Economics of Indoor Air Quality

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ABSTRACT

Buildings represent a major end use of energy throughout the world and are typically the dominant sector for electricity. The use of that energy is to provide buildings services, the most important of which is Indoor Environmental Quality (IEQ). Heating and air conditioning systems typically handle the thermal comfort aspects of IEQ; the energy impacts and economics of such systems is well studied. The most important remaining aspect of IEQ is Indoor Air Quality (IAQ). IAQ combines health aspects odour and moisture but is typically not represented by a health-based performance metric. As a result, ventilation rates are used as a surrogate for IAQ. Recent research has developed "Smart Ventilation" technologies that economically optimize ventilation by considering utility rate structures, exposure to outdoor contaminants, as well as peak loads and total energy demand. Enabling this optimization of Smart Ventilation requires IAQ performance metrics that can be monetized. Lawrence Berkeley National Laboratory and others have used Disability Adjusted Life Years (DALYs) to quantify health impacts of contaminant exposure, which shows IAQ may be a critical economic driver. This paper reviews these general concepts and presents some of the most recent work we have done on both Smart Ventilation and economic metrics for IAQ.

KEYWORDS:
Indoor Air Quality (IAQ), Smart Ventilation, DALY, Metrics

1   INTRODUCTION

Buildings use a roughly one-third of energy production in western countries. After the oil shocks of the 1970s, the developed world began looking for ways to reduce energy use in buildings. Since as much as half of the space conditioning energy was attributable to leaky building, there was a major effort first on research and finally on implementation of air tightening for both new and existing buildings.

As buildings got tighter and the energy loss from infiltration was reduced, there was a concern in the health community and elsewhere that there would be insufficient ventilation to control exposures from indoor-generated contaminants. While Indoor Air Quality had not been a major concern before the oil shocks, it became one by the 1990s.

The leading professional and standard-writing societies then developed or expanded their IAQ-related work and released standards on minimum ventilation rates for providing acceptable IAQ. Currently standards by ISO, CIBSE and CEN are available for international use, with the most utilized one being the Standard 62 series by the American Society of Heating Refrigerating and Air Conditioning Engineers.

What such standards have in common is that at their core they set a minimum ventilation rate in order to control contaminant exposure; the rates themselves were fundamentally set for odour control—assuming that that would also deal with health. Such a ventilation rate is set

based on the engineering judgement of experts because there are no performance metrics that can be quantified or monetized.

The ideal standard would look at the impact of exposure to contaminants to set minimum performance standards. The economic impact to all affected parties, ideally, could be calculated to determine the economic optimum for meeting or exceeding those standards. Unfortunately, the information, research and technologies necessary to fully realize this ideal does not currently exist.

This paper will point out some of the recent and current efforts being made to advance this ideal by looking at appropriate metrics for IAQ. The first issue to consider is Smart Ventilation, which allows the user to meet existing ventilation standards while optimizing other economic criteria. The more forward-looking approach allows a monetization of the health impact on the occupants of contaminant exposures. We will examine Disability Adjusted Life Years as an IAQ metric.

2   PROBLEM IDENTIFICATION AND BASIC PRINCIPLE

Building materials and systems, and the activities carried out in them, can be a source of contaminants that are harmful to human health. For example, there is evidence that some of the materials used to construct and furnish buildings emit harmful gases and harbour biological organisms. Unvented combustion processes for space and food heating emit gaseous and particulate contaminants and can be a source of moisture that is a primary driver of biological growth. Human activities, such as cooking and vacuum cleaning, also emit particulates, cleaning and deodorizing products emit gaseous contaminants and particulates, and smoking emits over 7000 different compounds of which many are harmful (CfDC, 2010). Pets harbour and transport biological contaminants and can themselves be allergens. People and pets also emit gaseous bio-effluents that are disagreeable to smell, and harbour pathogens that produce disease. These examples show the many potential hazards and contaminant sources in buildings, for which there are multiple exposure pathways, and not all of them are airborne.

The measurement of airborne contaminant concentrations is generally a task carried out by experts and reported in academic journals and technical reports. The presence and concentrations of contaminants is often measured without careful consideration of their relevance, and those measured may not be the most prolific or the most harmful. Some contaminants are inappropriately grouped together; for example, there are over 1 million volatile organic compounds and their toxicities are generally unknown, yet they are sometimes reported as single values and referred to as total VOCs. Carbon dioxide (CO_2) is often used as an indicator of poor IAQ, although it does not negatively affect the health of occupants in the concentrations usually found in buildings, it is a marker of human bio-effluents. Its presence is a function of occupancy, occupant activity, gender, age and physiology, combustion, and transport from elsewhere. Without an understanding of these variables, indoor CO_2 cannot be used to assess indoor air quality or ventilation. And, it can never be used to indicate the presence of other important indoor contaminants, such as formaldehyde emitted from building materials, whose emission is unrelated to CO_2 concentration.

However, existing measurements of contaminants, whose type and toxicity are known, still give cause for concern (Logue et al., 2011). They could negatively affect the health of occupants of any building they were found in and, when extrapolated to larger building stocks, could adversely affect healthcare systems and economies.

3   SMART VENTILATION

Ventilation is the primary method of contaminant dilution and removal in buildings. Ventilation standards generally agree that indoor air should be perceived as fresh and pleasant by a significant majority of occupants and so they set a baseline ventilation requirement of around 8 l/s per person to dilute bio-effluent odours to an acceptable level for anyone who enters an occupied room from relatively clean air (Persily, 2015). They then attempt to account for other contaminants, such as building materials and furnishings, by increasing the baseline rate to around 10l/s per person, although the increase is not based on specific contaminants (Persily, 2006). Ventilation rates in national standards around the world differ by up to 4 times, and their origins aren't always known or documented (Borsboom, 2017).

Smart Ventilation is a way of providing ventilation in an economically optimal way that still achieves a prescriptive ventilation goal. The Air Infiltration and Ventilation Center describes Smart Ventilation as "a process to continually adjust the ventilation system in time or by location to provide the desired IAQ benefits while minimizing energy consumption, utility bills and other non-IAQ costs (such as thermal discomfort or noise)".

A Smart Ventilation system adjusts ventilation rates in time or by its location in a building to be responsive to one or more of the following: occupancy, outdoor thermal and air quality conditions, electricity grid needs, direct sensing of contaminants, operation of other air moving and air cleaning systems.

In addition, Smart Ventilation systems can provide information to building owners, occupants, and managers on operational energy consumption and indoor air quality, and signal when systems need maintenance or repair. Being responsive to occupancy means that a Smart Ventilation system can adjust ventilation depending on demand and reduce ventilation if the building is unoccupied.

Smart Ventilation can time-shift ventilation to periods when indoor-outdoor temperature differences are smaller and away from peak outdoor temperatures and humidity, or when indoor-outdoor temperatures are appropriate for ventilative cooling, or when outdoor air quality is acceptable.
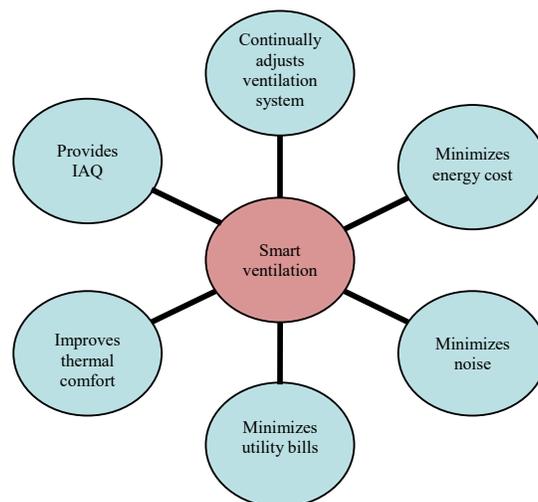

Figure 1: Main economic features of a Smart Ventilation system.

Being responsive to electricity grid needs means providing flexibility to electricity demand

(including direct signals from utilities) and integration with electric grid control strategies. Conceptually a Smart Ventilation system can be displayed by Figure 1.

Smart Ventilation systems can have sensors to detect, for instance, air flow, systems pressures or fan energy use in such a way that systems failures can be detected and repaired, or when system components need maintenance, such as filter replacement.

Walker et al. (2017) have conducted a literature review on current research on Smart Ventilation. There are many active projects utilizing Smart Ventilation approaches. For example, Less and Walker (2016) have studied how Smart Ventilation can be used to minimize periods of high indoor humidity in homes in humid climates in order to reduce the risk of mould.

Figure 2 is taken from that paper and demonstrates how one particular Smart Ventilation strategy (based on measured indoor and outdoor humidity identified as "Control 7" in the paper) can significantly reduce the number of at-risk hours (i.e. hours over 60% relative humidity) in six humid climates in the United States and the increase in energy necessary to achieve that.
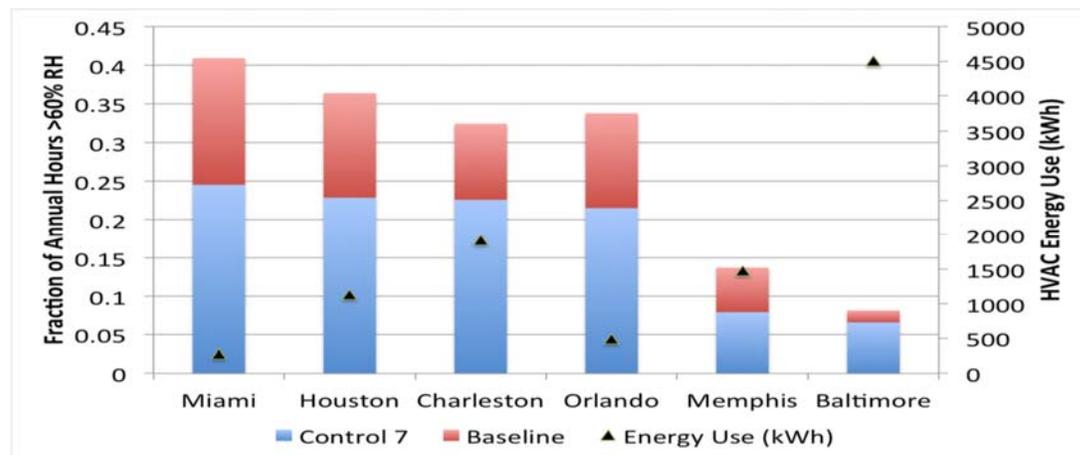

Figure 2: Fraction of the year >60% RH in Baseline (red) vs. Control 7 (blue) cases, and changes in annual HVAC energy consumption from baseline when using Control 7 (black triangles, 2nd y-axis).

That study concluded that various Smart Ventilation strategies could be used to reduce high humidity levels but that all of them would increase energy use. The economic impact of increased energy use is straight-forward to estimate, but the economic impact of high humidity levels awaits further study because of the indirect aspects. While initial cost and energy metrics can be expressed in monetary terms many indoor environmental quality metrics either don't exist or have yet to be monetized.

4   IAQ METRICS
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.

One method of analysis is to ask occupants to personally assess IAQ. The human nose is as sensitive to some gaseous contaminants as chemical analyses and using it indicates occupant

preference and ensures that people are the focus of an assessment. Perceived air quality (PAQ) is the basis of most ventilation standards and is used to assess indoor odours (ISO, 2014) and air quality in buildings (Wargocki et al., 2004). However, its very subjectivity, the inability of the nose to smell all harmful contaminants (Carbon monoxide is odourless, for example), its high dependence on temperature and relative humidity (Fang et al., 1998), and the propensity of people to adapt to malodours after only a few minutes (Berg-Munch et al., 1986), are acknowledged by some as fundamental concerns.

A second method might be to identify properties of a building that are known to affect IAQ directly, for example using a tick-box approach. Each feature could be weighted according to their hazard and aggregated to produce a single metric. This method could be used to develop a third-party rating system, similar to many existing energy rating schemes, and should be helpful to someone who is particularly sensitive to specific contaminants in choosing a house to live in.

To obtain a comprehensive picture of the IAQ in a building it would be necessary to measure a range of contaminants, but their individual concentrations may be incomparable because of different health impacts and time scales, and units; for example, radon ($Bq.m^{-3}$) and particulate matter ($\mu g.m^{-3}$). One approach is to convert the individual contaminant concentrations into sub-indices, which may be a function of their health risks, before they are aggregated into a single index. However, the summing of sub-indices can lead to situations where they are all under individual health thresholds, but the final index shows exceedance. Conversely, the averaging of sub-indices can lead to a final index that indicates acceptable IAQ when one or more sub-indices are greater than their individual thresholds. One solution is to use the maximum of all sub-indices as the final index (Sharma and Bhattacharya, 2012), but this does not indicate overall IAQ. Other methods weight the sub-indices before aggregation (Abadie et al., 2016).

Exposure limit values are used in occupational environments to prevent or reduce risks to health from hazards, such as vibrations (HSE, 2008), by setting a maximum quantity experienced per person per day. This principle could be applied when measuring the concentrations of a range of contaminants in a building. Here, the ratios of their maximum concentrations to their respective ELV concentrations give a quick indication of risk, where a ratio $\ll 1$ might be acceptable but one approaching or exceeding unity may be problematic. A problem with IAQ indices and ELVs is that it isn't clear how a change to either metric, say by 10%, would affect occupant health and comfort. Here, an indication of the relationship between exposure and health consequences is required.

Health-adjusted life years (HALYs) are population health measures that allow morbidity and mortality to be described simultaneously (Gold et al., 2002). One type of HALY is the disability adjusted life year (DALY), which is a measure of time where a value of unity is one year of healthy life lost to some disease or injury. DALYs are calculated as the sum of years of life lost to premature mortality and morbidity in a population for some negative health effect. Disability is weighted by its effect on person's life in general, and so can account for mental illness. In the case of IAQ, the burden of disease is a measurement of the difference between the current health status of a population of building occupants and an ideal situation where they all live into old age, free of disease and disability (WHO, 2009). The DALY has been used by the AIVC (2016) to prioritize indoor contaminants found in houses for mitigation; see Figure 3. DALYs are used hereon as a focus for our discussion on IAQ, although there are other HALY metrics, because it is appropriate for assessing the health of populations (Gold et al., 2002; AIVC, 2016) and because it can be monetized.
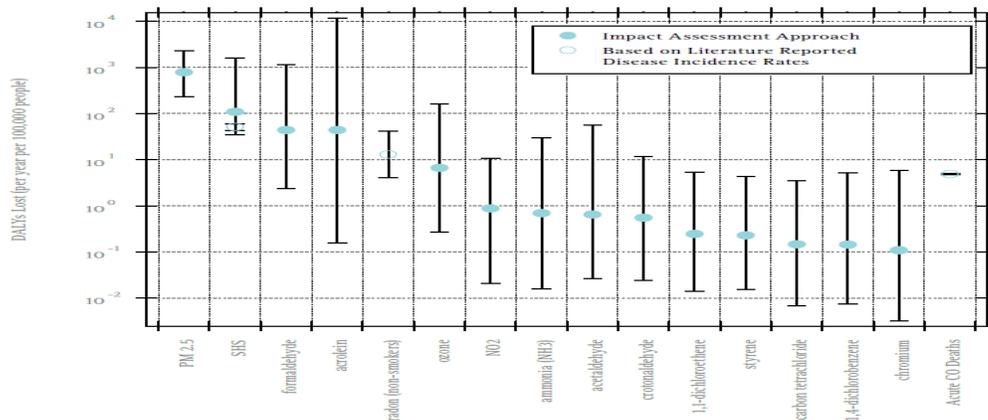
Figure 3: Estimated population averaged annual cost, in DALYs, of chronic air contaminant inhalation in U.S. residences (AIVC, 2016).

5   ECONOMICS DISCUSSION

Traditionally economics has entered the IAQ debate through optimizing the costs providing ventilation. The benefit of meeting the criteria were not monetized.

There are the first costs of designing, purchasing and installing the ventilation system and there are the operating costs of running the system including not only the direct operating costs (e.g., the electricity to run the fans), but the indirect costs (e.g., the energy to condition the outdoor air that is brought in to dilute contaminants).

For ventilation systems the simple operating costs usually exceed the first costs, which encourages technology such as heat-recovery ventilators to optimize the life-cycle costs. In any case, the economic optimization is straight-forward with all the usual economic assumptions. This does not include the far larger economic impact of productivity.

With the advent of Smart Ventilation, the optimization becomes a bit more complex and valuable, because it can provide other services while still meeting the IAQ criteria. Some of those services are easily incorporated in a standard economics model and some are not.   Time shifting ventilation and reducing over-ventilation can save energy costs or utility peak charges. Taking account of ventilative cooling or exogenous local exhausts can also cut these energy costs.

Smart Ventilation can also provide benefits that are not as easily monetized. For example, it can shift ventilation away from times where the outdoor air quality is bad thus reducing exposure. An example of this would be to shift ventilation away from afternoons in urban air basins that typically see high outdoor ozone concentrations. It is clearly a benefit to reduce exposures to ozone, but it is not easy to put a value on that benefit and thus determine what mitigation is worth.

IAQ metrics, such as DALYs, provide a method of monetizing contaminant exposure because various economic studies have been done to determine what a DALY is worth to people. Unfortunately, there is no single value for what a DALY is worth because it depends strongly on the culture and socio-economic status of the person whose DALY one is considering. We would expect a DALY in a developed western society to be worth more (measured in a hard currency) than in a poor country based simply on standards of living.

We will not develop the monetization of a DALY any further in this report, but to provide context a rough value of a DALY in a developed country is on the order of magnitude of $150,000. This monetization, however, does not include loss of productivity or costs of health care; it only includes the value of the lost health to the individual and therefore represents a lower limit of the economic cost.

The DALY approach can monetize the health aspects of the IAQ. Other efforts are underway to quantify the comfort aspects of the indoor environment and increases in productivity (Allen et al. (2016)) or improved learning (Haverinen-Shaughnessy (2011)). Looking forward, we can see that both the health and perceived aspects of IAQ could be fully monetized.

The advantage of being able to put a monetary value on indoor contaminant exposure is that it facilitates a more efficient means of providing economic value:
- A designer can trade-off source control, ventilation, and air cleaning options to meet performance requirements.
- A Standards-writer will be able to create standards by looking at the monetized value that its protections provide and allow performance-based rather than prescriptive approaches.
- A policy-maker can determine the relative costs and benefits of specific policy options such as those intended to protect occupant health.
- Future IAQ systems can be based more on the control of contaminants and their impact rather than on providing ventilation.

6   CONCLUSIONS, SUMMARY AND RECOMMENDATIONS
Until recently the economics of indoor air quality was limited to finding the least cost way of providing and operating prescribed ventilation systems. Advances in Smart Ventilation are allowing ventilation systems to provide other benefits, but many of them cannot be yet be quantified.

Advances in IAQ metrics are providing means for the impact of contaminants and the benefits of controlling the indoor environment to be quantified. Monetizing those metrics such as the DALY is a key step in being able to use the full power of economic analyses to improve the indoor environment.

Further research is needed to monetize the metrics that are being developed by the indoor environmental community. Such tools would allow the appropriate engineering and design communities to implement the most economically efficient systems, which would provide high occupant value at least cost.

7   ACKNOWLEDGEMENT

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9 ABBREVIATIONS

AIVC: Air Infiltration and Ventilation Center
ASHRAE: American Society for Heating Refrigerating and Air Conditioning Engineers
CIBSE: Chartered Institute of Building Services Engineeers
DALY: Disability Adjusted Life Year
DOE: Department of Energy (United States)
ELV: Exposure Limit Values
HALY: Health adjusted life year
ISO: International Standards Organization
IAQ: Indoor Air Quality
IEQ: Indoor Environmental Quality
TVOC: Total Volatile Organic Compounds
VOC: Volatile Organic Compounds
WHO: World Health Organization