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Perspective

Ventilation Without A Meter: Energy, Health, and Buildings We Cannot Sense

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***Abstract*—Ventilation often accounts for 20%–40% of HVAC energy, yet most buildings verify outdoor-air supply once, i.e., at design or commissioning, rather than in the occupied zone. Too little outdoor air degrades indoor air quality and raises the risk of infection and reduced cognitive performance; too much locks in heating and cooling load for the life of the plant. Without a room-level measurement, the delivered rate is unknown, and operators gamble between waste and stale air. Humans cannot smell carbon dioxide or see respiratory aerosols, and they adapt within minutes to the odors they can detect, so occupants never generate the complaint signal that produced thermostats and smoke detectors. A century of chamber science was frozen into prescriptive per-person and per-area ventilation rates; a dedicated mammalian olfactory pathway for near-atmospheric CO_2 was lost in haplorrhine primates, and many burrowing species became tolerant of high CO_2 rather than better at metering it. A smoke-detector-class sensor in each occupied zone, coupled to dampers and to a dual performance rule, i.e., breathing-zone CO_2 together with measured ventilation energy or heat-recovery effectiveness, would close that loop. Until outdoor air is metered where people breathe, claims that a building is both efficient and healthy remain hypotheses.**

ABBREVIATIONS

GC-D	guanylyl cyclase D
DCV	demand-controlled ventilation

Stay in an office, a ward, a classroom, or a hotel room for some time and then ask two questions: what is the quality of the air in this room now, and where did that air come from? In almost every building the honest answer is that nobody knows. The occupant cannot tell. The operator has, at best, a design flow at the air handler and a setpoint on a thermostat. The outdoor air that the building has already paid to heat or cool is rarely metered where people breathe.

That gap is an energy problem before it is a metaphor. Ventilation is one of the last major HVAC end uses that are specified on paper but rarely verified in the occupied zone. In commercial buildings, it commonly accounts for 20%–40% of HVAC energy use. In cold weather, the load is simply the enthalpy difference between outdoor air and the indoor setpoint, delivered hour after hour, often at a constant rate chosen for peak occupancy rather than actual need. Too little outdoor air leaves bioeffluents, moisture, and exhaled aerosol undiluted; too much wastes fuel or electricity conditioning air for people who are not present. Without a room-level measurement, ventilation rate selection is a gamble, not a control problem.

The gamble persists for a reason in monitoring and sensing that is easy to overlook. Too high temperature produces an occupant complaint within minutes. Smoke produces a flight response. A water leak stains the ceiling. Carbon dioxide, fine particles, and most indoor chemistry provide no comparable warning. Occupants adapt to many odors they can detect, and humans have no organ for the gas they exhale with every breath. Prescriptive standards filled that silence with a calculation: a per-person rate plus a per-floor-area rate, verified once, then treated as true for the life of the building. Meanwhile, filters load, dampers stick, occupancy changes, and heat-recovery cores foul. None of these changes is required to announce itself.

This perspective argues that the binding constraint on both ventilation energy and indoor air quality is not a missing formula, but a missing meter. A century of chamber science has already shown that the required outdoor-air rate depends on what is measured and where. Comparative physiology helps explain why occupants cannot provide that measurement themselves. The implication for power and energy systems is straightforward: Until outdoor air is sensed in the breathing zone, and until that signal can actuate fans and dampers and populate a compliance record, buildings will continue to purchase energy for an environmental service whose delivery they cannot verify.

1. AN UNEVEN MATURITY IN BUILDING TECHNOLOGIES

It is useful to compare three enclosure problems that may look similar in a specification but behave very differently in the field.

Thermal insulation has been industrialized. Mineral wool,

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foams, polyisocyanurate, and vacuum panels are sold with stated resistance per unit thickness. Their performance is largely a bulk property: A small gap or compressed edge reduces the effective *R*-value, but it does not usually void the entire layer. The supply chain is mature, installation practices are standardized, and prices have followed scale.

Moisture management is similarly advanced in its logic, even if execution remains uneven. A rain screen or drainage plane assumes that some water will pass the outer skin and provides a second path for it to leave. Failures also tend to announce themselves. A stain, damp patch, efflorescence, or mold growth is a sensory signal. That signal has driven detailing, insurance, and litigation for decades. The market can see the defect.

Air tightening and ventilation have not reached the same condition.

The aim of air tightening is to stop uncontrolled flow through the envelope. The materials, tapes, sealants, membranes, and gaskets work when the substrate is clean, dry, and well pressed. But the physics is unforgiving. Insulation resists conductive heat transfer through the envelope. An air barrier resists advective flow through holes. One missed seam, unsealed penetration, or gap at a sill can dominate the leakage of an entire wall. Unlike a rain screen, a conventional air barrier has little redundancy. It is only as good as its weakest point.

Part of this lag is physical. Part of it is sensory. An air leak is often a faint draft, a slightly higher heating bill whose cause is never isolated, or hidden condensation that rots sheathing over a decade. There is no stain on the day of handover. Demand for more industrialized sealing has therefore been weak. The blower-door test provides a valuable metric, but it is typically taken once, at whole-building scale, and rarely repeated.

Ventilation faces the same deficit at a finer spatial scale. Its task is to deliver outdoor air to every occupied zone and remove stale air. Yet codes generally do not ask whether that happened this afternoon. They ask whether a per-person rate plus a per-floor-area rate was included in the design, and perhaps whether a commissioning measurement at the air-handling unit was acceptable. After that, the drawing is often treated as the building. Filters load, dampers stick, occupancy changes, pressure relationships drift, and heat-recovery effectiveness declines. None of these changes is required to produce a room-level signal.

There is no equivalent of a thermostat for outdoor-air delivery: No cheap, stable, ubiquitous sensor that tells the occupant or the control system whether the intended air has reached the breathing zone. Temperature control closed its loop because people feel heat and cold. Moisture control improved because leaks become visible. Ventilation remains largely open loop because its failures are slow, mixed, and mostly outside the senses. The blower door and the commissioning traverse are prosthetic measurements. They are applied once. They are not a nervous system.

The rest of this paper asks why that loop was never closed, what the missing measurement costs in energy and air quality, and what a room-level meter would have to do.

II. THE REQUIRED RATE ITSELF IS A MEASUREMENT PROBLEM

The outdoor-air rates written into today's codes did not descend from a single physical constant. They emerged from chamber experiments that disagreed about what was being measured, and where.

In the 1930s, Yaglou and colleagues seated occupants in a closed room, allowed body odour to accumulate, and asked visitors entering from fresh air to rate acceptability [1]. As occupant density increased, the outdoor air required per person to keep the air "fresh" also increased: roughly 15 cubic feet per minute (cfm) per person in a sparsely occupied room, and 30 cfm per person or more in a crowded one. That density-dependent curve entered early ventilation guides. It matched intuition: Crowded rooms feel stuffier, so each person appears to need more air.

Cain and colleagues revisited the problem under tighter experimental control and isolated body odor as the only pollutant source [2]. They found that the ventilation rate per person required for a given acceptability did not increase with density. If the number of people doubled and the total outdoor-air supply doubled, perceived air quality remained approximately constant. Steady-state dilution predicts the same result. If each person emits bioeffluents at a roughly constant rate, concentration is governed by total emissions divided by total outdoor-air flow. The per-person rate alone determines the outcome.

Fanger then added the building. People are not the only sensory source indoors. Materials, carpets, furnishings, and air-handling systems emit odorous and irritating compounds. He quantified those sources in *olfs* and perceived air quality in *decipols* [3], [4]. Building emissions are, to first order, an area-based load, largely independent of how many people are present. In a crowded room, the large outdoor-air flow required for occupants also dilutes that background. In a sparse room, the building source dominates, and the outdoor air required *per person* to achieve a target perceived quality is higher. Fanger's curve therefore ran opposite to Yaglou's: Crowded spaces require less outdoor air per person, not more.

A later interpretation is that the two traditions were probably not measuring the same air. Yaglou's visitors walked among the seated occupants and sampled the near-field plumes of heat, moisture, and breath around individual bodies. In a denser crowd, those plumes were difficult to avoid. Cain's and Fanger's assessors, by contrast, sampled air at a controlled distance, closer to the far-field, better-mixed condition. Near-field exposure and well-mixed concentration are not the same quantity. Standards that collapse them into a single number risk mis-sizing the system.

ASHRAE Standard 62.1 and related standards resolved this disagreement by addition rather than by measurement. A per-

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person component (R_p) represents occupants; a per-floor-area component (R_a) represents the building [5]. The sum is calculated once at design. It then becomes the compliance definition of acceptable ventilation. But no one is required to measure the actual *olf* load of a particular carpet, the real occupancy of a room in a given hour, or the concentration in the breathing zone rather than the return grille.

That matters for energy as much as for odor. If a large conference room is empty but the air handler continues to deliver design outdoor air; the thermal penalty is locked in. If the same room is densely occupied and near-field plumes dominate exposure, the design rate may be too low at the nose even when the room-average CO_2 appears acceptable. Without knowing whether a zone is people-limited or building-limited, and without knowing whether a sensor, if present, samples the plume, the breathing zone, or the mixed core, the designer cannot tell whether the system is wasting heat or starving the occupants of dilution. The required rate is not a fixed cubic meter. It is the answer to a measurement question that most buildings are not asked to keep answering.

Table 1 is not a verdict on who was right. It is evidence that ventilation rates move when the measurement protocol moves. A code that freezes one protocol at the design stage, and then never samples the occupied room, has already chosen to absorb that uncertainty as an energy and health margin rather than observe it directly.

TABLE 1
THREE MAJOR STUDIES ON THE VENTILATION REQUIREMENT

Study	What was judged	Per-person outdoor air as occupant density rises
[1]	Visitors in the occupant plume	Increases
[2]	Body odour only, far-field	Constant
[3]	People plus building sources	Decreases

III. THE OCCUPANT CANNOT BE THE SENSOR

Yaglou, Cain, and Fanger all used unadapted visitor panels for a reason that buildings still live with: People already in a room are poor judges of steady-state air quality. Within fifteen to thirty minutes, the human nose adapts almost completely to a constant background odor [6]. Occupants may accept air that a person entering from outdoors immediately finds stale. The visitor panel was therefore a temporary prosthesis: A sensor that had not yet adapted. But that prosthesis is narrow. It reports only a subset of volatile compounds from bodies and materials. Most of what ventilation is asked to control never reaches consciousness.

Carbon dioxide, the usual proxy for occupancy and outdoor-air supply, has no odor at normal indoor concentrations. The "stuffiness" that people attribute to high CO_2 is, in chamber studies, driven mainly by temperature and humidity. Subjects who breathe elevated CO_2 through a mask in otherwise fresh air do not report worse perceived air quality [7]. That result concerns perception. It does not make rebreathed air harmless. CO_2 remains a practical marker of the fraction of air that has already been in other people's lungs, and that fraction matters for infection risk and may matter for some cognitive outcomes. The operational fact is simpler: Humans have no conscious sensory channel for the gas they exhale.

Humans are not without CO_2-sensing physiology. Central chemoreceptors in the brainstem and peripheral chemoreceptors in the carotid bodies regulate breathing to keep arterial PCO_2 near 40 mmHg. But those sensors evolved to stabilise blood pH, not to report the mixing ratio of CO_2 in a room. For most of later mammalian history, and for the history of Homo, the outdoor CO_2 mixing ratio was low and relatively stable. Ice-core records place glacial-interglacial CO_2 between roughly 170 and 300 ppm. Inspired air at 280 ppm rather than 420 ppm barely shifts alveolar PCO_2. There was little selective pressure to smell ambient CO_2. Permanent tight rooms are about ten thousand years old. Crowded, mechanically sealed interiors are far newer.

Other mammals did evolve an ambient CO_2 sense. In mice, olfactory neurons that express guanylyl cyclase D (GC-D) and carbonic anhydrase II detect CO_2 near atmospheric levels, with a behavioral threshold of about 0.066% [8]. The same gene, *Gucy2d*, remains intact in rats, dogs, and wet-nosed primates. In haplorrhine primates, including tarsiers, monkeys, apes, and humans, it is a pseudogene. That loss occurred early, more than about forty million years ago [9]. Humans did not simply fail to invent a CO_2 nose. We inherited one and lost it.

The same sensory deficit applies to many other ventilation-relevant hazards. Fine and ultrafine particles, including respiratory aerosols and infectious airborne viruses, are invisible and tasteless. A person can sit half a meter from an infected speaker and inhale a concentrated exhaled plume with no immediate signal; illness, if it comes, arrives later [10]. Radon is imperceptible. Carbon monoxide is odorless until intoxication is advanced. Formaldehyde and many other organic compounds irritate at high levels, but chronic low-level exposure may never become a complaint [11].

This is why fire and thermal comfort produced universal hardware and codes, while indoor air quality did not. Heat is felt. Smoke is smelt. Water leaves stains. But ventilation failures are slow, mixed and mostly silent. The occupant cannot close the control loop. Any building that treats comfort votes or the absence of complaints as evidence of adequate outdoor air is reading a sensor that was never installed.

IV. THREE STRATEGIES, NOT ONE PARABLE

If humans cannot monitor the air they breathe indoors, animals that live in confined spaces offer an obvious comparison. But the comparison is useful only if three distinct strategies are kept separate: sensing, tolerance, and architecture.

A burrow is a poorly ventilated enclosure. Oxygen can fall and CO_2 can rise far above outdoor levels. That is not the

same task as detecting a few hundred parts per million above a 400-ppm background in an office. Surface-dwelling mice solved the second task with the GC-D olfactory subsystem. Many fully fossorial mammals solved the first by becoming tolerant.

The naked mole-rat is the best-studied case. Colonies live in crowded tunnels where nest CO_2 is often around 1%–2% and can be higher. Concentrations that would cause headache, dyspnea, and hyperventilation in humans produce little obvious distress. The known physiology is mainly about pain and breathing, not about a high-resolution CO_2 nose. A species-specific variant of the nociceptor channel $Na_v1.7$ allows protons to block spike initiation, so tissue acidosis from high CO_2 does not produce the same pain response [12]. Whole-animal ventilation often does not increase until CO_2 reaches several percent, and some studies report preference for nest chambers with elevated CO_2. In effect, the complaint signal has been turned down. That is the opposite of a building management system. It is an evolutionary decision to treat chronically stale air as normal.

Social insects illustrate a different strategy: sensing coupled to action. Leaf-cutting ants carry CO_2 receptors in antennal sensilla ampullacea. These cells respond from near-atmospheric levels, encode CO_2 over a wide range, and do not adapt during prolonged stimulation, so they can report the standing CO_2 concentration of a chamber rather than only a transient change [13], [14]. Workers use those cues in nest modification and brood care. Honeybees increase fanning when hive CO_2 rises [15]. The molecular hardware is not the mammalian GC-D pathway, but the control logic is similar: a dedicated, slowly adapting or non-adapting sensor linked to behavior.

Termite mounds are often over-read as a ready-made control system. A mature mound of *Odontotermes* and related species is a respiratory structure, with porous walls, chimneys, and surface conduits. Much of the exchange is passive, driven by diurnal temperature differences, wind, and geometry rather than by a calculated flow rate per insect [16]. Workers do open and close openings, but the architecture performs much of the work. The useful lesson is not that buildings should copy termite mounds. It is that a confined colony can keep air breathable if something measures the outcome, or if the structure itself is allowed to exchange gas and is then adjusted.

These examples separate three strategies:

- Measure ambient CO_2 and act.
- Stop treating high CO_2 as an emergency.
- Let the structure exchange gas, then adjust it.

Occupants of modern buildings already live too much by the second strategy. They do not smell CO_2, they adapt to many odors they can smell, and they remain in place. Prescriptive codes are a paper version of the third strategy: assume the design structure and airflow path will perform as intended. Energy-efficient and healthy ventilation requires the first strategy. The missing hardware is a small, cheap, non-adapting sensor in the breathing zone, able to change airflow and document performance. That is the biological case for a meter. Humans are not sensorless about CO_2 in blood. They are sensorless about CO_2 in the room.

V. THE ENERGY GAMBLE

Too little outdoor air harms health. Too much wastes heating and cooling energy. Without a room-level measurement, the delivered ventilation rate is unknown. That is the gamble.

The scale is substantial. In commercial buildings, ventilation commonly accounts for 20%–40% of HVAC energy use. In a heating climate the load is the enthalpy difference between outdoor air and the indoor setpoint, paid continuously. A system that supplies 10,000 m^3/h of outdoor air at −10 °C and holds the room at 20 °C requires on the order of 100 kW of heating for ventilation alone, before distribution losses and latent loads are considered. Over a winter, that becomes a large fuel or electricity bill, often incurred at a constant design flow whether the rooms are full or empty.

Prescriptive rates make overventilation the default in sparsely occupied spaces. The per-floor-area term, R_a, does not fall when people leave. A large conference room or atrium with a handful of occupants still calls for outdoor air as if the floor area itself required dilution at the design rate. If the air handler is balanced to that flow and left there, the thermal penalty is locked in for the life of the plant. The energy cost is the price of not knowing occupancy, and of not knowing whether this zone is people-limited or building-limited.

Demand-controlled ventilation (DCV) was meant to close that particular loop. CO_2-based DCV has long been proposed as a way to modulate outdoor air in response to occupancy rather than design assumptions [17]. Modulating outdoor air with a real-time occupancy proxy, usually CO_2, can reduce ventilation thermal loads by 30%–60% in principle [18]. Field performance has been less tidy. Sensor drift, poor placement—return ducts, dead corners, or a single probe for several rooms—and conservative control logic often send the system to maximum outdoor air as a fail-safe [19]. The intended savings disappear, and the operator may not notice, because the only number on the screen is often a damper command, not a breathing-zone concentration or a measured outdoor-air enthalpy flux.

Heat recovery is another unwatched saving. A core that transfers 80% of the exhaust enthalpy at commissioning can fall to half that effectiveness after fouling, frost and neglected maintenance. The ventilation heating load then roughly doubles. Incoming and outgoing temperatures and flows are almost never logged continuously, so the degradation has no alarm. The building goes on paying for a recovery effectiveness that exists only in the schedule.

Envelope tightening has exposed a second energy problem. In a leaky pre-2000 apartment building in a cold climate, infiltration can be 30% or more of the heating load. Passive House and similar standards, with leakage below 0.6 air changes per hour at 50 Pa, have cut that loss sharply. But internal gains

from people, lights, equipment and sun then have fewer escape paths. Mechanical ventilation, sized only for a low indoor-air-quality rate, may be unable to purge heat when the outdoor air is cool enough to help. Estonian apartment studies have recorded overheating, more than 150 h per year above 27 °C, in highly insulated dwellings, especially in the shoulder seasons and summer [20]. London modelling under a mid-century climate found most naturally ventilated flats at risk of night-time overheating, and mechanically ventilated dwellings at risk unless rates can be raised [21]. The same missing meter that allows winter overventilation in one zone can prevent adaptive cooling in another.

Health and energy are coupled here, but they should not be confused with household solid-fuel pollution. The World Health Organization's estimate of millions of premature deaths from household air pollution is largely a cooking-fuel problem, not a failure of commercial HVAC. The relevant non-residential evidence is different but still large: Outdoor-air rate and perceived air quality affect sick-building symptoms and work performance [22]; CO_2 and ventilation rates in offices have been associated with cognitive scores [23]; exhaled aerosol can transmit infection in crowded, poorly diluted indoor spaces, where risk is shaped jointly by spaciousness level and ventilation rate [10], [24]. Those are reasons not to solve the energy gamble by simply turning the outdoor-air damper down.

The gamble is worse in large, coupled buildings, because the air in a given room is not a private supply. It is a mixture of outdoor air, recirculated air, and air that has moved under doors, up shafts, and along corridors. Stack effect can join floors that the drawings treat as separate. In a hotel, toilet exhausts, fan-coil units, and door undercuts set the corridor pressure; a guest's exhaled plume can be carried under the next door. On a cruise ship, a small imbalance can allow exhaust from one cabin to re-enter another. The Diamond Princess outbreak, with transmission after cabin confinement, was a case of an unmapped airflow network, not only of a virus [25]. No room-level record of where air came from or how much was delivered was available to the people who needed it.

Buildings account for roughly a third of final energy use and of energy-related CO_2 emissions [26]. The International Energy Agency has estimated that better ventilation and heat recovery could save on the order of 10 exajoules a year, comparable to the annual energy use of a large industrial country [27]. Those figures will not be captured by another tightening of the paper rate. They require knowing, in each zone, whether the outdoor air that has already been paid to heat, cool, filter, and move is present, excessive, or absent.

The four failures have the same shape. Design flow without occupancy. DCV without a trusted sensor. Recovery without a measured effectiveness. An airtight envelope without a measured purge. Each is an open loop. Closing it is an energy-control problem that happens to be identical to the indoor-air problem.

VI. A METER, THEN A CODE

The occupant cannot supply the missing signal. The visitor panel cannot be scaled. The animal comparisons are useful only as a reminder that a confined space stays breathable when something measures the outcome and can change flow. The engineering task is to install that something in the room.

The instrument is not a laboratory analyser. It is closer to a smoke detector: A sealed module that reports a few quantities-CO_2, particulate matter, and perhaps TVOC—as a screening set with enough stability to inform both an occupant display and a control loop. It must be cheap enough for every occupied zone. The sensing cell itself is no longer the main cost. Low-cost NDIR CO_2 sensors and optical particle counters can be made for tens of dollars. The remaining problem is the rest of the system: calibration drift, placement, silent failure, legal defensibility, and an action protocol. A probe that reads 30% high for two years can waste more energy than no probe, if demand-controlled ventilation opens to maximum outdoor air and stays there. A probe in a dead corner can starve the breathing zone while the return looks fine. A probe that reports nothing leaves the operator with a dark point on a map. Until the market converges on a life-of-building module whose uncertainty is known and whose faults are visible, "cheap sensors" will not by themselves close the loop.

The signal must do work. A fluctuating CO_2 reading in one room can mean occupancy, a stuck damper, a short-circuiting diffuser, poor mixing, or a failed sensor. Most building-management systems have no automated diagnosis for those cases. Data without a rule becomes noise, and facility teams ignore it. The minimum rule is simple: Raise outdoor air or purge when the breathing zone is stale; reduce outdoor air when the zone is empty and recovery is effective; flag the zone when the sensor or the damper disagrees with the others.

A computational model of the building's pressure cascades, fed by the same network, would answer questions that are now unanswerable in ordinary operation. Where did the air in this room come from? If a contaminant is released on this floor, which other zones see it? Is the heat-recovery core still at its rated effectiveness? That is not a call for a decorative digital twin. It is a call for a model that is constrained by measured temperatures, flows, pressures, and concentrations, and for one that can be wrong in a way that the next sensor reading can correct.

None of this will spread on goodwill. The present code asks for a flow rate on a drawing. It creates no demand for a continuous record. A performance rule would. One defensible indoor-air form is: Breathing-zone CO_2 shall not exceed the outdoor concentration by more than 800 ppm for 95% of occupied hours, demonstrated by monitoring. For this journal, that rule is incomplete unless an energy rule sits beside it. The second requirement could be a measured outdoor-air heating and cooling energy per square metre, or an in-situ heat-recovery effectiveness from supply and exhaust temperature and flow, logged through the season. Compliance would then be a file of

room-level concentrations and plant-level energy, not a calculation from the year of permit. The monitoring record would be the evidence.

A visible metric would also change the market for air sealing. If airtightness and delivered ventilation were numbers that persist after handover, industrialized sealing and factory-made assemblies would have a buyer beyond the niche of voluntary standards. Aerosol sealing and modular envelopes already show that leakage can be made more consistent than site taping. They remain optional while the only legal test is a one-time blower-door result, or no test at all.

The code of the future should not say only "provide 10 L per second per person." It should say: show, from the hours occupied this year, that the air in the breathing zone stayed within bounds, and that the energy spent putting it there was the energy of a plant that still recovers heat. That is the difference between specifying a service and metering it.

VII. LIMITATIONS

Continuous monitoring will not, by itself, make buildings healthy or efficient. A reading is only as useful as the decision that follows it. A drifting or poorly placed sensor can open dampers that should stay shut, close dampers that should open, or certify a room that is stale at the nose and fresh at the wall. In that case, the meter is worse than the open loop it was meant to replace: It wastes energy with apparent authority. Using low-cost sensors as legal evidence therefore raises questions of calibration, liability, privacy, and data custody that are not yet settled. Those questions are reasons to specify the instrument class, not reasons to keep flying blind.

Nor should the animal examples be read as a design template. The physics of a multi-zone building with fans, ducts, leakage paths, and stack effect is not the physics of a termite mound or a mole-rat tunnel. The comparison was about feedback, not about copying an organism. Buildings need a sensor attached to an actuator. They do not need a chimney that breathes with the diurnal cycle, and they should not adopt the fossorial solution of treating stale air as normal.

Monitoring is also not a substitute for source control or for a competent envelope. Low-emitting materials, moisture management, filtration, and airtightness remain the first moves. A meter that shows high particles from an indoor source, or high CO_2 from a blocked outdoor-air path, is useful only if someone can change the source or the path. The argument here is narrower. Design rates, commissioning snapshots, and the absence of complaints have been asked to do the work of a measurement they cannot provide. Adding that measurement does not retire the rest of building science. It makes the rest of building science testable.

In closing, fire has a detector in every room because the harm is acute and the liability is immediate. Ventilation energy is slow. Stale air is diffuse. Their costs appear as a heating bill, a warm night in an airtight flat, a lost afternoon of work, or an infection whose origin is never assigned to a duct. Because those costs do not announce themselves in the moment, the service that produces them was left unmetered. A design flow and a commissioning snapshot were asked to stand in for a year of occupied hours.

That bargain is now too expensive. Outdoor air is conditioned at a scale that matters to national energy use. The same unmeasured low rate that saves winter heat can fail to purge the building when the climate warms. The same unmeasured high rate that was meant as a health margin burns fuel in empty rooms. Occupants will not close the loop: They do not smell CO_2, they adapt to odor, and they stay. The building must close it, with a sensor in the breathing zone and a rule that can change flow.

The hardware is no longer exotic. What is missing is the decision to treat delivered outdoor air as a performance recorded in the occupied zone and in the plant's energy, rather than as a number on a drawing. Until that decision is taken, claims that a building is efficient, or that it is healthy, remain hypotheses about a flow that no one has required to be seen.

No measurement, no control.

Declaration of competing interest

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REFERENCES

[1] C. P. Yaglou, E. C. Riley, and D. I. Coggins, "Ventilation requirements," *ASHVE Trans.* , vol. 42, pp. 133–162, 1936.

[2] W. S. Cain, B. P. Leaderer, R. Isseroff, L. G. Berglund, R. J. Huey, E. D. Lipsitt, and D. Perlman, "Ventilation requirements in buildings—I. Control of occupancy odor and tobacco smoke odor," *Atmos. Environ.*, vol. 17, no. 6, pp. 1183–1197, Jun. 1983.

[3] P. O. Fanger, "Introduction of the olf and the decipol units to quantify air pollution perceived by humans indoors and outdoors," *Energy Buildings*, vol. 12, no. 1, pp. 1–6, Apr. 1988.

[4] P. O. Fanger, J. Lauridsen, P. Bluyssen, and G. Clausen, "Air pollution sources in offices and assembly halls, quantified by the olf unit," *Energy Buildings*, vol. 12, no. 1, pp. 7–19, Apr. 1988.

[5] *Ventilation for Acceptable Indoor Air Quality*, ANSI/ASHRAE 62.1-2019, 2019.

[6] W. S. Cain and F. Johnson Jr, "Lability of odor pleasantness: influence of mere exposure," *Perception*, vol. 7, no. 4, pp. 459–465, Aug. 1978.

[7] L. Fang, G. Clausen, and P. O. Fanger, "Impact of temperature and humidity on the perception of indoor air quality," *Indoor Air*, vol. 8, no. 2, pp. 80–90, Jun. 1998.

[8] J. Hu, C. Zhong, C. Ding, Q. Y. Chi, A. Walz, P. Mombaerts, H. Matsunami, and M. M. Luo, "Detection of near-atmospheric concentrations of CO_2 by an olfactory subsystem in the mouse," *Science*, vol. 317, no. 5840, pp. 953–957, Aug. 2007.

[9] J. M. Young, H. Waters, C. Dong, H. J. Fülle, and E. R. Liman, "Degeneration of the olfactory guanylyl cyclase D gene during primate evolution," *PLoS One*, vol. 2, no. 9, pp. e884, Sep. 2007.

[10] C. C. Wang, K. A. Prather, J. Sznitman, J. L. Jimenez, S. S. Lakdawala, Z. Tufekci, and L. C. Marr, "Airborne transmission of respiratory viruses," *Science*, vol. 373, no. 6558, pp. eabd9149, Aug. 2021.

[11] T. Godish, *Indoor Environmental Quality*, Boca Raton, FL: CRC Press, 2001.

[12] E. S. J. Smith, D. Omerbašić, S. G. Lechner, G. Anirudhan, L. Lapatsina, and G. R. Lewin, "The molecular basis of acid insensitivity in the African naked mole-rat," *Science*, vol. 334, no. 6062, pp. 1557–1560, Dec. 2011.

[13] C. Kleineidam, R. Romani, J. Tautz, and N. Isidoro, "Ultrastructure and physiology of the CO_2 sensitive sensillum ampullaceum in the leaf-cutting ant *Atta sexdens*," *Arthropod Struct. Dev.*, vol. 29, no. 1, pp. 43–55, Jan. 2000.

[14] C. Kleineidam and J. Tautz, "Perception of carbon dioxide and other "air-condition" parameters in the leaf cutting ant *Atta cephalotes*," *Naturwissenschaften*, vol. 83, no. 12, pp. 566–568, Dec. 1996.

[15] T. D. Seeley, "Atmospheric carbon dioxide regulation in honey-bee (*Apis mellifera*) colonies," *J. Insect Physiol.*, vol. 20, no. 11, pp. 2301–2305, Nov. 1974.

[16] H. King, S. Ocko, and L. Mahadevan, "Termite mounds harness diurnal temperature oscillations for ventilation," *Proc. Natl. Acad. Sci. USA*, vol. 112, no. 37, pp. 11589–11593, Aug. 2015.

[17] S. J. Emmerich and A. K. Persily, "State-of-the-art review of CO_2 demand controlled ventilation technology and application," National Institute of Standards and Technology, Gaithersburg, MD, NIST IR 6729, 2001.

[18] W. J. Fisk and A. T. De Almeida, "Sensor-based demand-controlled ventilation: a review," *Energy Buildings*, vol. 29, no. 1, pp. 35–45, Dec. 1998.

[19] B. Merema, M. Delwati, M. Sourbron, and H. Breesch, "Demand controlled ventilation (DCV) in school and office buildings: lessons learnt from case studies," *Energy Buildings*, vol. 172, pp. 349–360, Aug. 2018.

[20] M. Maivel, J. Kurnitski, and T. Kalamees, "Field survey of overheating problems in Estonian apartment buildings, " *Architect. Sci. Rev.* , vol. 58, no. 1, pp. 1–10, Mar. 2015.

[21] K. J. Lomas and S. M. Porritt, "Overheating in buildings: lessons from research," *Build. Res. Inf.* , vol. 45, no. 1–2, pp. 1–18, Jan. /Apr. 2017.

[22] P. Wargocki, D. P. Wyon, J. Sundell, G. Clausen, and P. O. Fanger, "The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity," *Indoor Air*, vol. 10, no. 4, pp. 222–236, Dec. 2000.

[23] J. G. Allen, P. MacNaughton, U. Satish, S. Santanam, J. Vallarino, and J. D. Spengler, "Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: a controlled exposure study of green and conventional office environments," *Environ. Health Perspect.*, vol. 124, no. 6, pp. 805–812, Jun. 2016.

[24] W. Jia, P. Cheng, J. Hang, H. Qian, and Y. G. Li, "Quantifying crowding-ventilation effect on respiratory infections," *Nat. Commun.*, vol. 17, no. 1, pp. 6697, May 2026.

[25] P. Azimi, Z. Keshavarz, J. G. Cedeno Laurent, B. Stephens, and J. G. Allen, "Mechanistic transmission modeling of COVID-19 on the *Diamond Princess* cruise ship demonstrates the importance of aerosol transmission," *Proc. Natl. Acad. Sci. USA*, vol. 118, no. 8, pp. e2015482118, Feb. 2021.

[26] United Nations Environment Programme, *2022 Global Status Report for Buildings and Construction*, Nairobi, Kenya: United Nations Environment Programme, 2022.

[27] International Energy Agency, *Energy Technology Perspectives 2016: Towards Sustainable Urban Energy Systems*, Paris, France: International Energy Agency, 2016.



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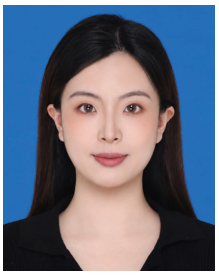

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