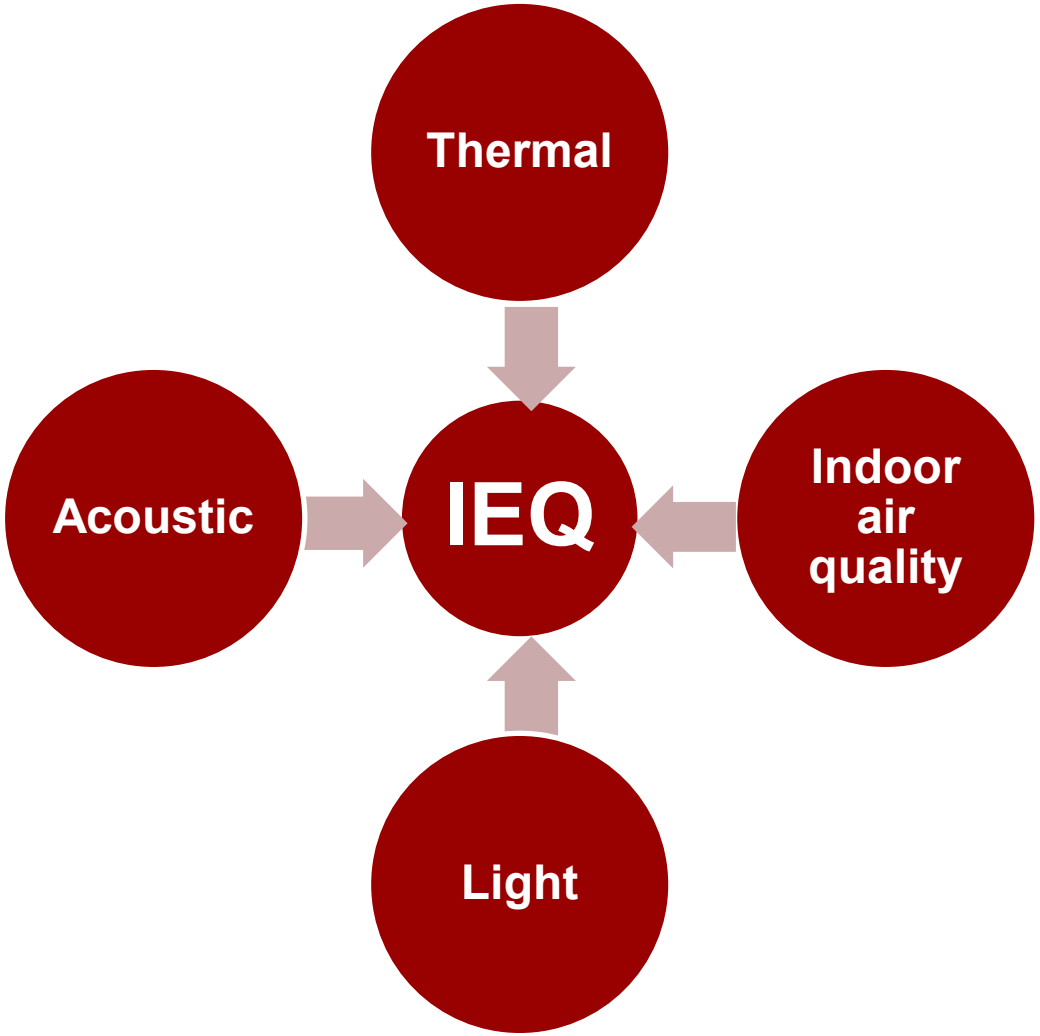
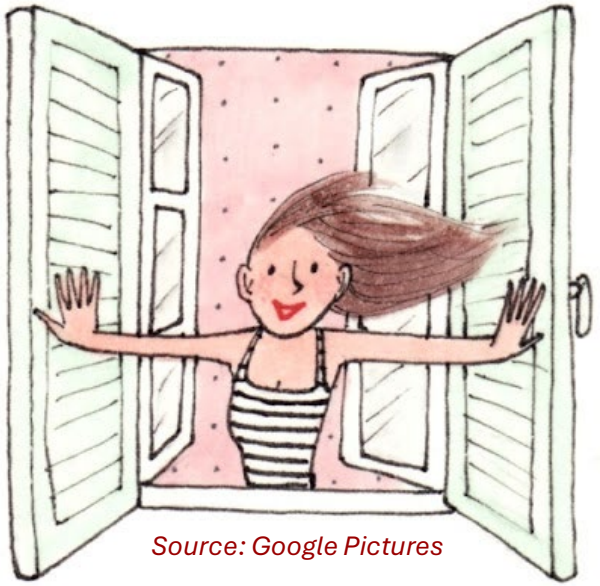
Pawel Wargocki (pawar@dtu.dk)
International Centre for Indoor Environment and Energy
Dept. of Environmental and Resource Engineering (DTU Sustain)
Technical University of Denmark

The role of indoor environments for well-being, health, work performance, learning, and sleep

Definition of IEQ



+



Source: Google Pictures

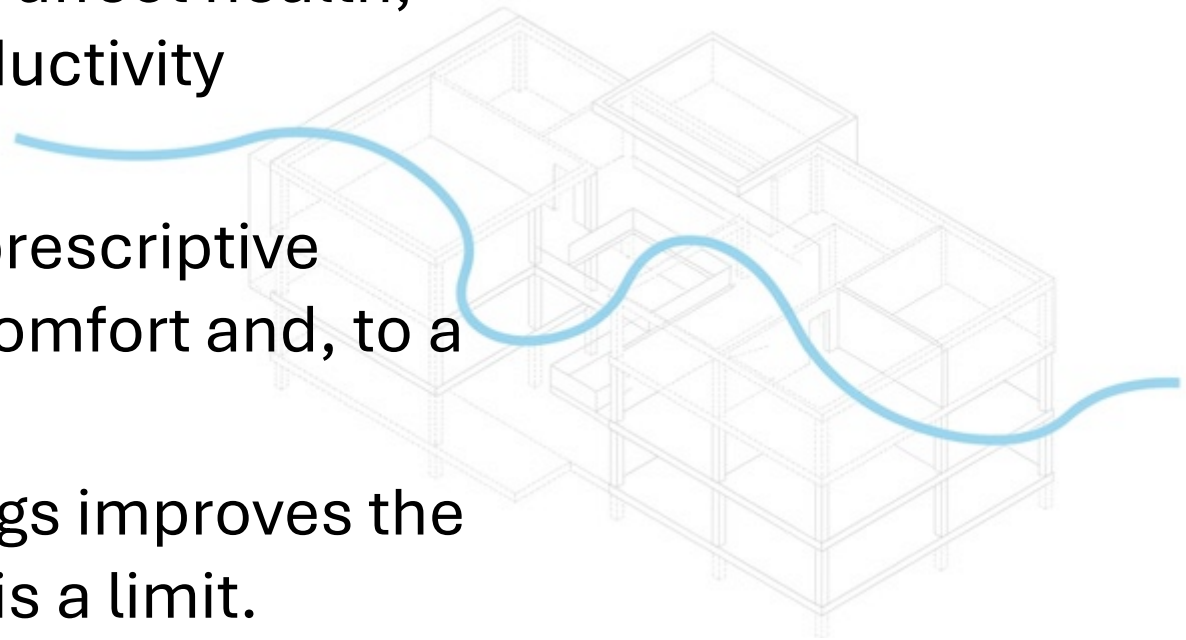
Human behavior

Source: ArchDaily

Biophilia – contact with nature

What we know already

- Ventilation, air quality, thermal conditions, lighting, and acoustics significantly affect health, cognition, sleep, learning, and productivity indoors.
- Standards and guidelines provide prescriptive values supporting predominantly comfort and, to a lesser extent, health.
- Improving IEQ conditions in buildings improves the well-being of occupants, but there is a limit.
- The evidence is not a bottleneck to advancing building science.



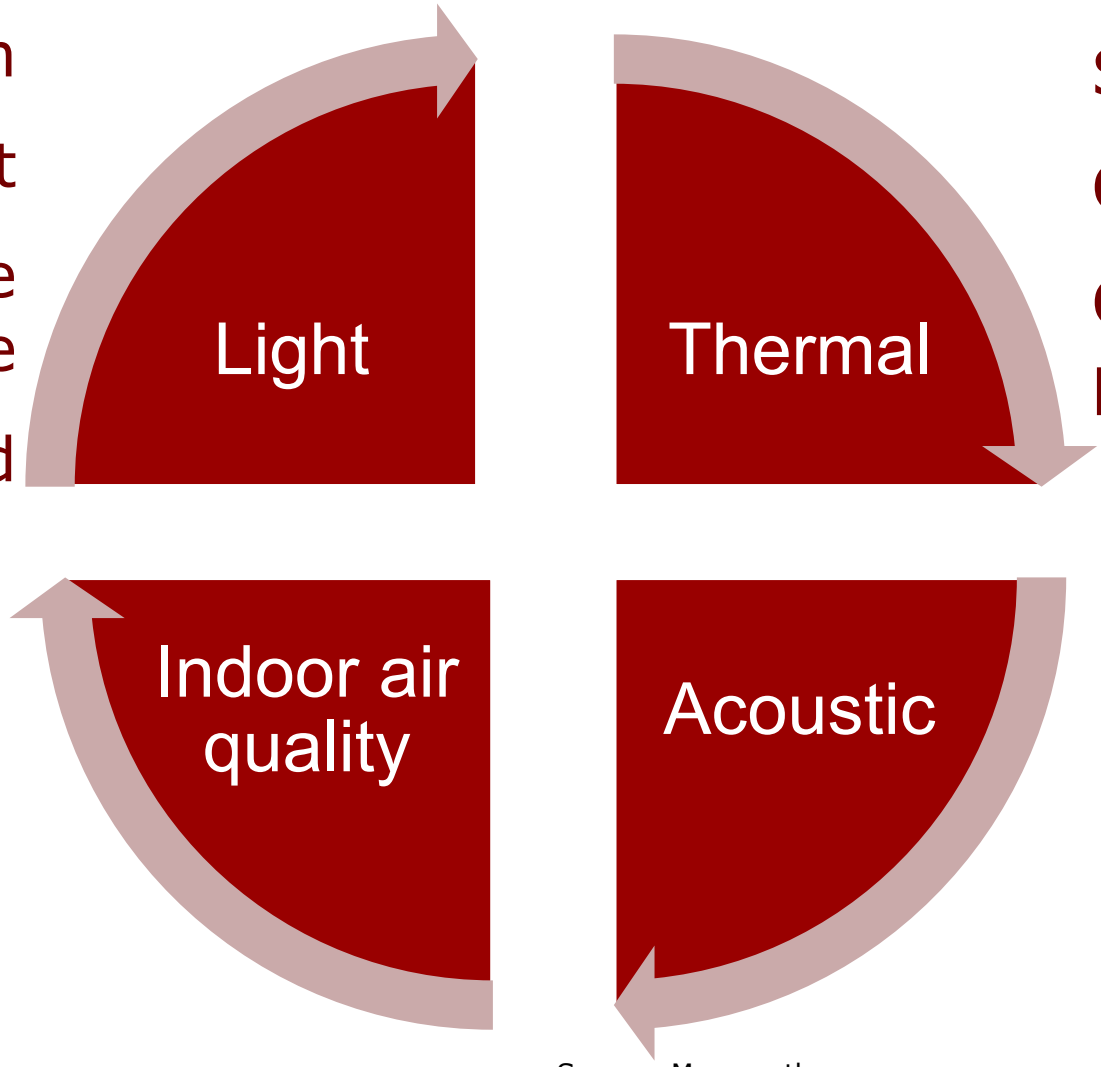
Documented effects

Sleep/circadian rhytm

Health and comfort

Cognitive performance

Mood



Sleep

Comfort

Cognitive performance

Sleep

Health and comfort

Cognitive performance

Comfort

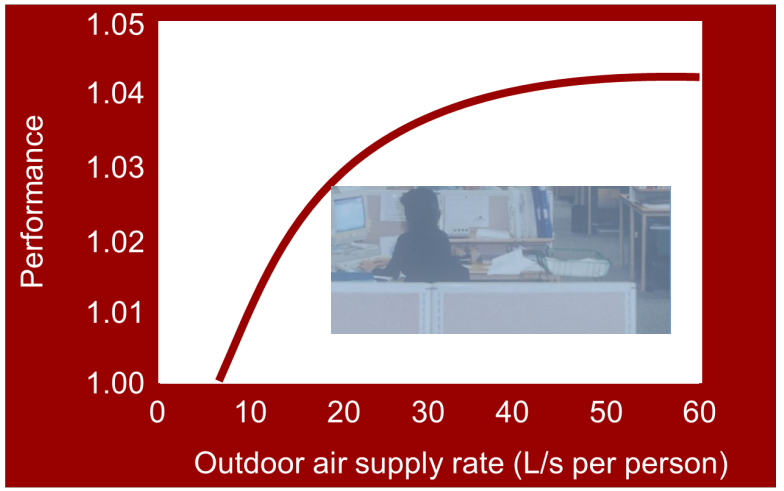
Cognitive performance

Mood and disturbance

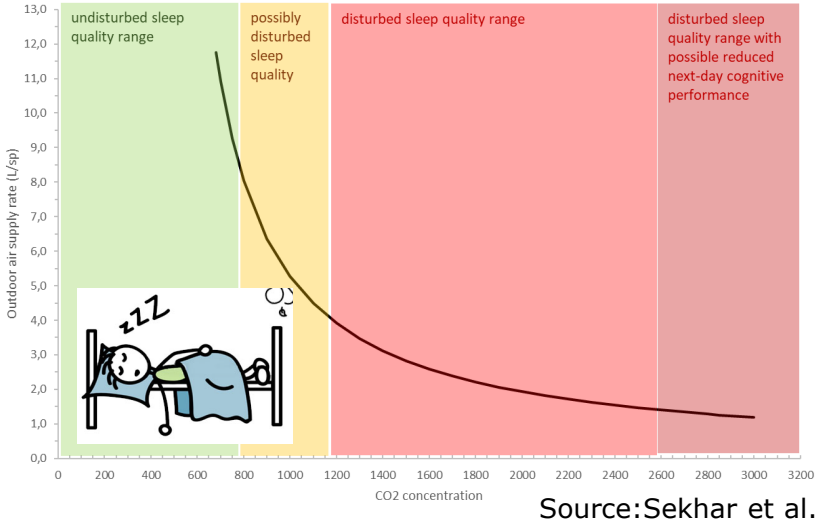
Source: Many authors

Effects on work, learning & sleep

- Reduced work performance, expected loss is at least up to 5%
- Increased absenteeism and presenteeism
- Reduced learning of children, expected loss of up to 10-15%
- Disturbed sleep quality, poor sleep quality => reduced health, cognitive performance

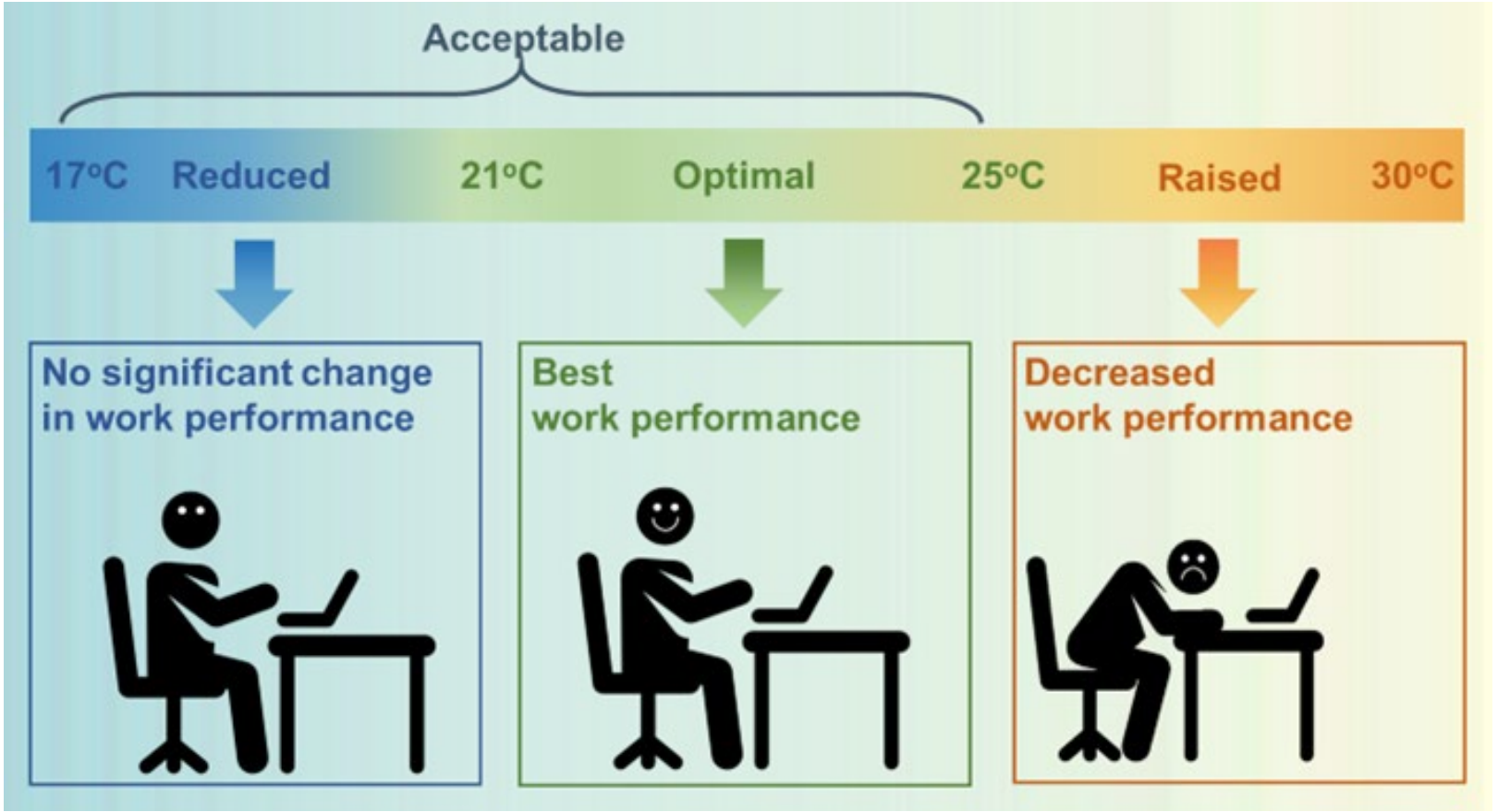


Source:Seppanen et al. (2006)



Source:Sekhar et al. (2020)

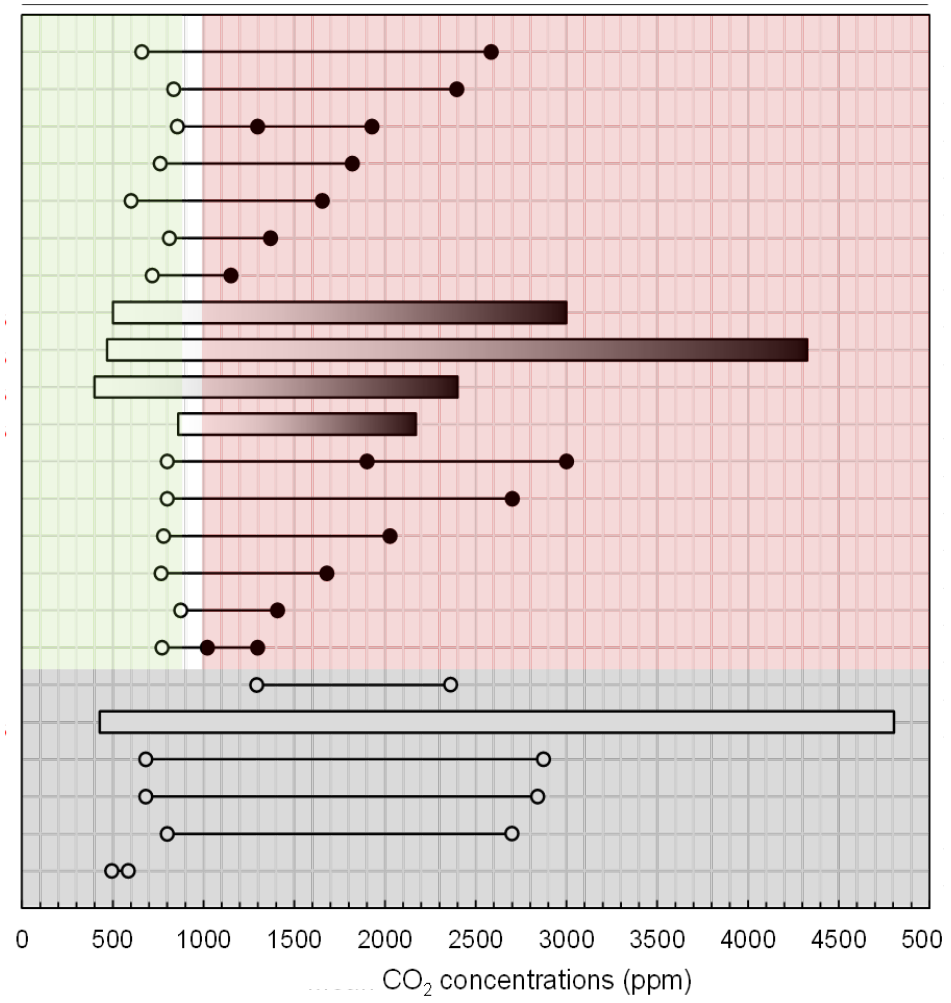
Thermal environment and cognitive performance



The decline in work performance was more pronounced in skilled work and with extended exposure (>1 h), while a relatively minor impact on simple routine work

Lin et al., 2025

Ventilation and sleep quality



CO_2 < 800-1,000 ppm

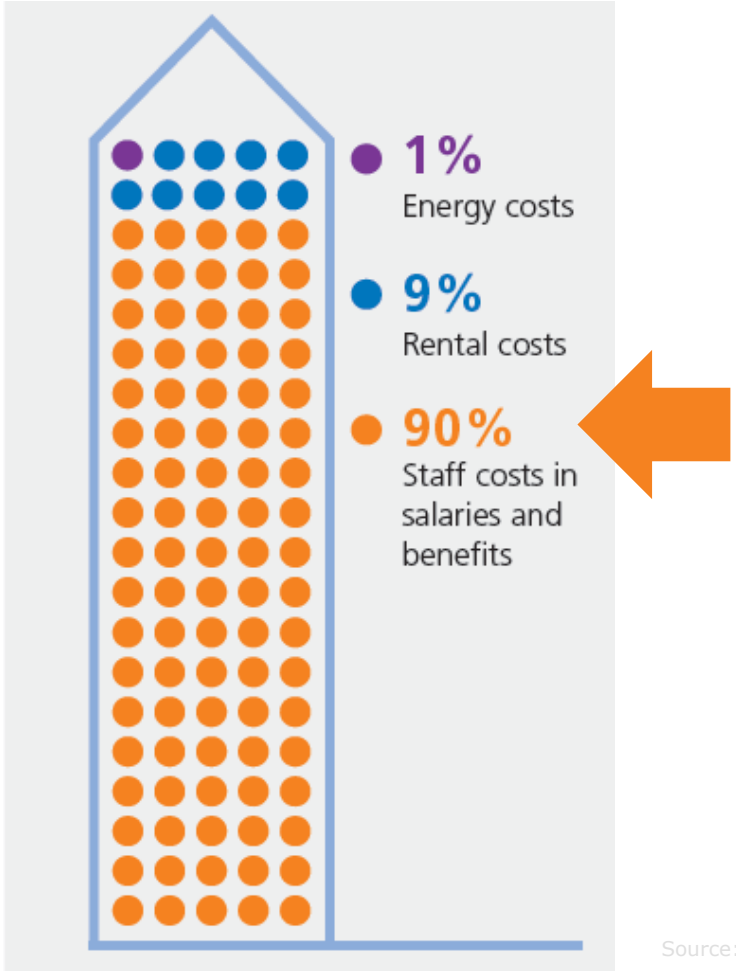
Ventilation >8 L/s per p

At least 1 h^{-1}

Akimoto et al. (2025)

Economic implications are considerable

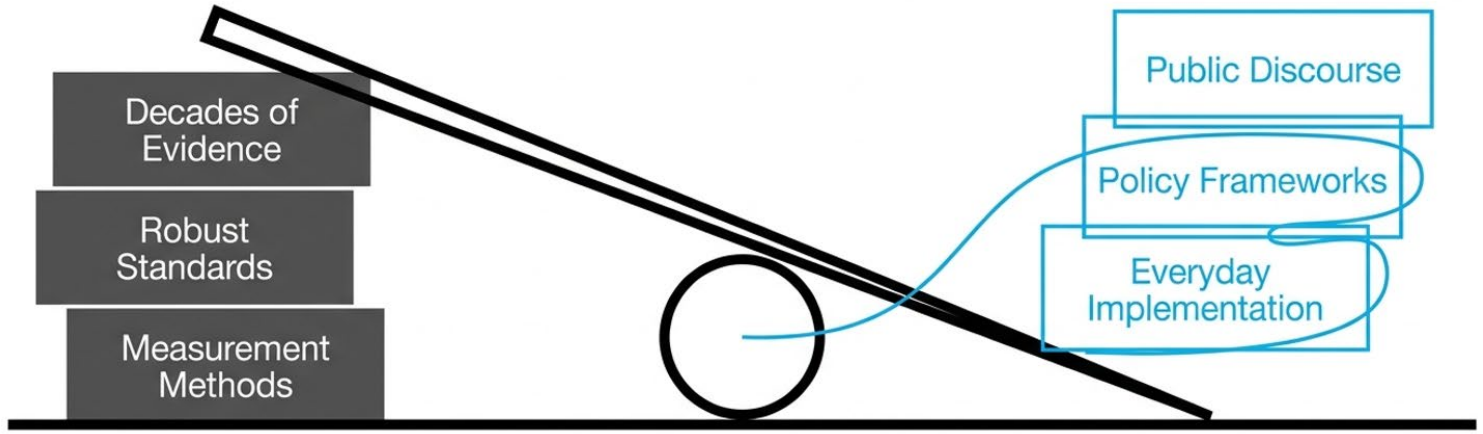
- Modest gains in work performance can deliver significant financial benefits – even 1% increase in productivity is cost-effective



Source: WGBC (2014)

Costs and benefits, examples

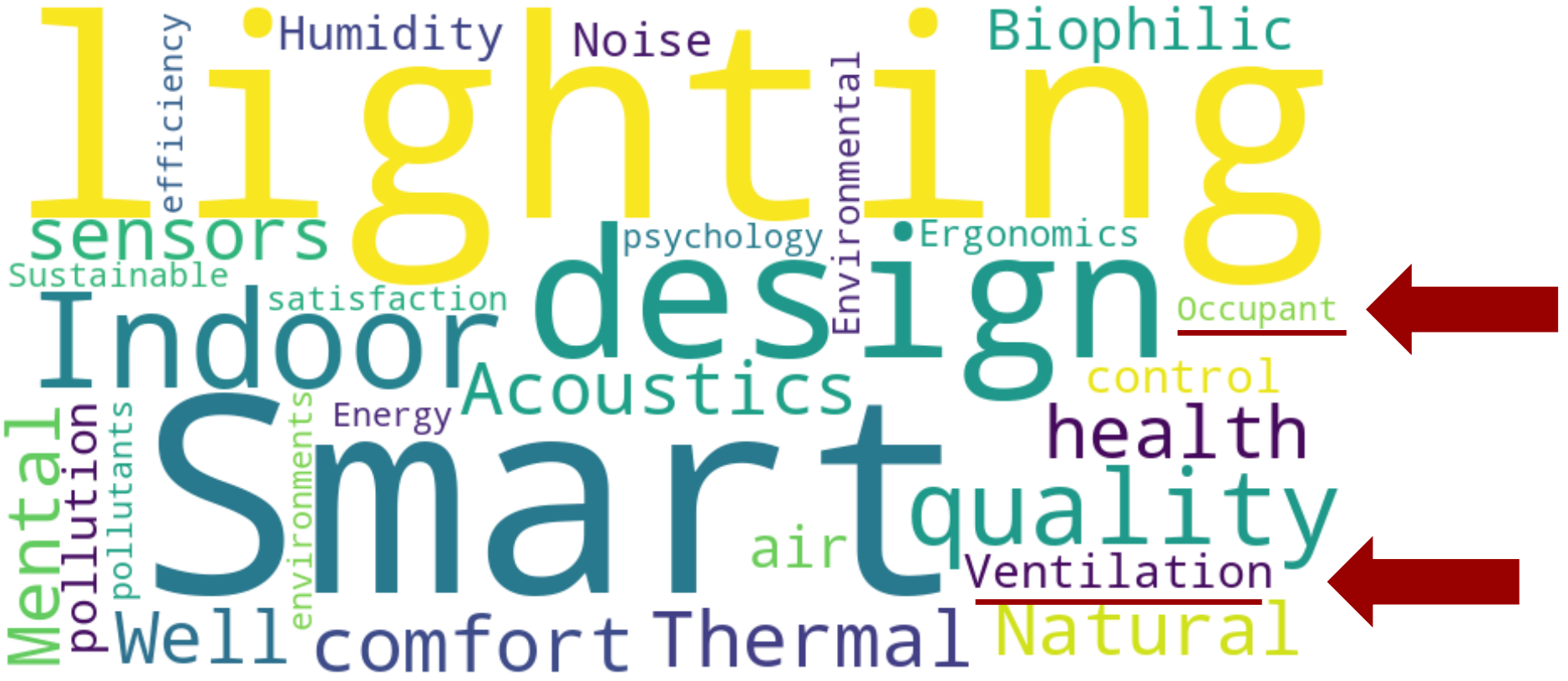
- Exposures in buildings are estimated in the EU to cause >2 million healthy-life years lost due to poor IAQ (ca. €200 billion annually)
- This effect is comparable with, e.g., road traffic injuries, with costs similar to the GDP of Cyprus
- Most of the improvements to IEQ have a pay-back time below 1-2 years because of productivity gains
- Inadequate ventilation in schools in Denmark is estimated to cost at least €200 mil annually
- Too short sleep is estimated to cause 3 to 6 working days lost annually



The paradox related to indoor environmental quality research: High certainty – low priority

The problem is not a lack of data, but probably how we have framed the issues related to IEQ

A concerning trend....



IEQ research over the past 5 years. Generated with Microsoft Copilot on July 23, 2025

Have we forgotten humans and solutions?

- We write papers to advance knowledge
- We simulate, model, analyze, publish, and monitor using advanced black-box AI and complex tools
- We advance buildings and control

??

The blind spot:

- Do we ask the right questions?
- Are human needs sufficiently addressed?

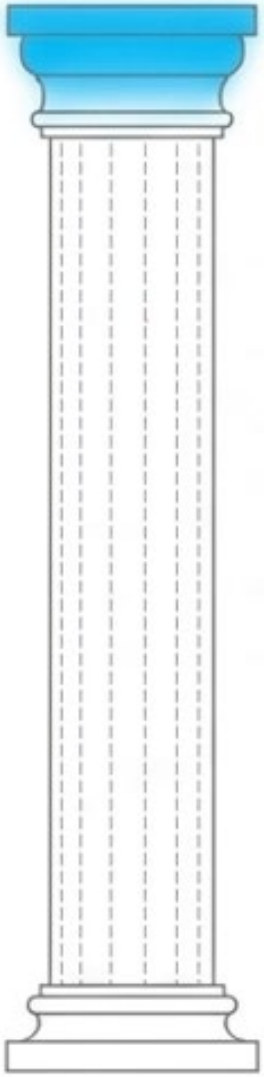
The comfort paradigm is no longer sufficient and rational

It was an excellent starting point, but has become a conceptual ceiling

From comfort to health paradigm

- Health is complete physical, mental, and social well-being, not merely the absence of disease, comfort being subordinated to it.
- Health is not subjective. It is objective, cumulative over time, and lays the grounds for resilient buildings. It is not about momentary satisfaction.
- Supports human functioning across the life course.
- It is a non-negotiable collective obligation.
- It demands environments that are explicitly health-protective and health supportive.
- It creates much stricter requirements for IEQ in buildings.
- It creates a bridge to the medical profession and much stricter requirements regarding building standards and performance monitoring.

Three non-negotiable shifts in building practice when health sustaining definitions are used



Monitoring is Normal

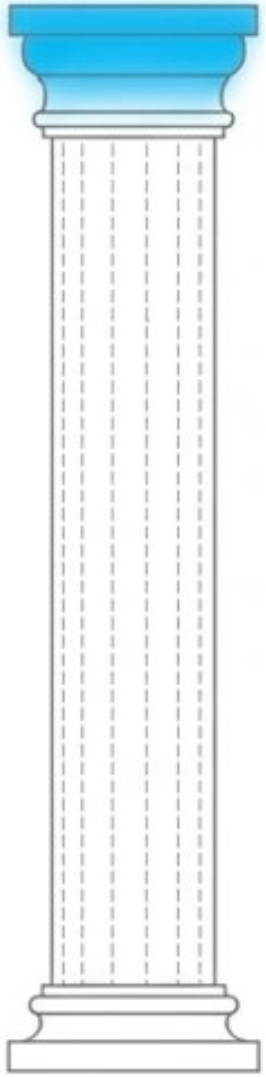
Conditions affecting health cannot be assumed; they must be measured and verified. This applies to air quality, thermal stress, noise, and lighting.

Health-Anchored Thresholds

The goal shifts from pleasing the mathematical average to protecting vulnerable groups. We must must establish non-negotiable health baselines.

Distributed Responsibility

Health-relevant exposures cannot be left to individual preference. Institutional obligation replaces voluntary action, comparable to clean drinking water provision.



The existing IEQ terminology falls short

Conceptual clarity affects how IEQ is measured, regulated, and valued

The intent-driven definitions

- IEQ terminology is unclear to the public and policymakers, limiting its influence outside research circles.
- The focus is on parameters, levels, and comfort, not on outcomes.
- It is a passive description.
- IEQ must adopt understandable, positive, and outcome-oriented terminology to shape effective policy and “sell” the value to the public.
- The link to ecosystems and healthy living is necessary.

Valuing air as a societal resource

- Water and energy are treated as resources that are monitored, priced, regulated, and protected.
- Air, despite being continuously inhaled (mostly indoors, 90% of the time), is rarely treated this way.
- Even modest IAQ improvements yield productivity and health gains that vastly exceed the marginal costs of improving the air quality (e.g., ventilation or air cleaning).
- Recognizing air as a resource raises fundamental questions of value, governance, and equity. What is clean air worth in terms of avoided disease and supported productivity?
- If we price the resource, we can fund the infrastructure to guarantee it.
- What is the willingness to pay (WTP)? What is 1 m^3 of clean indoor air actually worth? Can/should we put the price (fee) or just value it?

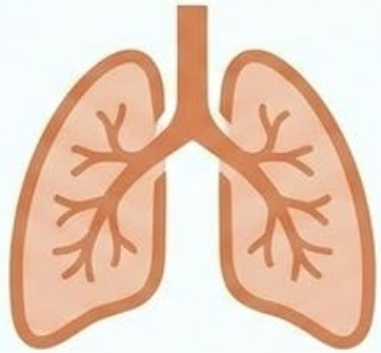
Air is an invisible commodity

Water

We pay ~€2-3/m³ for clean tap water. We consume ~150L daily.
(2-3 L/day drinking water)

Energy

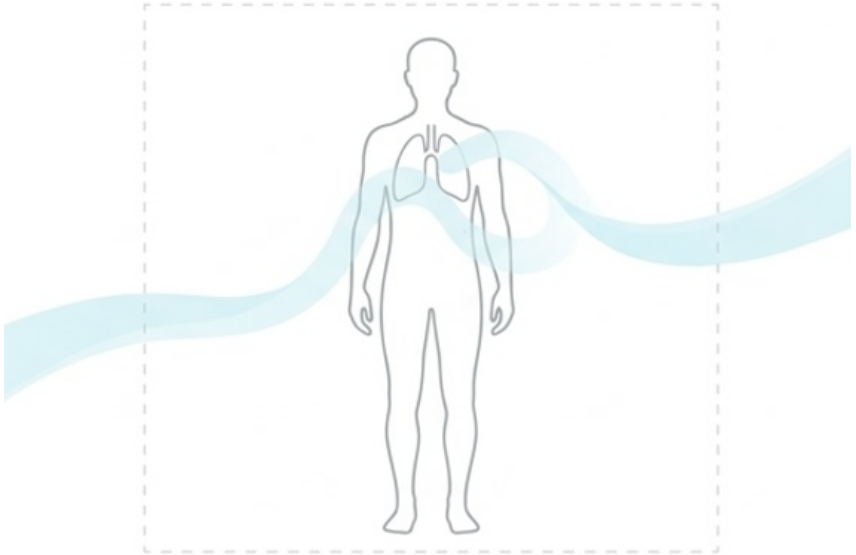
We measure and monetize every kilowatt to guarantee reliability.



Air (The Gap)

We inhale 12,000 liters (12m³) of air daily (4,500m³ annually). Currently unpriced and unprotected.

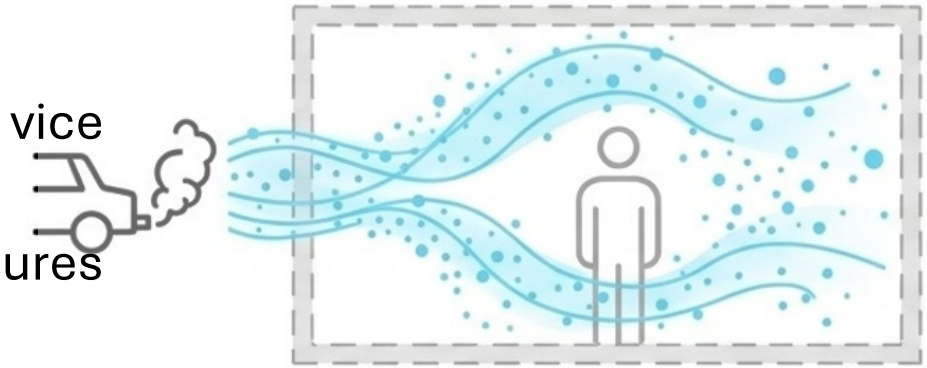
Pricing can be considered provocative, but it is more instrumental. Can be both the cost and a resource.



The indoor-outdoor air continuum
The ONE AIR principle

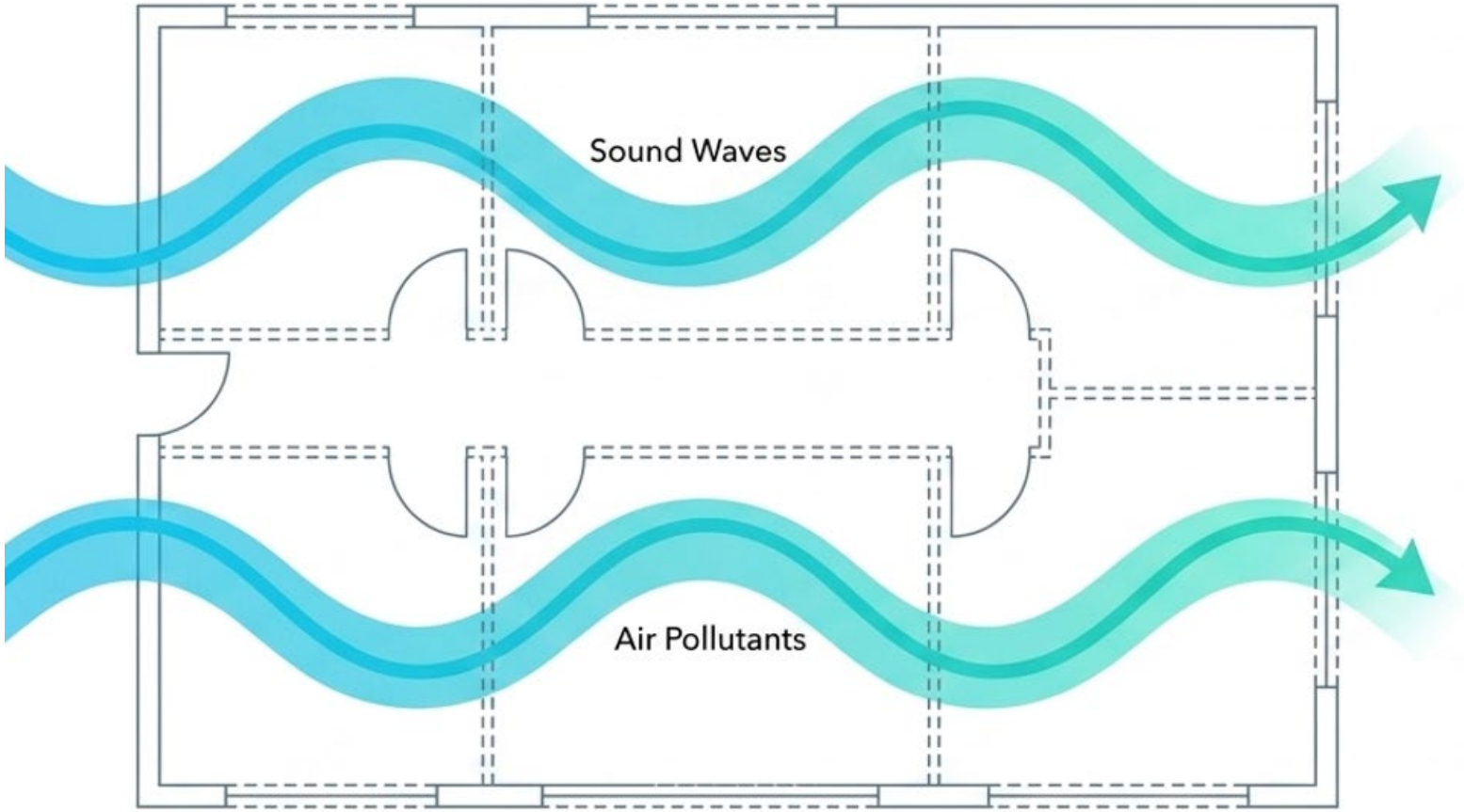
The indoor-outdoor fallacy

- Walls define architectural spaces, not human exposure. Pollutants cross boundaries and transform inside: exposure does not care about facades.
- Humans inhale the vast majority of outdoor air indoors.
- Indoor air policies cannot compensate for outdoor air and vice versa. Indoor air cannot be regulated in isolation.
- Treating indoor and outdoor air as separate domains obscures continuity and limits effective governance.
- Effective air quality policies must integrate indoor and outdoor strategies due to their interconnected nature.
- ONE AIR paradigm frames air quality as a shared resource and a basic human right for all.



- **There is no indoor or outdoor air. There is only ONE AIR**

The sound analogy



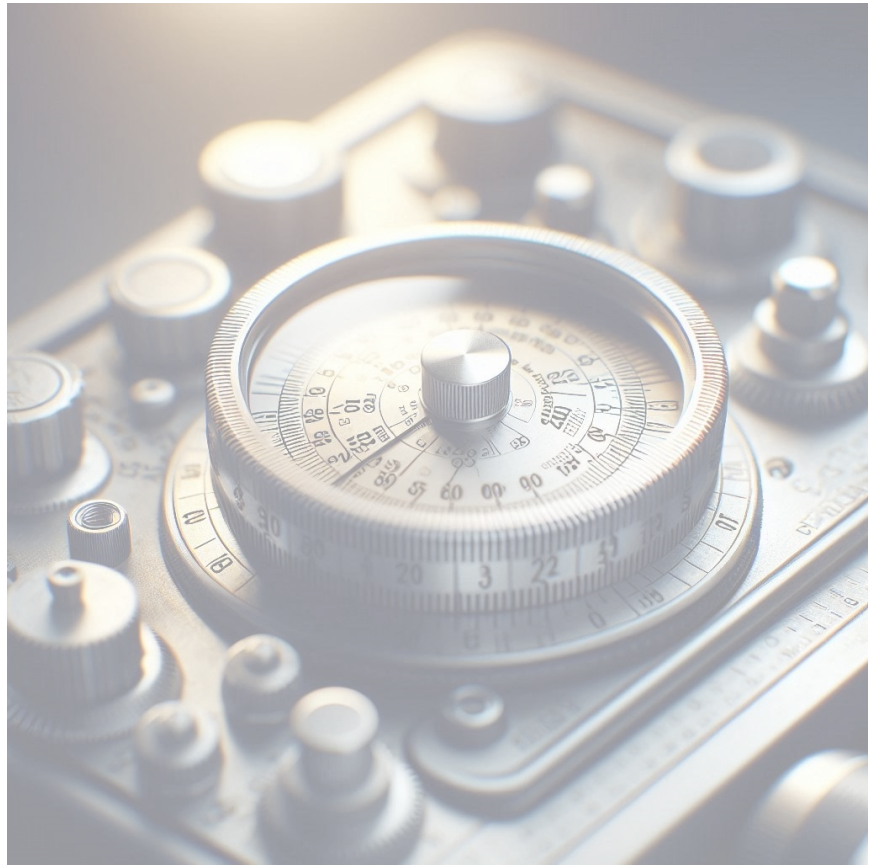
Sounds fill the room walls

Where do we draw the lines?

Outside folds within

Air behaves exactly like sound.

The walls that define a room do not define exposure.

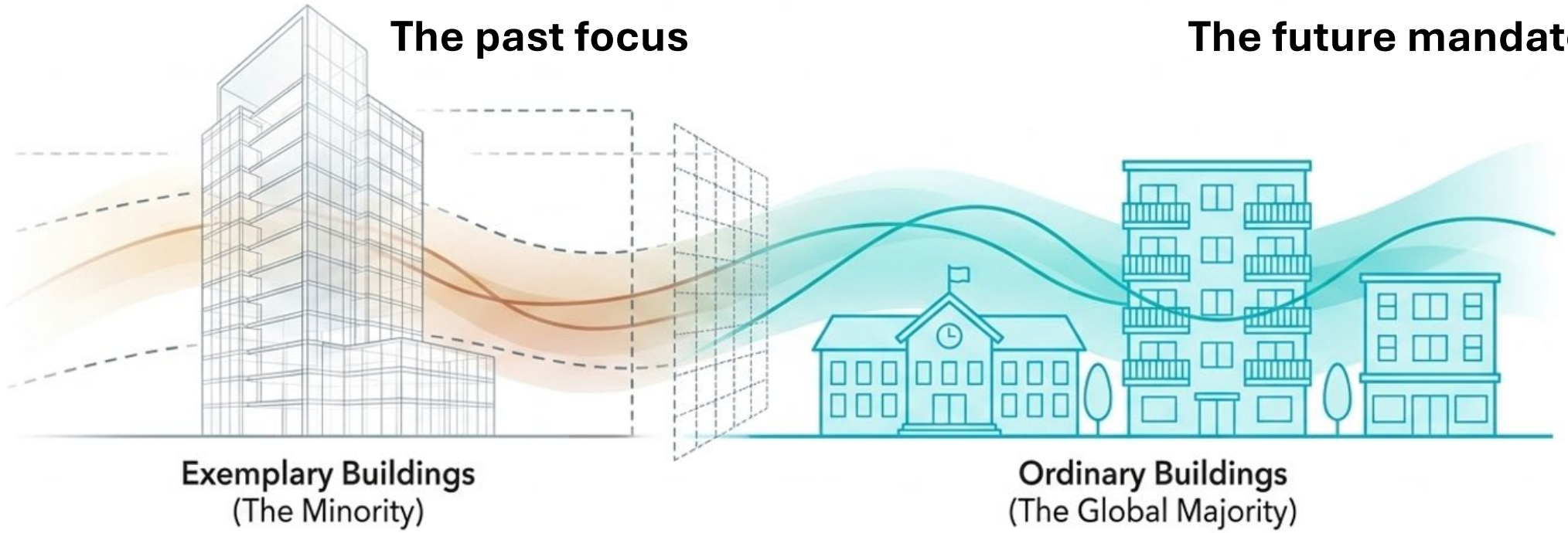


Benchmarking is a clue to the success

The 2024 European EPBD could be a turning point

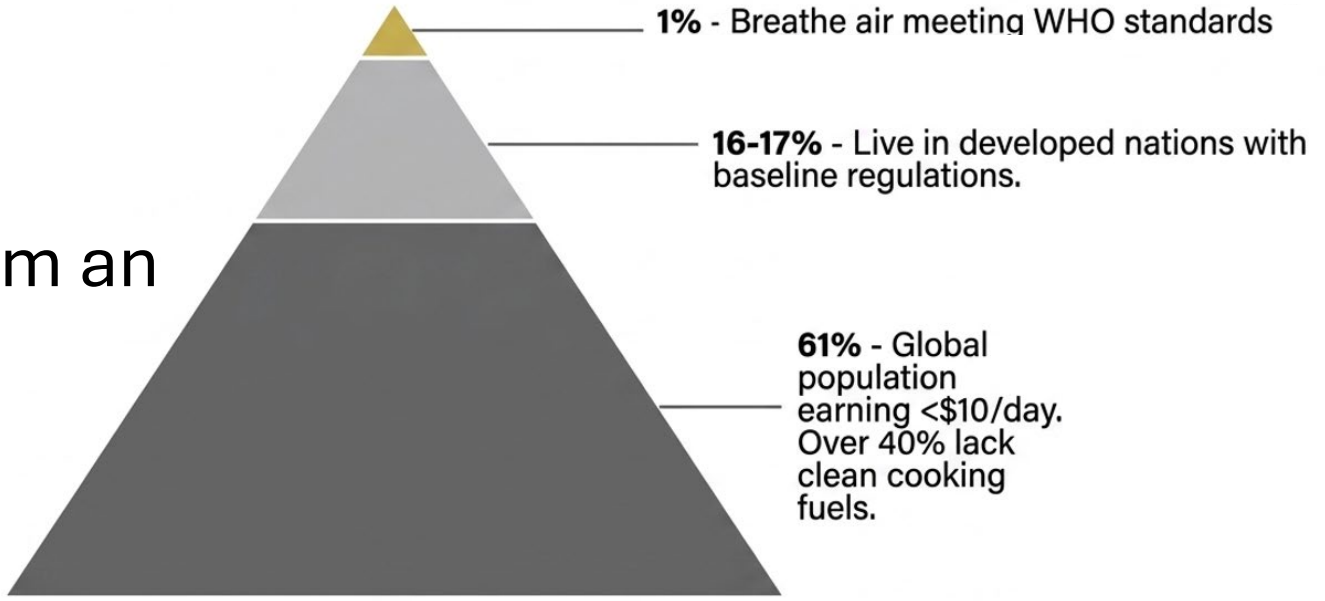
- Policy is now catching up with what evidence has shown for decades
- Monitoring is mandatory
- IEQ is recognized as inseparable from building energy performance
- Poor IEQ undermines energy goals.
- Performance monitoring is non-negotiable for automatic control.

Healthy buildings are not only for affluent populations and elite certifications, if remaining relevant

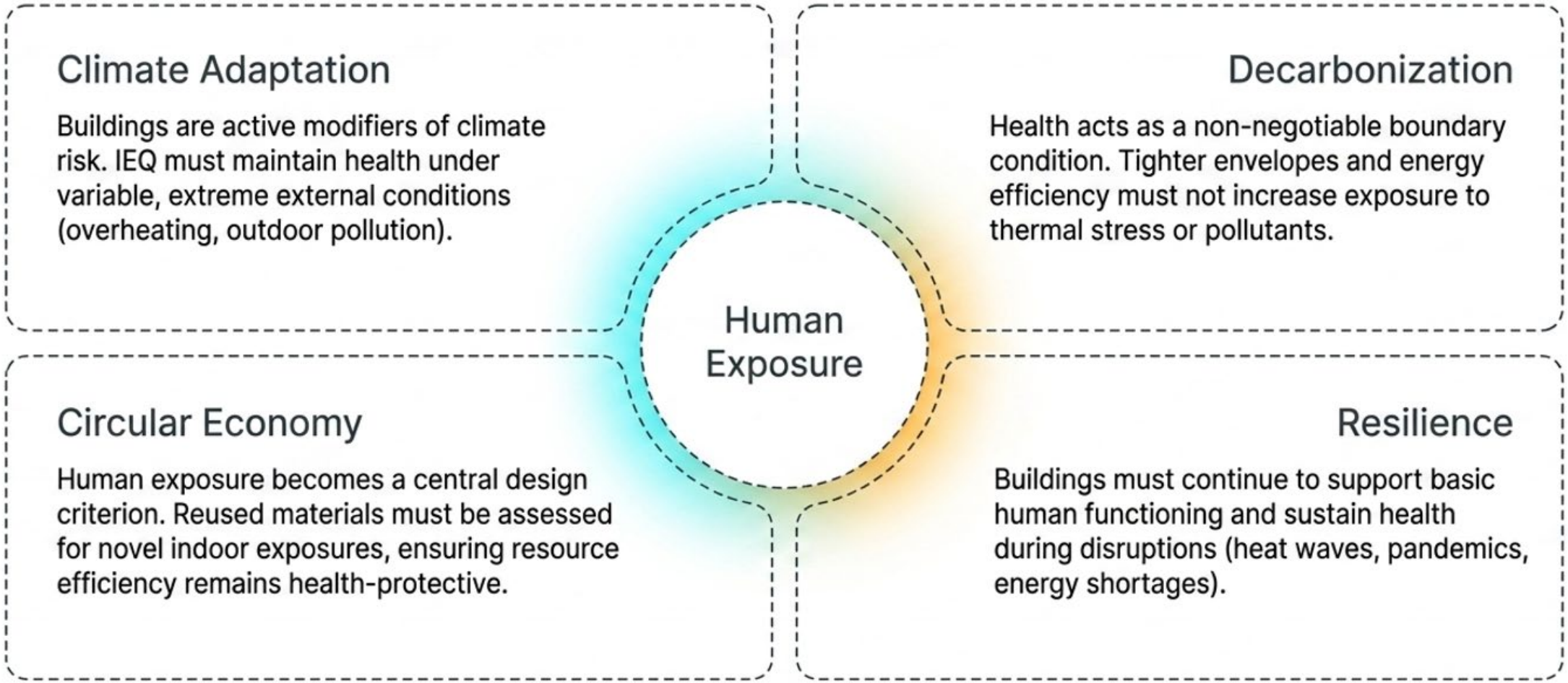


The democratization challenge

- If IEQ cannot scale beyond the affluent, it risks irrelevance.
- It is right, not a luxury.
- High IEQ must be moved from an affluent luxury to a standard building code baseline
- Affordable, robust, and low-tech solutions must secure democratizations of sustainable living. There is no other way.



IEQ at the frontline



Public health implemented through buildings

"The question will no longer be whether we can afford to provide healthy indoor environments, but whether we can afford not to."

Disclaimer

- This presentation reflects my personal opinions and does not represent the views of any affiliated institution
- It is a combination of the thoughts, ideas, the result of conversations, and the LinkedIn posts that are public
- It shows excerpts from the longer lecture given on May 13 at Waseda University on reflections on future challenges in IEQ
- I want to thank all the contributions and inspirations from other people
- The sole purpose of this talk is to engage discussions and actions so that the healthy buildings movement and IEQ can be put in the right place where it belongs

Courtesy: La Linea

Please connect with pawar@dtu.dk for questions and comments and check my LinkedIn at linkedin.com/in/pawel-wargocki-88090124/

Thank you