CEC-SVACH Indoor Air Quality Valuation

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Introduction

California is on a path toward zero net energy (ZNE) homes. The air-tightness of new and existing homes with electric heating and cooling is expected to increase as homes become more energy efficient. As homes become more energy efficient through air-sealing (or tightening), the possibility of poor indoor air quality (IAQ) increases (Levin and Phillips 2015). Poor IAQ associated with stringent energy-efficiency requirements is a major barrier to California's energy-savings policy goals. Additionally, improvements in building thermal envelopes imply that the nominal energy needed to provide and condition ventilation air to achieve acceptable indoor air quality will represent a larger fraction of home energy use going forward. New approaches and technologies, including smart ventilation, are needed to keep California on the path toward healthy ZNE homes while saving energy. The purpose of this project is to develop smart ventilation technology approaches that reduce ventilation energy use and cost while maintaining IAQ. To ensure that smart ventilation technology incorporates air cleaning, IAQ metrics will be developed for optimizing ventilation.

This report provides an overview of existing residential programs for assessing IAQ in new and existing homes. The purpose of this report is to establish the framework for developing and evaluating new IAQ metrics for smart ventilation. Specifically, this report includes a summary of current metrics used to evaluate IAQ and considerations for development of new metrics.

New metrics need to be developed that go beyond a simple air flow requirement, or simple DCV systems if we want to better address health, moisture and odor concerns and to enable the use and valuation of new technologies and ventilation approaches among a greater diversity of market actors.

New metrics for evaluating IAQ are needed to focus more on contaminants of concern rather than the generic or surrogate contaminant approaches of current ventilation standards and industry practice. The metrics will include health-based assessments using the contaminants of concern as well as moisture and odor to address occupant perception and acceptability.

The metrics need to focus on being a method of test: a way to obtain a score, rather than setting a standard for performance, or a minimum level of performance as these will be set by building codes and/or performance standards. Without the new metrics, codes and standard bodies will not be able to act on many significant IAQ-related building industry changes. There are a couple of recent and developing changes related to IAQ that require new metrics. The first change is the development of smart ventilation strategies and controls that attempt to meet IAQ targets with varying ventilation rates. These smart ventilation strategies employ energy saving strategies that move ventilation around in time to avoid times of higher energy requirements to condition the air, accounting for operation of all mechanical air flow systems in a home—not just the whole dwelling ventilation system—pollutants in outdoor air (such as high ozone or particle levels), and deliberate pollutant removal (such as particle filtration systems). The second change is the emergence of pollutant sensing technologies that will allow specific contaminants to be targeted.

Current Metrics used in Implementation

Checklists, Guidelines, and Protocols

Several checklists are currently available for addressing features of homes that may contribute to indoor air quality (IAQ). Many of these lists focus on reducing emissions of contaminants into homes, primarily from building materials, that use third-party assessments of emission rates. The following is a non-comprehensive list of such checklists:

- Scientific Certification Systems
- Green Guard
- Green Seal
- Carpet and Rug Institute
- Collaborative for High Performance Schools products database
- Pharos database
- Cradle-to-Cradle
- GreenScreen assessed
- Living Product Challenge

More detailed guidelines and protocols are also available for new and existing homes. For example the American Lung Association provides the Health House Builders Guidelines that contains detailed protocols for building new homes, which include inspecting the site location, foundation, framing, ventilation system, and finishes and furnishings. The EPA's IndoorAirPLUS program, also for new construction, includes specifications for addressing moisture and radon control, pest control, combustion appliance inspections, as well as using low-emitting materials. Like the Health House Builders Guidelines and Indoor AirPLUS, the WELL certification program includes many aspects of healthy buildings beyond air quality. However, WELL primarily focuses on non-residential applications and includes aspects beyond IAQ such as lighting, comfort, and mental health. The LEED for Homes Indoor Air Quality Assessment includes two approaches for establishing better IAQ. The first approach does not have IAQ metrics, instead the building is flushed prior to occupancy. The second approach allows for one-time air sampling and measured levels of contaminants must be below tabulated levels. Listed contaminants include PM2.5, PM10, ozone, CO, TVOC and a targeted VOCs.

For existing homes, EPA's Healthy Indoor Environment Protocols for Home Energy Upgrades provide guidance and references to resources on improving or maintaining indoor air quality and indoor environments during home energy upgrades, retrofits, or remodeling. Healthy Indoor Environment Protocols for Home Energy Upgrades provides assessments and actions for controlling harmful contaminants (e.g. Asbestos, combustion emissions, environmental tobacco smoke, lead, ozone, radon, polychlorinated biphenyls), moisture, pests, building materials, and ventilation.

Although these checklists, guidelines, and protocols provide valuable guidance for assessing IAQ, none provide methods for easily comparing new and existing homes, strategically targeting IAQ issues, or performing more detailed evaluations for mitigating risk while optimizing smart ventilation for energy savings.

Mechanical Control Systems

CO_2 as an IAQ metric: Demand Controlled Ventilation (DCV)

DCV systems have been used for many years in commercial HVAC systems for controlling comfort and air quality associated with occupancy. For these systems, measured CO_2 is used as an indicator of occupancy and, quantitatively, of human bioeffluents. When the measured CO_2 exceeds a set threshold, the system circulates air to control comfort and odor-related issues in the building. Although this method is effective for high-occupancy commercial buildings, the use of CO_2 levels as a metric representing occupancy (and bioeffluent emissions) is less applicable to residential applications for the following reasons:

1. Occupant densities are much lower and the available CO_2 signal is much harder to discern from background concentrations. This makes CO_2 much harder to use as an occupancy indicator and a control parameter for operating the ventilation system.
2. Due to the proportionally lower source strengths, there can also be considerable delays between initiation of occupancy and CO_2 levels reaching the control limit for operation of ventilation system.
3. Lower occupancy densities and a larger range of activities mean that occupants are no longer the primary source of pollutants (and thus CO_2 is a less meaningful indicator) that we want to control. A primary example of this is the emissions from building products and materials.
4. The nature and degree of air mixing can be quite different in residential buildings.

Despite these drawbacks, CO_2 concentrations have been used as a ventilation evaluation metric in some European building energy codes, often in conjunction with relative humidity (RH). The metrics differ in detail from country to country but have the general form that limits the concentration and exposure time of CO_2 and/or RH. For example, French regulations use a limit of hourly average CO_2 concentrations of 2000 ppm. Each hour above this limit is weighted by the CO_2 concentration for that hour. These products are summed for the year and cannot exceed 400,000 ppm-h (see Equation 1). For RH the limit is set at an hourly average of 75%, and the number of allowable hours above this limit is set at 600 hours in kitchens, 1000 hours in bathrooms and 100 hours in other rooms (see Equation 2). Both these requirements must be met. Note that the RH regulation is a multi-zone metric because it sets different levels for different rooms. Further details for European DCV metrics can be found in the literature review performed by Guyot *et al.*[1].

$$E_{2000} = \sum_{t=0}^{T} C_{CO_2>2000}(t) * t < 400\,000\ ppm.h \quad \textbf{(1)}$$

where: C_{CO2} is CO_2 concentration (ppm),
t is time (hours)
E_{2000} is the CO_2 exposure indicator

$$T_{RH>75\%} = \sum_{t=0}^{T} t < 600\ h\ in\ kitchen, 1000\ h\ in\ bathrooms, 100\ h\ in\ other\ rooms \quad \textbf{(2)}$$

where: T_{RH} is the RH exposure indicator

Equivalent Ventilation

Equivalent ventilation is a key metric for evaluating different ventilation approaches. The central idea behind this technique is that there is a baseline ventilation strategy that can be used as a basis for comparison and that any other ventilation approach should result in the same, or lower, exposure to pollutants. Hence, it would be "equivalent". The only current implementation of this approach is in ASHRAE Standard 62.2-2016. The methods therein were developed by LBNL[2] based on some of the assumptions integral to the ASHRAE Standard, i.e., that the pollutants can be represented by a generic contaminant emitted at a constant rate. The continuous ventilation rate from the ASHRAE standard can then be used as a basis of comparison with time-varying ventilation rates. An equivalent ventilation

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[1] Guyot, G., Walker, I.S., Sherman, M.H. and Clark, j. D. 2017. Residential Smart Ventilation: A Review. LBNL Report (in press).
[2] Walker, I., Sherman, M., Dickerhoff, D., 2011. Development of a Residential Integrated Ventilation Controller (No. LBNL-5401E). Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA (US)
Sherman, M.H., Walker, I.S., Logue, J.M., 2012. Equivalence in Ventilation and Indoor Air Quality. HVACR Res. 18, 760–773. doi:10.1080/10789669.2012.667038

system is one that produces the same (or lower) exposure to this generic contaminant averaged over a year.

This basic approach only applies (as most residential ventilation requirements) to chronic exposures. However, the calculation procedure has been adapted to limit peak contaminant levels and avoid acute exposures. This is particularly useful for ventilation control strategies that are occupancy-based and the equivalency principle can be adapted such that it is evaluated only during times of occupancy. This equivalency approach can also be used with time-varying emission rates, e.g., a reduced emission rate can be stipulated during unoccupied times, and studies are underway to investigate this approach. Although this equivalency metric is for ventilation rather than IAQ directly, the principles and adaptations discussed here will also be useful for direct IAQ metrics.

This equivalency metric has been used by LBNL in the development of the RIVEC controller that allows for time-varying ventilation rates to:

- shift ventilation to times of lower indoor-outdoor temperature difference (or humidity difference)
- account for operation of kitchen, bath and clothes dryer and economizer fans
- pre-calculate required fan sizes and temperature cutoffs for outdoor temperature-controlled ventilation
- ventilate less during unoccupied times
- pre-ventilate for pre-cooling energy conservation and peak demand reduction
- include the use of passive ventilation systems
- avoid exposure to acute pollutant levels

IEA-EBC Annex 68

The International Energy Agency (IEA) established an Implementing Agreement on Energy in Buildings and Communities (EBC) in order to undertake research and provide an international focus for building energy efficiency. The purpose of Annex 68 is to provide a scientific basis for the design and operational strategies of low-energy residential buildings, while maintaining high IAQ standards by controlling sources, sinks and flows of heat, air, moisture, and pollutants when buildings are occupied. Additionally, Annex 68 aims to collect and provide data about properties for transport, retention and emission of chemical substances in new and recycled building materials under the influence of heat and moisture transfer.

Annex 68 will provide data and tools that can be used to guide the operation of buildings that are energy efficient and ensure very good indoor environmental conditions for human occupancy, the project will develop the following:

- Definitions of IAQ performance metrics
- Mechanistic emission source and sink models to estimate pollution loads under realistic environmental conditions

- A database of material storage and transport properties, as well as pollution loads in existing buildings
- A modeling framework and design tool for integrated and coordinated design of low-energy and high-IAQ buildings
- A guidebook on operational strategies for optimal energy performance and good IAQ in residential buildings
- A report presenting and analyzing residential green buildings that achieve optimal energy and IAQ conditions under various climatic situations
- Recommendations for regulatory authorities and guidelines for occupants and building operators

A report for defining IAQ performance metrics for low-energy residential buildings (Subtask 1 of Annex 68) is currently under review. The purpose of this report is to define target pollutants in low-energy residential buildings and identify metrics required to evaluate IAQ and its relation to energy consumption. Specifically, this report compiles published indoor air pollution data in residential buildings from several countries (Australia, Belgium, China, France, Japan and USA). This information was used to compare pollutant concentrations from residential buildings that qualify as low-energy with residential buildings that do not qualify as low-energy. The document also identifies target pollutants that negatively affect indoor air, compiles corresponding pollutant Exposure Limit Values (ELV) associated with the pollutants, identifies IAQ indices developed previously, and defines metrics for achieving very good indoor environmental conditions while maintaining low energy consumption.

Generally, Annex 68 Subtask 1 concludes from published indoor air pollution data that the average pollutant concentrations in qualified low-energy buildings are lower than non-low-energy buildings, with the exception of, α-pinene, hexanal, styrene, trichloroethylene, and dodecane (and note that the ranges largely overlap for the two housing types for these exceptions). The maximum (peak) pollutant concentrations in low-energy buildings are lower than measured in the current building stock, except for styrene, α-pinene dodecane, and hexanal.

Based on the above results, sixteen target pollutants were selected as potential short-term and long-term exposure risks in low-energy residential buildings: acetaldehyde, acrolein, α-pinene, benzene, carbon dioxide, formaldehyde, naphthalene, nitrogen dioxide, PM10, PM2.5, radon, styrene, toluene, trichloroethylene, TVOC, and mold.

Recommended IAQ Metrics

Two methods are recommended for incorporation into an IAQ metric to assess the health risk of these sixteen pollutants. The first method compares measured exposure concentrations to existing exposure standards or Exposure Limit Values (ELVs). ELVs correspond to concentration thresholds above which exposure presents a potential health concern. ELVs are often based on Toxicity Reference Values (TRVs) and Guideline Values for Indoor Air (IAGV). TRVs are based on animal experiments and applying a safety factor of at least 100, while IAGVs are determined from epidemiological studies examining correlation between health symptoms observed in a population of individuals exposed to the compound indoors. Although ELVs can easily be communicated to building contractors, the combined effects of multiple pollutants is currently unknown and averaging or multiplying risks can lead to further uncertainty.

The second recommended method is evaluating the direct health impacts of the pollution through the estimation of Disability-Adjusted Life Years (DALYs) lost. Details for this method are described in Logue *et al.* (2012). The major advantage of using DALYs over ELVs is that individual pollutants can be summed to estimate a combined effect of exposure. However, this approach is easier to communicate to policy and decision makers than building contractors or building occupants.

Although the Subtask 1 report for Annex 68 presents several ideas for developing an IAQ metric, the methods and data analysis specifically focus on low-energy buildings. Because some of the IAQ hazards and metrics identified may not be equally applicable across the current housing stock. For example, air tight low-energy buildings include design elements that can eliminate hazards, such as using conditioned crawlspaces that are air and ground sealed thus reducing the possibilities for moisture and mold problems. For this reason, further evaluation and expansion of the proposed methods is needed for developing a more universal IAQ metric that easily compares residential buildings, regardless of energy efficiency.

Development of new metrics

Due to the limitations described in the previous sections, new metrics are required for comparing IAQ in residential buildings across the range of existing housing stock. These new metrics must be applicable to the entire housing stock, which includes new and old homes of varying energy efficiency, and enable the use and valuation of new technologies and ventilation approaches. The metrics must also be expanded beyond a simple airflow requirement or DCV systems. Additionally, the metrics must focus only on IAQ and exclude cost or energy criteria for the following reasons:

- The cost and energy use of individual measures is highly variable and selecting a fixed cost would be very misleading in most circumstances.
- It is better to allow builders/contractors and other users to determine if their specific costs are worthwhile in terms of IAQ metric improvement.
- Cost (and energy use to a potentially lesser extent if it can be modeled) cannot be determined for emerging technologies that have yet to develop a track record.

- The cost of various measures varies in time – as new technologies are adopted and increase in number their costs can be reduced substantially and these changes would be very difficult to incorporate.
- Cost and energy vary significantly in time and location and it would be impractical to track this and constantly be updating the metric. This also leads to ratings given to the given features changing with time and location, which would result in confusing and inconsistent ratings.
- Building occupants (or others in the marketplace, e.g., property appraisers) may also place value on other potential benefits such as comfort, and this could change rankings compared to those that are determined by considering only by energy costs.

The marketplace needs metrics that assess health, moisture, and odor. If all of these are not addressed a metric is likely to be less acceptable to the building industry. If a health-only metric is used then a home may receive a good rating under that metric but still have moisture or odor problems that would be unacceptable to occupants and the metric will be seen as having little value and/or as being an unreliable indictor for IAQ. Therefore it is likely that even if a single metric were emphasized when evaluating a home, it would be a good idea to have several individual sub-metrics such as for health, moisture and odor. Without the new metrics, code and standard bodies will not be able to act on many significant IAQ-related building industry changes, such as: IAQ valuation of smart ventilation systems, reduced material emissions, improved air filtration, accounting for outdoor pollutants.

Because IAQ is of great value to homeowners, builders, and energy auditors, and code and standard bodies, we will develop new metrics that focus on managing IAQ to reducing the risk of degraded IAQ. The metrics will focus on identifying features and characteristics of the home that both increase and decrease risks of poor IAQ. This “asset rating” approach (discussed in more detail below) is strongly supported by the key constituents of builders (based on feedback from discussions at home performance conferences such as RESNET, EEBA and HPC), DOE’s Home Energy Score program, and appraisers (see Appendix A). Broader concerns associated with Indoor Environmental Quality (IEQ), such as lighting and comfort may be noted, but will not be addressed by these new metrics.

To appropriately manage real and perceived IAQ, the metrics will include health-based assessments using the contaminants of concern as well as moisture and odor to address occupant perception and acceptability. The outcome from these metrics will be a score, rather than a standard for performance or a minimum level of performance. This will allow flexibility for building codes and performance standards to set minimum performance targets.

In the following sections, we provide potential methods for developing new IAQ metrics that address health, moisture, and odor. The methods are designed for IAQ risk reduction and expand beyond current checklists, guidelines, and protocols.

These metrics will also allow the user to compare health, moisture, and odor concerns across the residential building stock (including new and existing homes).

Key Aspects of IAQ

Health

The IAQ Health Metric should focus on identifying home features and characteristics that cause contamination or may help to manage IAQ, and on evaluating the chronic hazards associated with contaminants. Standard metrics such as ELVs and DALYs could be used as quantitative tools for quantifying the potential harm of pollutant intake.

For example, previous studies (Logue et al. 2012) investigated health impacts to prioritize pollutants. Logue et al. (2012) used DALYs to identify the most important pollutants in homes. The results, shown in Figure 1, indicate that PM2.5, NO_2, Formaldehyde, acrolein, ozone, radon, and secondhand smoke are the highest-risk pollutants. Based on these results, the metrics could suggest the use of low-formaldehyde building products or a good range hood to remove particles from cooking. Pollutants associated with the behavior of occupants, such as smoking, will not be considered by the metric. However, tobacco contaminated materials will be considered, as they are now a part of the asset.

Acute health issues (such as CO poisoning) are beyond the scope of this metric, as they are rare, difficult to predict, and sometimes the result of occupant behavior as opposed to inherent characteristics of the building. However, chronic conditions caused by acute exposure such as allergies or asthma will be included. Also, there may be some ways to include acute issues in metrics. For example, a home ventilation system with a high flow "boost" mode might be able to respond to extreme heat, moisture, and bioeffluents in a tight energy efficient home during times of high occupancy (e.g., birthday parties). The inclusion of some aspect of this flexibility to deal with extreme events would be very useful in an IAQ metric.

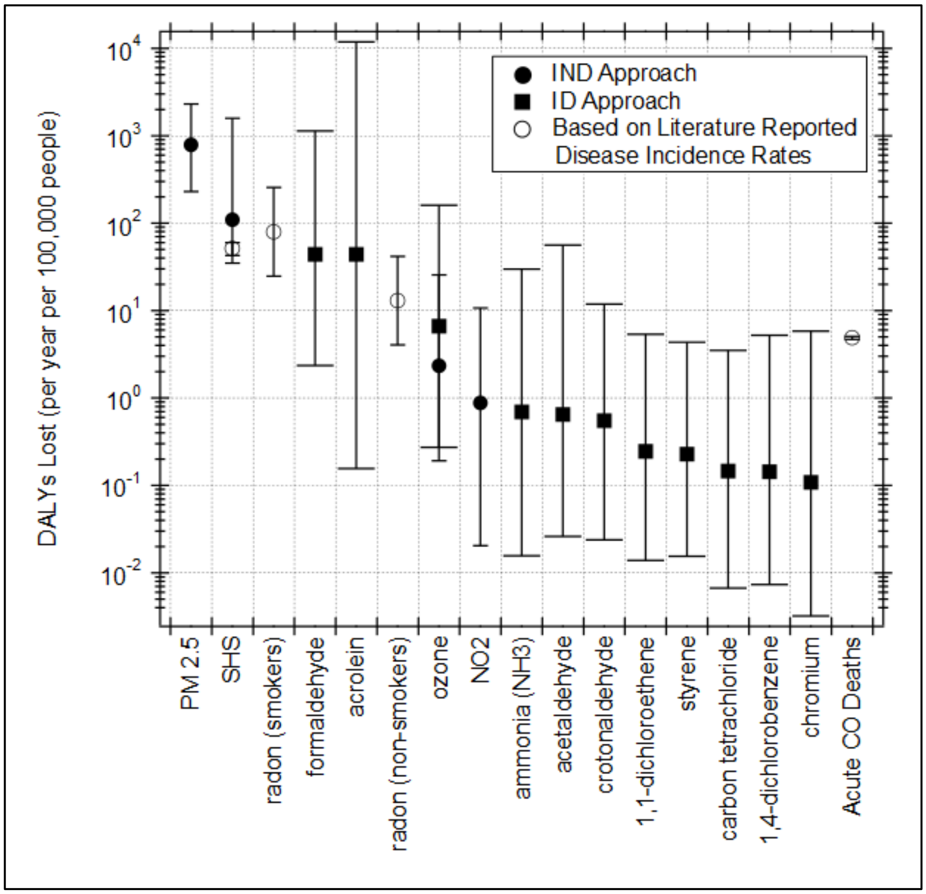

Figure 1: DALYs Lost from exposure to different pollutants taken from Logue et al. 2012.

Moisture

Health hazards associated with moisture (specifically excessive moisture as a substrate with a food source for microorganisms and mold potential) are well established. However, it is difficult to predict how much (quantitatively) home features increase or decrease the risk of mold growth. Additionally, the risk of moisture and mold through certain asset deficiencies or conditions is not clearly quantified. For example, having high relative humidity may lead to moisture and mold issues, but the threshold may vary greatly between homes. Therefore, the IAQ Moisture Metric will focus on addressing features that are known to increase moisture, such as the following:

- **Water leaks** – either from interior plumbing or exterior foundation or rainwater. These are basic construction integrity issues and are the source of many indoor humidity problems. Their solution is more likely in the remedy of the building envelope of plumbing issue rather than through systems that dehumidify indoor air.
- **Air humidity** – including outdoor air and operation of humidifiers and dehumidifiers. The latter includes latent moisture removal by cooling equipment.

- **Interior sources** – there are usually three main indoor sources of moisture: cooking, bathing, and human respiration.

Often a home will have exhaust fans to remove cooking and bathing moisture, but human respiration (and perspiration) moisture is removed by general household ventilation or the operation of dehumidification systems. For comfort and perceived IAQ, the metric will include humidification during the winter in cold dry climates. Although the IAQ metrics will not address all aspects of comfort (such as radiant thermal issues or drafts), comfort associated with IAQ will be included.

Odor
Odor, as well as moisture, is commonly associated with perceived IAQ. Presently, data and quantitative methods for evaluating odor in residential buildings are not readily available because individual human odor response is highly variable. Some guidance for addressing odor are available for commercial buildings, specifically related to ventilation and airflow requirements based on human and environmental bioeffluents, and could be extrapolated to develop an IAQ Odor Metric for residential buildings.

Historically, odor was often the basis for setting ventilation air-flow requirements – based on human and environmental bioeffluents. Additionally, because odor is classically dealt with by dilution using uncontaminated (or less contaminated) air or source reduction, there may be opportunities to use technologies such as carbon filtration (that can also be used for VOC control) to control odor rather then only using dilution. Other considerations for developing an IAQ odor metric are addressing activities such as cooking or other fragrant hobbies, and pets. Because odor is linked to perceived IAQ by many homeowners, addressing these concerns and quantifying the results is of utmost importance. One approach for synthesizing the risk, benefits, and occurrences of odor and odor related activities are through expert elicitation.

Desirable Characteristics of New Metrics

Asset rating
The focus of these new metrics is on an asset rating rather than an in-use rating because we want to evaluate the dwelling and not its occupants. This allows consistent use between new and existing construction and is a better measure for future occupants to assess the IAQ they would experience. It also makes the metrics more robust in that the same house will receive the same rating independent of its occupants and that the rating is not dependent on day-to-day activities of the occupants that could lead to inconsistent ratings (i.e., the same house on different days would get different ratings).

Outdoor Air Valuation
New metrics may consider the impact of outdoor air conditions. Some pollutants, such as particles, NO_2 and ozone, have outdoor air as a primary source. In which

case moving more air from outside to inside without paying attention to filtering may lead to worsened IAQ. These pollutants tend to be location- and climate-specific (as does another key pollutant: radon) In some cases they are also seasonal, e.g., in areas of the US with chronic summertime wildfire seasons and the associated degradation of outdoor air quality. Any new metric should attempt to account for outdoor air quality.

Identifying target audiences
The metrics will be designed so that they can be created and used by building industry professionals, including energy raters and home inspectors. Because they will be broadly useable by the building industry and likely encountered by home occupants or prospective buyers and intermediaries involved in the sale and purchase of homes, the final result must be easy to understand for non-professionals – a single numerical score would be preferable. Discussions with builders have indicated that they like the ideas of a numerical score. This allows users to compare different homes in marketing strategies, get credit for a home with better IAQ, and to assess how best to invest in home upgrades (this is analogous to the $/point exercise they currently use for home energy ratings).

A key audience for IAQ metrics for existing homes will be home appraisers. Once the value of good IAQ is included in a home appraisal it will be easier for the IAQ industry to get homeowners to act and move away from only addressing acute issues, thereby drawing attention to chronic health and other IAQ issues. Appraisers report specific interest in IAQ related issues such as: tobacco odors, pet odors, and signs of moisture damage, etc. Therefore it will be important to include these in IAQ metrics for evaluating existing homes. Appraisers also report that it would be easier to discuss and value IAQ in homes if there were a rating system.

Appendix A discusses more of the issues surrounding IAQ assessment by home appraisers. This includes appropriate language to use when engaging with the appraisal industry that should be borne in mind when discussing the choice of metrics, and that any metric must be very robust so that it is credible and reliable.

Multizone Approaches
As new homes become tighter and high-efficiency heating and cooling systems move away from central forced air, homes are becoming more zonal in terms of their airflow and thermal loads. It is becoming increasingly popular to use zoned systems to condition energy efficient homes – in particular mini-split heat pumps. New homes are also getting tighter with a resulting reduction in natural infiltration airflows. This results in less air mixing inside homes and presents an opportunity to remove pollutants from the rooms where they are generated that can use less airflow compared to whole-house dilution approaches. One example would be bedroom ventilation at night – where an isolated bedroom with a closed door can be ventilated to control for odors, moisture and bioeffluents, enabling lower rates of ventilation in the rest of the home. Current metrics tend to view the house a single well-mixed zone and new metrics are required to address these zonal issues. For

example, one could imagine a metric for IAQ that is applied to individual zones of a home and combined to produce a single metric for the home. This would help guide requirements for zonal approaches to ventilation. Another approach (as discussed above in the example of French regulation) is to produce metrics for multiple rooms, all of which must be considered individually. Lastly, the approaches summarized in the Annex 68 work attempt to combine sub-metrics in different ways that account for dominant metrics.

Some ventilation standards in Europe and Canada have an implied zonal approach in which they require specific airflows to individual rooms (often accomplished with a ducted balanced/HRV system). A metric that allowed the assessment of this approach compared to the single zone approach could be valuable if US (and California) ventilation standards were to use a zonal approach.

A zonal metric would also enable technology development where pollutants known to be common to specific home locations (particles in kitchens, moisture in bathrooms, etc.) could be managed in those locations, or providing pollutant control in occupied rooms. An example of this might be a particle filtration system in a kitchen or a dehumidifier in a bathroom or bedroom.

The multi-zone simulations for this project could be used to inform the potential development of zonal metrics.

Ease of use

A consistent message we have heard from builders, designers, trainers, code officials, standards writers, code bodies, equipment manufacturers, appraisers, and home raters is that any metrics that are developed need to be easy to use. Approaches that require expensive expert and a time consuming research level testing and evaluation of a home will not be successful. At the same time, metrics must have sufficient quality, predictive power, reproducibility, and robustness that they can be relied upon by the buildings industry and potential users to provide good guidance. This is clearly a balancing act, and the primary issue is one of the ease with which a metric can be used rather than its inherent calculation complexity. The underlying calculations can be hidden inside automated software, but any user-facing checklists, field measurements or design considerations need to rely on easy to obtain information (for a building professional). Therefore, the development of metrics will not consider, for example, requirements to monitor individual pollutants for extended periods of time, as we would do for a research project. Instead the focus will be on checklists, observations about a home and some simple field diagnostics, most of which are already conducted in high-performance homes. Examples of field testing include envelope and duct leakage, ventilation system airflows, combustion appliance flue venting assessments, etc. The typical target audience for those who will use the metrics will be some one like a home energy rater, IAQ consultant or HVAC contractor.

IAQ Score – An Example Metric

One metric that we will investigate in this study is the idea of a home IAQ Score that is also being developed by LBNL for the US DOE Building America Program. Home energy scores have provided an important tool in the market place for assessing a buildings energy performance. Energy scores have allowed the market to place a value on energy efficiency and have allowed home buyers to identify homes that will have lower utility bills and less of an environmental impact. A similar tool for IAQ would allow homeowners to identify homes that have a lower health/irritant impact. An IAQ score would also provide a driver for homebuilders to design healthier homes since an IAQ score would likely have a market value and application in real estate transactions.

The overarching goal of the IAQ score is to create an asset-rating tool for a home with respect to its indoor air quality. As an *asset* rating it will necessarily assume certain baseline conditions, such as occupant behavior, and thus does not predict the actual IAQ of the actual home. The development of the IAQ score for homes is being supported by the US DOE Building America program.

The Score has a scale similar to that for a HERS Score, where a score of zero is a very healthy home with an extremely low potential for IAQ issues and a core of 100 would be a typical current home with little or no addressing of IAQ issues. It will be possible to have a score greater than 100 for a home with many serious IAQ hazards and insufficient mitigation.

How to create a numerical score

To create a numerical score, the individual IAQ hazards and mitigation strategies for a home are identified. The various hazards add to the score and the mitigation strategies subtract from the score.

Different hazards have different IAQ impacts and are given numerical values reflecting these differences. These can be summed to give a total hazard score for the home if there are no mitigation strategies in place.

Mitigation strategies impact the score in several ways. Firstly they are evaluated for their potential effectiveness for on each hazard – i.e., what is the risk reduction if the mitigation strategy is implemented as intended. Few mitigation strategies will affect all hazards in a home. For example, a kitchen range hood has a strong impact on cooking-related contaminants, but much less impact on formaldehyde from building contents. They are then assessed for their effectiveness. For example, a exhaust fan whose air flow is verified will be more effective than one that is not, or an automated range hood that does not require the occupant to operate it would be more effective than a manually operated hood. There will be negative and positive adjustments to the score for other aspects of mitigation strategies:

- Usability: How easy and intuitive is it to use or implement the measure?

- Durability: Is the measure likely to retain its utility and performance over time?
- Robustness: How commonly does the system work when implemented as intended?
- Maintenance: How much effort is required to maintain the measure?

This way, no measurements or diagnostics are require to obtain a score for a home, but homes that do have confirmed performance will get a better score.

There will be limits on mitigation for some hazards. Once mitigation strategies have completely addressed a hazard, additional mitigation will not further reduce the score. For example, if the subject home has an excellent range hood that removes all cooking-related contaminants, then other mitigation strategies that would affect these contaminants (such as an air filtration systems) will not influence the score.

Next Steps

This guidance and summary of IAQ valuation approaches will be used to develop metrics for the analysis of IAQ simulations that will investigate ventilation and IAQ approaches for high-performance California homes. This information will also be used in the development of an IAQ Score in collaboration with the US DOE Building America program.

Appendix A. Perspectives from the Home Appraisal Industry

This appendix begins with some context about appraisers, their methodologies, and the history of efforts to bring green and high-performance considerations into the residential valuation process. Key barriers and challenges are noted, along with recommendations for how they might be addressed in the context of efforts to promote LBNL's IAQ Score. Feedback from real-world appraisers on the IAQ score concept is provided. Appraisers from California, Colorado, Florida, and Kentucky were interviewed to gain perspective on how the industry views IAQ and how they might receive an IAQ score.

History and disposition of the industry

While efforts to quantify incremental property values conferred by high-performance features go back at least to the early 1980s, the vast majority of activity has taken place within the past five years. There have been scores of studies and an array of disjointed policy efforts to engage and compel the appraisal industry to consider building performance in their valuations. A detailed history of activities is given in Mills (2016). Federal agencies and others in the "high-performance homes" community have had little to show for all these years of work, largely due to lack of understanding of the appraisal practice as well as market and business conventions and constraints.

Many players have engaged in efforts to promote improved property valuation practices regarding green and high-performance features. These include the Appraisal Foundation, The Appraisal Institute, Colorado Energy Office, Earth Advantage, EcoBroker, Elevate Energy, Fannie Mae, Federal Housing Administration, Home Innovation Research Labs, The Institute for Market Transformation, Northwest Energy Efficiency Alliance, National Association of Homebuilders, National Association of State Energy Officials, National Association of Appraisers, RESNET, USEPA, USDOE and some of its National Laboratories, the U.S. Green Buildings Council, and the Vermont Green Homes Alliance. Many activities have resulted, ranging from trainings, to data-gathering instruments, and the emergence of a literature attempting (largely through Hedonic Pricing techniques) to statistically isolate the effects of green/high-performance characteristics on home values. In some cases, the results of studies have been analytically flawed, overgeneralized, and oversold.

Leading efforts to date have focused largely on energy, and to a lesser degree water and other "green" factors such as building materials. Little to no effort has been spent on indoor air quality, primarily due to lack of interest on the part of homebuyers (as perceived by appraisers), and, to a lesser degree, due to difficulty in quantification. The proposed IAQ Score will help with the latter and, perhaps, over time, with the former.

Worthy of consideration, the U.S. appraisal industry is in the doldrums. In part a reflection of the evolving economic and regulatory environment faced by appraisers, the demographics of the trade (residential and non-residential) show a shrinking and aging workforce with fewer new appraisers entering the field. Nearly two-thirds of appraisers are over 50 years old, with 80% having a bachelor's degree or less education. Median salaries are under $53,000 per year. As of mid-2015, there were 78,500 active real estate appraisers across the U.S., about three-quarters of which were men. The actual number has fallen by about 8,000 from the year 2011, or at the rate of 3% per year. The advent of Appraisal Management Corporation (AMC) clearinghouses has cut the fees received by appraisers by up to 50%, leading to a less skilled and motivated workforce. Approximately 80% of appraisers report dropping fees in 2015. Two thirds of these are sole proprietors. Only 4% of appraisers exclusively practice commercial appraising, 80% exclusively residential, and 15% both. Only 22% of appraisers are optimistic about the future of their profession. Two-thirds of appraisers do not belong to any trade association. Trade association membership is very fragmented, the top three being the Appraisal Institute, with membership representing about 43% of the those being members of any association, followed by State Coalitions (~25%), NAR (~20%), and NAIFA (~15%). These industry dynamics complicate outreach efforts.

How Appraisers See their Role

Traditional appraisers see their job as one of gathering property information on factors that are important to buyers (e.g., granite countertops and swimming pools) and translate that into an estimate of market value. Other use cases apply, e.g., for insurance appraisers who are focused strictly on the replacement cost of structures.

Most do not see their role as driving buyers to assign more value to specific factors or to consider new factors not currently on their radar. However, there is a strata of appraisers in the industry eager to educate their customers and who see their role more clearly reflect social responsibility and environmental values.

In the real world, there are of course influential drivers that are not property-specific (e.g. panic buying in hot markets, proximity to good schools, etc.). These tend to swamp considerations of building performance.

Appraisal Methodologies

Appraisers (both residential and non-residential) utilize three well-established methods of valuation, often used in tandem or in combination.

> The Cashflow method entails defining value as a multiple of income and expenses. While typically used only for non-residential "income" properties, it has been applied to assessing the incremental value of energy features in homes. This does not appear to be relevant for IAQ issues.

The Comparable Sales method requires finding “like” homes that have been recently sold and analyzing those outcomes, with adjustments up or down for differences in the subject property. Lacking IAQ data or scores that can be correlated with large numbers of home sales, makes this approach largely a non-starter in the near to medium term. Perhaps once there are large numbers of homes receiving IAQ scores and, if those data are publicly disclosed, sales data can be correlated with scores. Isolating the IAQ signal from all the other noise in the marketplace will be a major challenge. There is no sign of this happening any time soon, even with energy use, although efforts like the “Green MLS” are trying to do so. That said, the IAQ ratings and associated documentation can be valuable to appraisers via the “Cost Basis” method long before it is affecting the broader market in measureable ways.

The Cost Basis method sets value equal to cost, with adjustments. It can be applied to incremental improvements to a property, although potentially de-rating investments in particular new features if the appraiser deems that the market will not fully value the feature (e.g., maybe a $5k granite countertop project is only worth $3k to prospective buyers). Cost-basis appraisals must also consider changes in codes since the structure was built. This method is perhaps the most promising angle for IAQ if the costs of remediation can be identified and incorporated into the sales transaction/negotiation process. Appraisers interviewed for this study said that remediation costs for an “as-is” property can readily be subtracted from the preliminary valuation. Alternatively, the value can be given “as-repaired”, with the idea that sellers and buyers negotiate a credit in the case where a seller will correct the deficiency prior to sale. Where “comps” values are available, they can be adjusted based on information regarding deficiencies. By analogy, existing pest and structural reports generate familiar “cost-to-cure” lists that appraisers (and buyers) readily use in tuning their valuations. In some markets, the need for radon mitigation is a familiar instance of such costs. While initial scoring methods would not provide information on costs to correct deficiencies, other entities could do so. One appraiser suggested that training home inspectors (who are already in the building) to estimate these costs may be one way to achieve this.

The appraisal industry is not at all amenable to adding new high-level valuation “Methods” to their practices. Proposals from the buildings performance community need to fit into the existing three approaches in order to get any sort of traction. In practice this should not be an issue—the current methods are readily extensible for application IAQ considerations—but it is important to know that appraisers are sensitive to external proposals for changes in their tried-and-true methodologies.

Aside from the actual valuation methods, appraisals also serve an important role in assembling qualitative and quantitative documentation. This is where IAQ information could most readily make its mark.

Early examples of IAQ being recognized by appraisers

Over the course of a 5-year Memorandum of Understanding, the U.S. Department of Energy has collaborated with The Appraisal Foundation (TAF) to produce several reports. The first defines "competency" as it pertains to appraisers' ability to incorporate green and high-performance building considerations into their valuation assignments (Black *et al.,* 2015). This document references IAQ a number of times and points to various resources. A subsequent document in the series (Curry *et al.,* 2016) focuses on specific applications in residential settings. This document goes into slightly more detail on IAQ--including examples of issues to be on the lookout for and types of tests and reports to look for—and refers to the Information Atlas for appraisers (created by LBNL) for more information.[3]

In 2013, the Appraisal Institute (a 'competitor' of TAF) created a 5-page "Residential Green and Energy-Efficient Addendum," intended to be a template for assembling key information for attachment to a standard appraisal. The focus is primarily on energy. The addendum includes a single scant row for information in IAQ, with a set of three eclectic checkboxes for whether Indoor Air PLUS was applied, ERV or whole-building ventilation system, and/or Non-toxic Pest Control. There are no official statistics on how many appraisals are including this addendum, but indications are that the number is small and that appraisers have great difficulty finding the information asked for as well as justifying the effort/cost to do so. There is no specific crosswalk for using this information in the valuation process, with the implication that it is intended primarily as background contextual information. It could prove far more effective for the Addendum to simply reference the results of the score described here.

The 308-page tome entitled "Value Beyond Cost Savings: How to Underwrite Sustainable Properties" (Muldavin 2010) is often cited as a definitive report for appraisers, but has only passing references to IAQ (mostly pertaining to non-residential settings), and offers no practical techniques for appraisers. The report cites LBNL's IAQ Scientific Findings Resource Bank as "the best, and most scientifically sound summary of the potential health benefits of sustainable properties".[4]

A series of hands-on appraisals of Colorado homes with a range of green and energy-efficient features provides useful examples of how IAQ can be approached in practice (Desmarais *et al.,* 2015).

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[3] https://sites.google.com/site/appraisinghpbuildings/key-topics/indoor-environmental-quality
[4] http://eetd.lbl.gov/ied/sfrb

Challenges and Recommendations

In recent work for DOE (Mills 2015), we identified a high-level set of barriers to the incorporation of IAQ and other home performance considerations into residential valuations, along with recommendations. The following discussion includes observations on how these considerations might apply in the case of the proposed IAQ score.

Highly limited awareness and interest; sometimes aversion

Issue: The IAQ issue is hardly on the radar of appraisers, and they do not generally perceive homebuyers as caring about it. One very seasoned appraiser stated that "I have actually never had a Realtor, a builder, a developer, a buyer, or a seller express any concern to me about valuing the indoor air quality of a property." In the case of refinance appraisals, owners can be defensive about appraisal notations on mold, odor, etc. The situation will of course vary significantly by geography and local market conditions. For example, a Kentucky-based appraiser interviewed said there is nearly zero awareness of or interest in "green" in the local market, while those interviewed in Colorado noted high interest.

Recommendations: While "IAQ" may not be a familiar concept to appraisers, many, in practice, actually do observe relevant factors in a home (tobacco odors, pet odors, and signs of moisture damage, etc.). One interviewee mentioned a recently listed home in a very hot market that was well priced but had serious cat odors – 30 prospective buyers passed on the offering because of this. Some appraisers of course operate in areas where radon testing and mitigation are required. In these cases, they are more keenly aware of the need for assessment. One interviewee mentioned homes in proximity to chicken farms and pig feed lots (aka "external obsolescence" in industry parlance). In these cases, comparable sales can be sought for similarly disadvantaged homes or for otherwise similar homes without the problem as a means of identifying the effective impact on value. "Curable" obsolescence can be addressed, e.g., with air filtration systems.

All interviewees said that a scoring system would help back them up in terms of logging these otherwise nebulous and subjective issues. To ensure that appraisers are cognizant of the state of buyer sentiment, information should also be assembled to help characterize public views on IAQ, particularly at the time of home purchasing or refinancing. Per the American Housing Survey there are only a few questions of interest. AHS asked about mold, musty smell, thermal comfort (too hot / too cold), asthma, and general satisfaction. The results are what one might suspect. People who live in newer homes give their homes a higher rating. Older homes have more mold problems and more occupants reporting musty smell. Occupants report more problems with thermal comfort in older homes. Data show quite clearly a higher incidence of asthmatic children in homes that have mold. To be usable by appraisers, such information must have a high level of geographic specificity.

Realtors are important ‘trade allies’ in this regard, as they are a key source of information to appraisers.

Competency

Issue: Few appraisers are literate on matters of IAQ research, risk weightings, or mitigation technologies and have correspondingly few, if any, techniques for including IAQ in the valuation process.

Recommendations: It will be important to create appraiser-specific trainings to introduce an IAQ score or score and establish related literacy in IAQ concepts and third-party reports. Appraisers will need to understand this information and be comfortable adopting the findings. As the methods become more widely used, appraisers will need to know how to access the data needed to identify comparable scoreed or scored homes in their region.

Information deficiency

Issue: Appraisers have great difficulty obtaining information about the performance of a subject property. They have precious little time for research beyond the bread-and-butter aspects of their assignments. A numerical score, in and of itself, will not likely be usable in the valuation process although appraisers may still incorporate it in their reports for background.

Recommendations: It will be essential that the IAQ indicators are readily available and understandable to appraisers. Owners are a natural party to convey the information to the appraiser, but it can also come through other channels (realtors, inspectors, lenders, etc). For homes seeking FHA financing, FHA requires that appraisals be disclosed to buyers no later than three days before the purchase contract is signed. This provides an opportunity to expose buyers to IAQ information and recommendations before purchase negotiations are concluded. Until very large numbers of homes have been evaluated, appraisers will not have particular use of the score itself for comparables analyses, but the associated documentation stands to be more useful, particularly if specific deficiencies are identified and, ideally, costed.

Time/budget pressures and process commoditization

Issue: Financial regulations implemented in the wake of the 2008 housing market meltdown resulted in the entry of new “middle-men” into the appraisal process, along with efforts to automate and commoditize the appraisal process. Appraisers’ fees have been cut in about half in the process (appraisers take home maybe $100-$150 per typical appraisal and spend less than an hour at the property), and appraisers' discretion has also been reduced as the process has become more commoditized.

Recommendations: Transaction costs associated with IAQ score documents must be reduced to an absolute minimum. Entities creating appraisal templates and protocols should be engaged and compelled to recognize the relevance of this information. Financial incentives to help appraisers justify the added time to consider IAQ would no doubt increase their use of the information.

Professional differences between appraisers and building performance professionals

Issue: Few appraisers understand building science, or the associated terminology. Building performance experts, in turn, have limited grasp of the appraisal process or ability to put their points into a language that appraisers will understand and respond to. An example includes the near nil value of properties that are highly obsolete or not appropriate to the location and thus likely to be replaced by future buyers. Conversely, properties that are over-built ("super-adequate" in appraisal jargon) cannot garner additional value through performance enhancements.

Recommendations: The IAQ scores or indices need to utilize plain language. IAQ "experts" brought in to educate appraisers must be sensitized and not leave them in the dust with jargon and science-heavy presentation. These considerations will of course also apply to other target audiences. It would be wise to create a brief "primer" on the methodologies and reports written expressly for appraisers, using their language. Conversely, it behooves the building-performance community to better understand real-world property-valuation considerations and language. For example, the appraisal jargon for IAQ problems is "functional obsolescence" and the corrections would be known as "cures", and this language should be used to help acclimatize appraisers to the otherwise foreign information.

Risk aversion

Issue: Appraisers are cautious about extending the scope of their practices, partly due to aforementioned time/budget pressures, but also due to professional liability considerations and reputational risks such as those that "bit" appraisers when they were taken to task for being part of the housing bubble. As a result, attributing additional value to a property is something they are more cautious about than previously.

Recommendations: The credibility of the score, those applying it, and associated documentation will be key to appraisers' comfort level.

Public policy vacuum

Issue: DOE, EPA, HUD, Fannie Mae, state energy offices, and others thus far had little impact on appraisal practices (Mills 2016). This is largely because efforts have been limited largely to disjointed trainings, workshops, reports, etc., with no long-term strategy or staying power. One key strategy that has not been well explored is efforts to create demand for improved appraisals.

Recommendations: More two-way interaction with the appraisal community is needed, with increased emphasis on listening and adapting existing offerings to meet the needs of these stakeholders. Meanwhile, educating buyers to be asking the right questions is of central importance. Educating lenders, Realtors, home inspectors, and others will also result in better information received by appraisers.

Additional appraiser comments and suggestions regarding implementation

Following are an assortment of ancillary comments made by the appraisers interviewed:

There are already many ratings out there. Yet another 1-10 or 1-100 scale could easily add to confusion. One interviewee suggested denoting rating as "IAQ-1, IAQ-78," etc. to help reinforce the distinction.

Incorporating outdoor air quality data and consideration would be welcome. It is a known issue but appraisers don't currently have information at their fingertips about it.

Plain-language checklists (e.g., of curable deficiencies) are valuable, even if not quantitatively part of the score computation. Such checklists would, of course, serve multiple constituencies.

Getting scores into the MLS (there is already an extensive "Green MLS" movement) would be a good way to ensure that appraisers can readily find the scores through an information channel with which they are familiar.

Home occupants can sometimes seek to conceal IAQ problems (e.g., by using incense or diffusion sticks). IAQ assessors need to keep an eye out for such diversions.

Appraisers like the idea of considering particularly sensitive populations (allergies, asthma, children). However, they cautioned that having "modified scores or indices" for different groups could easily make the report difficult to absorb. A more elegant solution would be if certain thresholds (e.g. scores 80 and above) can be flagged as thresholds of acceptability for certain sensitive populations.

Stating the date of the assessment is important, along with guidance as to how rapidly circumstances can change in the home. The score should perhaps have an associated "expiration" date.

Appraisers agree on the importance of looking at "asset" vs the "occupancy" characteristics, and are familiar with this notion from energy ratings.

The Appraisal Institute's Addendum will be revised and there is interest in improving treatment of IAQ. A place for noting the IAQ Score could presumably be added to the report.

Severe hoarding is an important "red-flag" for IAQ problems. One appraiser noted that this often correlates with mold issues, pests, and hidden property damage, etc.

Photographs are a very important part of deficiency documentation. The IAQ score protocols should encourage photo documentation.

Insurance appraisers are also tasked with identifying and communicating observed risks back to the insurers. For IAQ these can involve readily observable issues such as moisture entry/damage, suspicious odors, unvented appliances, etc. Insurers then stand to become engaged in driving the remediation process. Insurers are already engaged in other aspects of green and high-performance buildings (Mills 2012). An IAQ score or score can thus be relayed to insurers via the appraiser.

Potential partnerships and collaborators

No one trade association has a large "market share", and many residential appraisers are not members of any association. Despite a 5-year collaboration with DOE, the Appraisal Foundation has been highly ineffectual and has shown little interest in disseminating the results or otherwise putting the results into practice. The other key professional organization working in the space is the Appraisal Institute. AI has a series of trainings and publications, and produces the Green Addendum.

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