **[101]**	A new method to identify a set of typical energy and/or demand periods and quantify yearly cost savings for various renewable energy investment options
Real Option Analysis **[102]**	A method explored for its potential to value investments in IAQ improvements. Specifically, in this case study, the cost benefits of reduction in sick leave, compared with the investment costs of increase ventilation beyond the minimum regulatory requirements (in terms of plantroom space, energy efficiency, energy production, and design / management)

Major steps in a cost-benefit analysis (for regulatory impact analysis)
1. Specify the set of options (at least 3). BAU (do nothing) is usually the base case
2. Decide whose costs and benefits count
3. Identify the impacts and select measurement indicators
4. Predict the impacts over the life of the proposed regulation
5. Monetise impacts (assign net dollar value of gains and losses)
6. Discount future costs and benefits to obtain present values
7. Compare net present value of each option
8. Perform sensitivity analysis
9. Reach a conclusion

SOURCE: Cost-Benefit Analysis, Office of Best Practice Regulation, Australian Govt.

"When conducting a health economic evaluation, the perspective that is adopted is a fundamental consideration. This determines the scope of the costs and benefits included. The Pharmaceutical Benefits Advisory Committee (PBAC) mandate a healthcare system perspective that considers costs and benefits relevant to the Australian health system"

Economic Evaluation of Medicines, 2017

4.2 Integrated Approach and Suite of Metrics

Eight key messages emerge from the information presented in this report:

1. Different user groups and individuals will have different indoor environment requirements and 'best' solutions [7, 9, 65, 103].
2. IEQ solutions can positively and negatively impact on each other and on energy consumption / demand.
3. IEQ criterion in green rating tools account for less than 25% of overall point allocations; may not include occupant satisfaction or may restrict it to overall satisfaction; and do not generally include health and wellbeing criterion [103, 104].
4. There is a need for an integrated design approach from the very beginning (IDA) [105, 106] of any HCF project.
5. There is a need for robust and evidence-based integration of engineering, sustainability, and environmental factors and measurement strategies with users at the focal point [8].
6. Building systems need to be commissioned and continuously monitored not only for energy impacts (e.g., consumption, demand, load factor, greenhouse gas emissions etc) but also for impact for building occupants.
7. The methodologies used for determining cost effectiveness by medical and engineering approaches need to be more closely aligned and focused on the achievement of health and societal value and co-benefits.
8. Overheating and power outage risks need to be specifically factored into design and operation, increasing the resilience of HCFs and their ability to protect the health of occupants.

> "The prioritization of energy efficiency starts with the earliest business and operations planning phases ... and continues through construction to long-term building operations...The integration of planning, design, construction and operations team members is absolutely critical."
>
> Advanced Energy Design Guide for Large Hospitals

The following table (Table 4-3) is based on an acknowledgement that whole of building KPIs (such as energy use intensity EUI) and equipment level KPIs (e.g., the COP of an air conditioner compressor) don't provide sufficient information to diagnose performance deviations, enable benchmarking across technologies, or enable matching of energy parameters with health parameters. On the other hand, some additional whole of building or whole of site KPIs are required to indicate the impact of the building or site on the electricity network and on the environment. This table, therefore, presents a suite of metrics at a building or site level as well as at a building services level, for each IEQ criterion. It adds resilience metrics and health metrics as additional factors for determining HCF benefit and value. It is hoped this suite will be the catalyst for continuing discussions among HCF designers, administrators, operators, and users.

Table 4-3 Suite of Metrics for Healthcare Facilities

Metric / KPI	Explanation	Building system / Subsystem	IEQ System
Electric load factor (ELF)	Average electric load divided by peak electric load (day | month | year)	Whole of building / campus / site	Not applicable, but in a resource constrained environment, expenses and revenues associated with these metrics can impact on the $ available for health care
Load shape	Electric load as a function of time		
Peak demand (30 min/month)	Highest 30 minute demand per month		
Reduction in peak demand (onsite)	Impact of intervention on reducing peak demand		
Demand Flexibility and Responsiveness	Load capacity (kW) that could be flexible and responsive to grid signals		
Grid support capability	Potential to provide frequency control ancillary services (FCAS)		
Carbon emissions | % reduction	Total ghge (CO_{2e}) for all stationary energy use + reduction from baseline		
Renewable energy %	% of total building/site/campus stationary energy met by onsite and off-site renewables		
Energy storage	Electric storage kWh_e Thermal storage kWh_{th} Charge / Discharge capacity and rate		
Onsite backup generation	Capacity (kW) Availability Grid-synchronous or not		
kWh/m²/yr	Energy | EUI	Lighting (interior, exterior, emergency)	Visual comfort and health and safety
kWh/m²	Demand |Power		
kWh/day	Energy | Energy Efficiency (annual, monthly, seasonal)		
Average Daylight Factor (ADF)	Average daylight illuminance on a horizontal plane		
Continuous Daylight Autonomy	Fraction of occupied hours met by daylight		
Useful Daylight Illuminance (UDI)	The % of occupied hours when the illuminance range is met by daylight		
Daylight Glare Index (DGI)	Predicts discomfort or reduction in visibility from daylight		
Luminance contrast ratio (relates to daylight)	The contrast between glazing and surrounding surfaces		
Unified Glare Rating (UGR)	Predicts level of discomfort produced by light sources		
Colour Rendering Index (CRI)	Accurate representation of colours under artificial light (i.e., as they would appear under natural light)		
Correlated Colour Temperature (CCT)	The hue of light output compared to a black body radiator emitting an equivalent hue. Denoted in degrees kelvin (K)		
Control	Building | Zone | individual control		

kWh/ m^2/yr	Energy | EUI	Heating and Cooling	Thermal Environment
W/ m^2	Demand | Power (hour, month, season, year)		
COP, EER, SEER, SCOP	Energy | Energy Efficiency (of whole delivery system, not just compressor)		
W/ m^2	Demand | Power		
kWh/(m^2*CDD)	Energy | EUI (normalised by cooling degree days)		
Actual working ratio	Ratio of actual working hours to theoretical working hours of economised (Energy | EE)		
Mechanical cooling ratio	Ratio of mechanical cooling hours to free-cooling hours		
W/gpm	Ratio of hydro-system (water, refrigerant) power to the flow rate transported		
Pump Energy Index (PEI)	Ratio of electrical input power of reference pump to input power		
Integrated part load value (IPLV)	Cooling part-load efficiency of a chiller		
Fan energy efficiency	Ratio of output power to input power		
Temperature T	Outdoor | Indoor | radiant | set point		
Relative Humidity RH	Outdoor | Indoor		
Control	Building | Zone | individual control		
m^3/h.m^2	Airflow rate per floor area (Energy |	Ventilation (dilution, filtration, air purification) and Building design, fitout, operation, maintenance	IAQ
W/m^3.h	Energy required for airflow rate (Demand | Power)		
Fan Energy Index (FEI)	Ratio of electrical input power of a reference fan to the electrical input power (Energy | EE)		
Delta ppm (CO_2)	Difference between indoor and outdoor air CO_2 concentration		
m^3/h.m^2	Average outdoor airflow rate in a given time period		
m^3/h.person	Average outdoor airflow rate in a given time interval per person		
Carbon dioxide CO_2	8 hours		
Carbon monoxide CO	15 minutes | 30 minutes | 1 hour | 8 hours		
Formaldehyde CH_2O	30 minutes		
Nitrogen dioxide NO_2	1 year | 1 hour		
Ozone O_3	8 hour, daily maximum		
Particulate matter $PM_{2.5}$	1 year | 24 hour (99^{th} percentile)		
Particulate matter PM_{10}	1 year | 24 hour (99^{th} percentile)		
Total Volatile Organic Compounds TVOC	1 hour		
Other contaminants as relevant to specific sites / zones			
Control	Building | Zone | individual control		

Sound Transmission Class (STC)	A surface's ability to block sound from being transmitted	Building materials/fitout HVAC systems	Acoustic Comfort
Noise Reduction Coefficient (NRC)	The fraction of sound that is absorbed by a material upon hitting it.		
Weighted Sound Reduction Index (Rw)	The sound insulation property of walls, floors, windows, doors.		
Spectrum adaption term (Ctr)	Modification of Rw to account for noise sources with a large low-frequency component		
Speech Intelligibility Index	The % of words clearly comprehended by listeners in a room		
Ambient Noise Level (dB)	The magnitude of background noise Continuous | intermittent		
Room reverberation time (RT)	Seconds it takes for a sound in a room to decrease by 60dB after a source stops generating sound		
Impact sound isolation	Sound generated through building surfaces when one objects hits another		
Hours taken to reach DI 28°C threshold	Hours a building (zone) can maintain safe conditions in the absence of mechanical cooling	Building Envelope Individual resident rooms Shared spaces	Thermal comfort
Indoor Overheating Degree (IOD)	Averaged sum of positive values of the difference between zonal indoor operative temperature and zonal comfort limit temperature		
Ambient Warmness Degree (AWD)	Sum of positive values of the difference between Tout and fixed base temperature		
Overheating Escalation Factor (OEF)	Proportion of IOD and AWD		
Unweighted Unmet Hours (month)	Number of hours of occupation outside comfort criterion		
Passive Survivability	Ability to maintain safe indoor thermal conditions in the absence of active cooling		
Thermal Autonomy	% of hours a building can passively maintain comfort conditions without active systems		
Recovery time	Hours taken for a building to cool down to the designed thermal conditions after failure of a cooling system / power		
Metabolic rate (met)	For different building occupants Resident | Patient | Staff		
Clothing insulation level (clo)			
WBGT | PHS	Heat stress measurements		

Resident | Patient vital signs	Temperature, heart rate, blood pressure, respiratory rate, blood oxygen saturation, hydration		Occupant health and wellbeing
	Cognition		
	Anxiety | Stress		
Other	Infection rates	Building envelope and building services	Occupant health and wellbeing; workplace health and safety; staff productivity
	Average Length of Stay		
	Medication level		
	Anxiety / stress		
	Cognition		
	Staff absences | turnover		
	Satisfaction ratings		

5 USEFUL RESOURCES

5.1 Websites

Air Infiltration and Ventilation Centre (AIVC), IEA EBC Annex 5 (https://www.aivc.org/)

Alliance for Deep RENovation in buildings. www.aldren.eu

ASHRAE www.ashrae.org

Australian Institute of Air-conditioning, Refrigeration and Air Handling (AIRAH) (www.airah.org.au)

Australian Building Codes Board (ABCB) (www.abcb.gov.au)

Global Green and Healthy Hospitals (https://www.greenhospitals.net)

IEA Annex 80 Resilient Cooling in Buildings (www.annex80.org)

Illuminating Engineering Society (www.ies.org)

Indoor Environmental Quality Global Alliance (www.ieq-ga.net)

5.2 Technical Notes and Guidelines

AIVC

Technical Note 68: Residential Ventilation and Health, Feb 2016

ABCB Handbooks

Sound transmission and insulation in buildings (2021)

Indoor Air Quality

AIRAH Design Application manuals

DA04 Air System Balancing – in HVAC (June 2021)

DA24 Hydronic System Balancing – in HVAC (June 2021)

DA07 Criteria for Moisture Control Design Analysis in Buildings (August 2021)

DA19 HVAC&R Maintenance (2019)

DA15 Air Filters and Cleaning Devices (2019)

DA20 Humid Tropical Air Conditioning (2016)

Illuminating Engineering Society (IES)

Lighting Practice: Designing Quality Lighting for People and Buildings (LP-1-20)

Acoustics, Ventilation and Overheating Residential Design Guide (Jan 2020)

Considers the interdependence of acoustics, ventilation and overheating (https://www.association-of-noise-consultants.co.uk/avo-guide/).

5.3 Health Facilities Guidelines

Australian Health Facilities Guidelines https://healthfacilityguidelines.com.au/standard-components

ASHRAE Advanced Energy Design Guide for Large Hospitals, 2012

Recommendations for achieving 50% energy savings below 2004 baseline standard

ASHRAE Advanced Energy Design Guide for Small Hospitals and Healthcare Facilities, 2009

Recommendations for achieving 30% energy savings below 1999 baseline standard

ASHRAE Standard 170 – 2021 Ventilation of Healthcare Facilities

Includes temperature standards in clinical settings; filter specifications

ASHRAE HVAC Design Manual for Hospitals and Clinics, 2nd Edition, 2013

CEN/TC 156 (Ventilation for buildings) and ISO / TC 205 (Building environment design)

These two standards focus on design aspects of natural and hybrid ventilation and ventilative cooling tackling both overheating and indoor air quality issues.

EN 16798 Part 3 and 4 – performance requirements for ventilation of non-residential buildings

Under development (Working group 2020, AIVC/IEA Annex 62): this standard deals with a technical specification on "Natural and hybrid ventilation systems in non-residential buildings" that focuses on indoor air quality aspects and overheating prevention.

International Health Facility Guidelines (v 4.2 Oct 2019) https://www.healthfacilityguidelines.com/

ISO /TC 205 Design process of natural ventilation for reducing cooling demand in energy-efficient non-residential buildings

Under development

Whole Building Design Guide (www.wbdg.org)

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