AMCA International

IAQ and Energy Efficiency

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ARCHITECTURAL ENGINEERING

Air System Engineering & Technology (ASET) Conference–Europe

Lyon, France • L'Espace Tête d'Or • 20 February 2018

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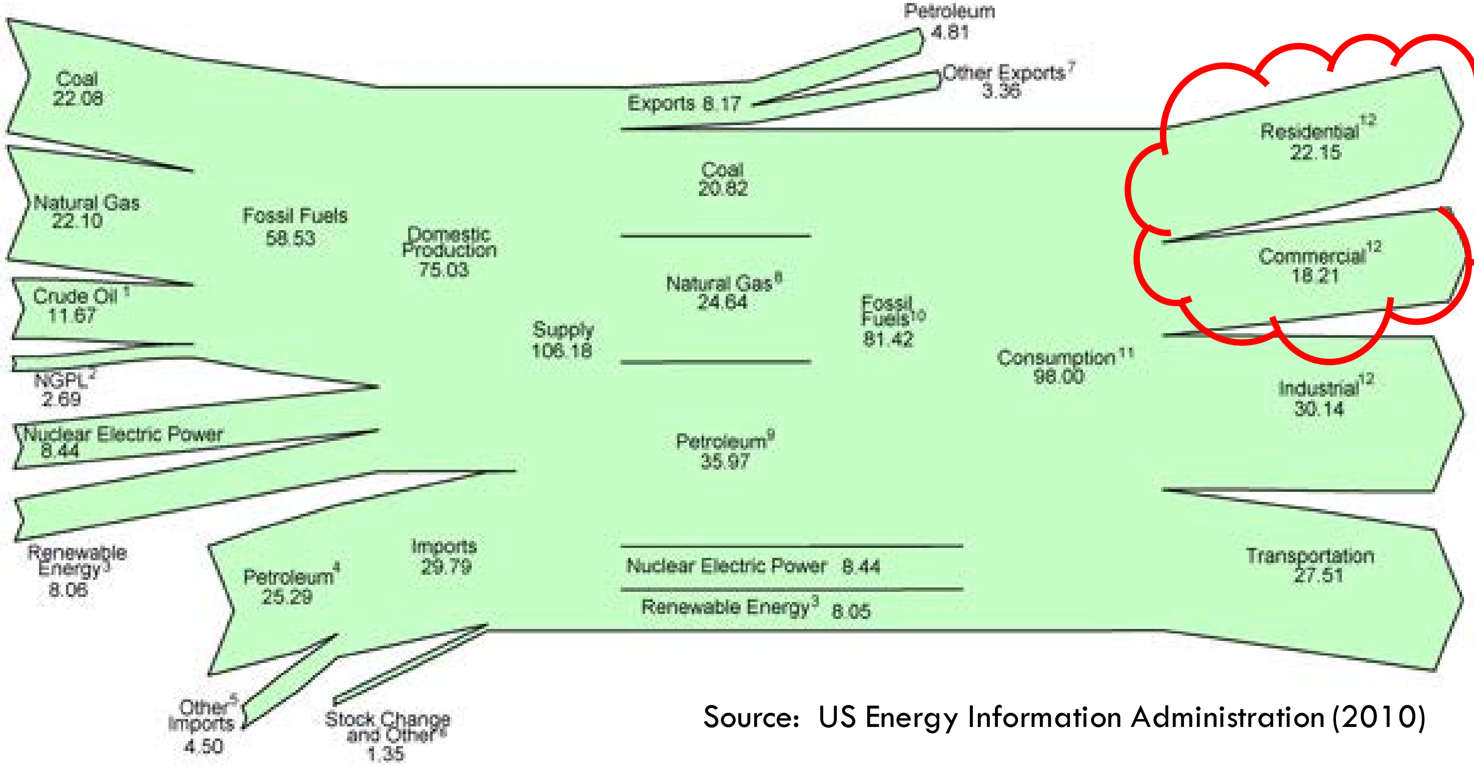
Learning Objectives

- Explain the connection between indoor air quality (IAQ) and building energy use.
- Compare the cost of health and performance impacts of IAQ with the cost of building energy use
- Explain the basis for current IAQ design standards
- Describe existing technologies with potential to improve IAQ with small or beneficial impact on energy use
- Explain how the design process should be modified to better integrate IAQ

Buildings are the largest energy end-use sector

- ~ 40% of US primary energy use



Source: US Energy Information Administration (2010)

<u>2016</u>

20.90

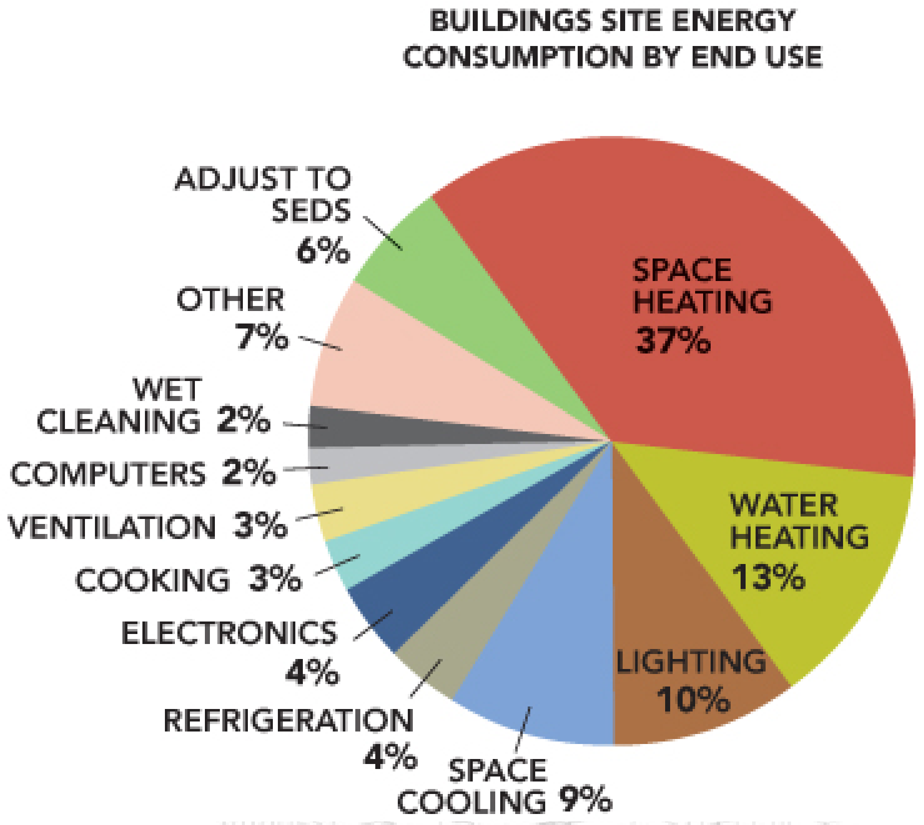
18.67

31.81

28.61

Most building energy use is for environmental control

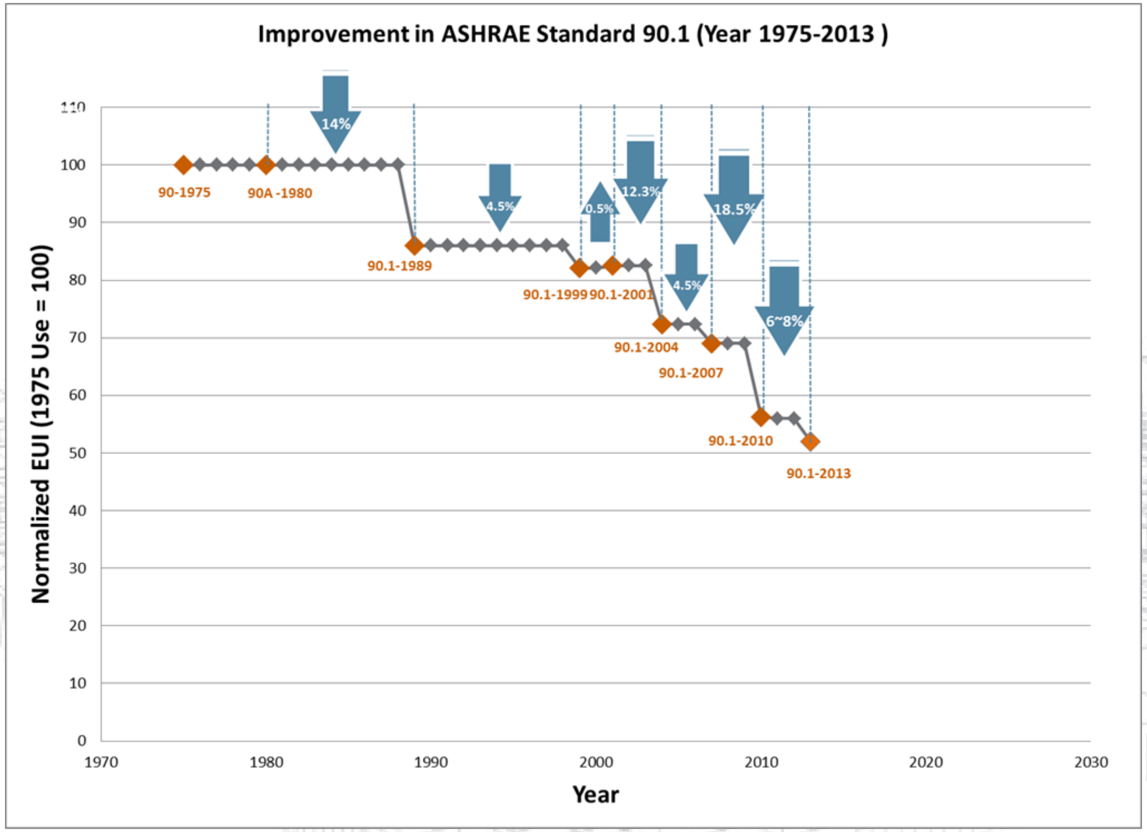
- US buildings, all types
  - Space heating 37%
  - Lighting 10%
  - Space cooling 9%
  - Ventilation 3%
  - **TOTAL 59%**
  - **HVAC 49%**



Source: US DOE Buildings Energy Data Book (2010)

Energy use and its impact on climate are recognized global issues

- More than 40 years of major effort
  - Energy standards (1970s)
  - Montreal protocol (1986)
  - Kyoto protocol (1992)
  - Energy source changes
    - Lower carbon fossil fuels
    - Wind and PV electric
  - Component and system efficiency improvements



Source: Pacific Northwest National Laboratory

Compared to energy/environment, indoor air quality is an emerging issue

“That all people should have free access to air and water of acceptable quality is a fundamental human right.”

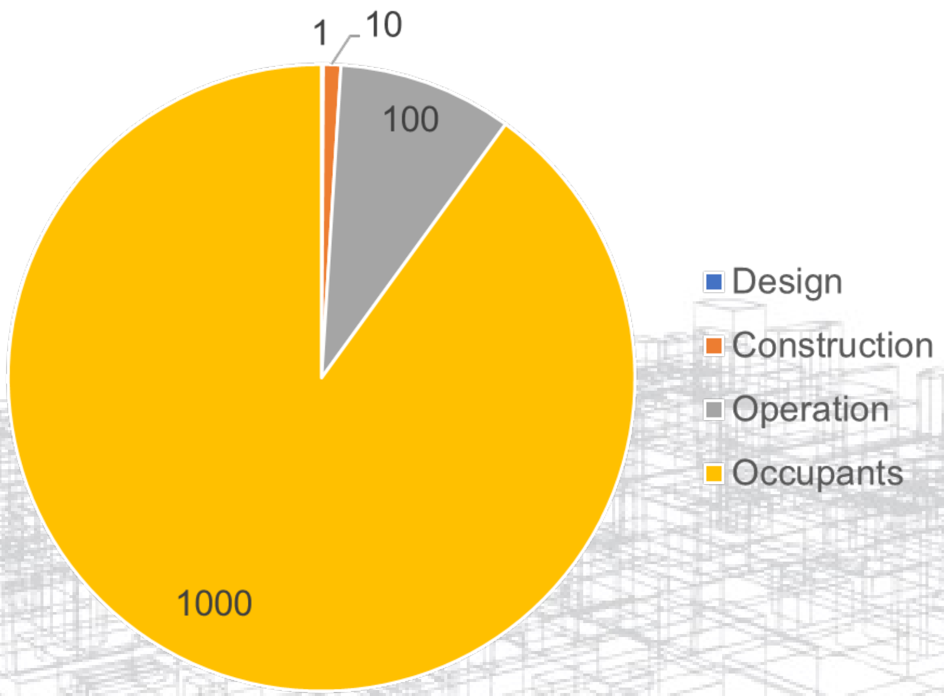
~World Health Organization (2000) *Air Quality Guidelines for Europe, 2nd ed*.

“An energy declaration without a declaration related to the indoor environment makes no sense.”

~B. Olesen, O. Seppänen, A. Boerstra (2006) *Criteria for the Indoor Environment for Energy Performance Of Buildings – A New European Standard*. Facilities 24 (11/12): 445-457.

Air quality has monetizeable effects

- 1:10:100:1000 rule of thumb
  - Design cost
  - Construction cost
  - Operation cost
  - Occupant cost



10% improvement in performance ≅ operating cost

Economic Impact of IEQ

(Fisk, W. How IEQ Affects Health, Productivity. ASHRAE J., May 2002)

Source of Gain	Potential Annual Benefits in US	Lower $B (2017)	Higher $B (2017)
Reduced Respiratory Illness	16 - 37 Million Avoided Cases of Common Cold or Influenza	6 (8.2)	14 (19.2)
Reduced Allergies and Asthma	8% - 25% Decrease in Symptoms - 53 Million with Allergies, 16 Million Asthmatics	1 (1.4)	4 (5.5)
Reduced Sick Building Syndrome Symptoms	20% - 50% Less SBS Symptoms at Work for ~15 Million Workers	10 (13.7)	30 (41.1)
Lighting/Thermal	Performance improvement	20 (27.4)	160 (219.2)
TOTAL		**37** (50.7)	**285** (285.0)

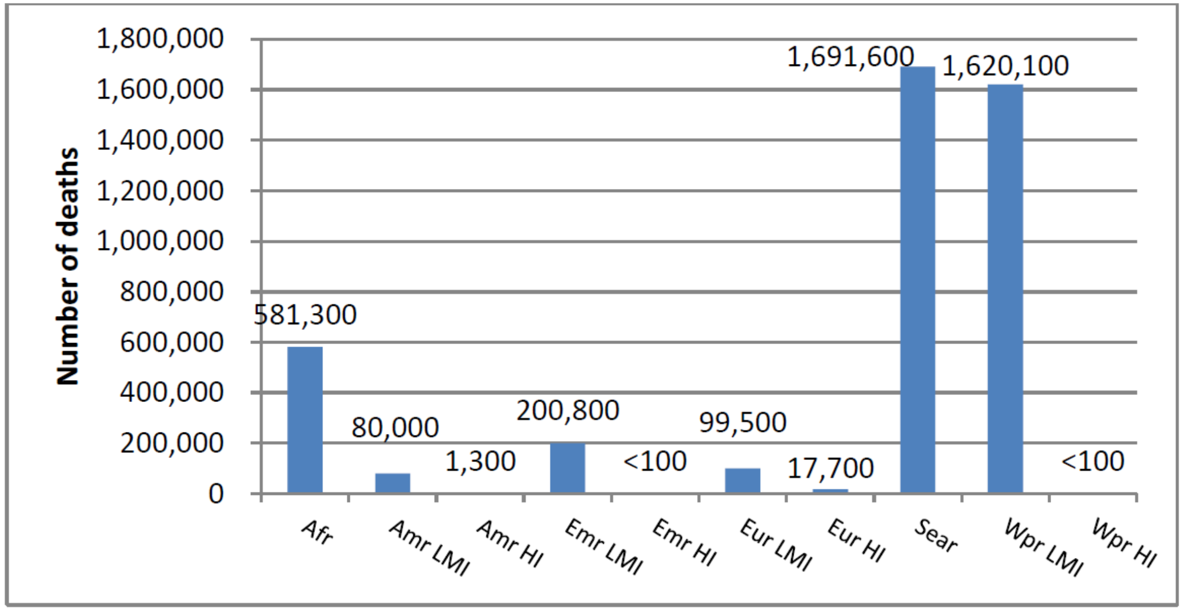
Higher estimate of economic loss is ~ annual US energy bill for buildings

Human cost of IAQ - asthma

- In US in 2015
  - 7.8 % of population/
    25 million people diagnosed
  - 11.6 million attacks
  - 10.5 million missed school days
  - 14.2 million missed work days
  - 439,000 hospital stays
    1.6 million emergency room visits
  - 3,615 deaths

- Indoor pollutants that are asthma triggers (CDC)
  - ETS
  - Dust mites
  - Outdoor air pollution
  - Cockroach allergens
  - Pets
  - Mold
  - Wood and grass smoke
  - Respiratory infections

Human cost of IAQ – developing world



HAP: Household air pollution; Amr: America, Afr: Africa; Emr: Eastern Mediterranean, Sear: South-East Asia, Wpr: Western Pacific; LMI: Low- and middle-income; HI: High-income.

- Health effects
  - 34% - stroke
  - 26% - ischemic heart disease
  - 22% - COPD
  - 12% - acute lower respiratory infections in children
  - 6% - lung cancer

Estimated 4.3 million excess deaths in 2012 due to indoor PM, mostly biomass combustion (WHO 2014)

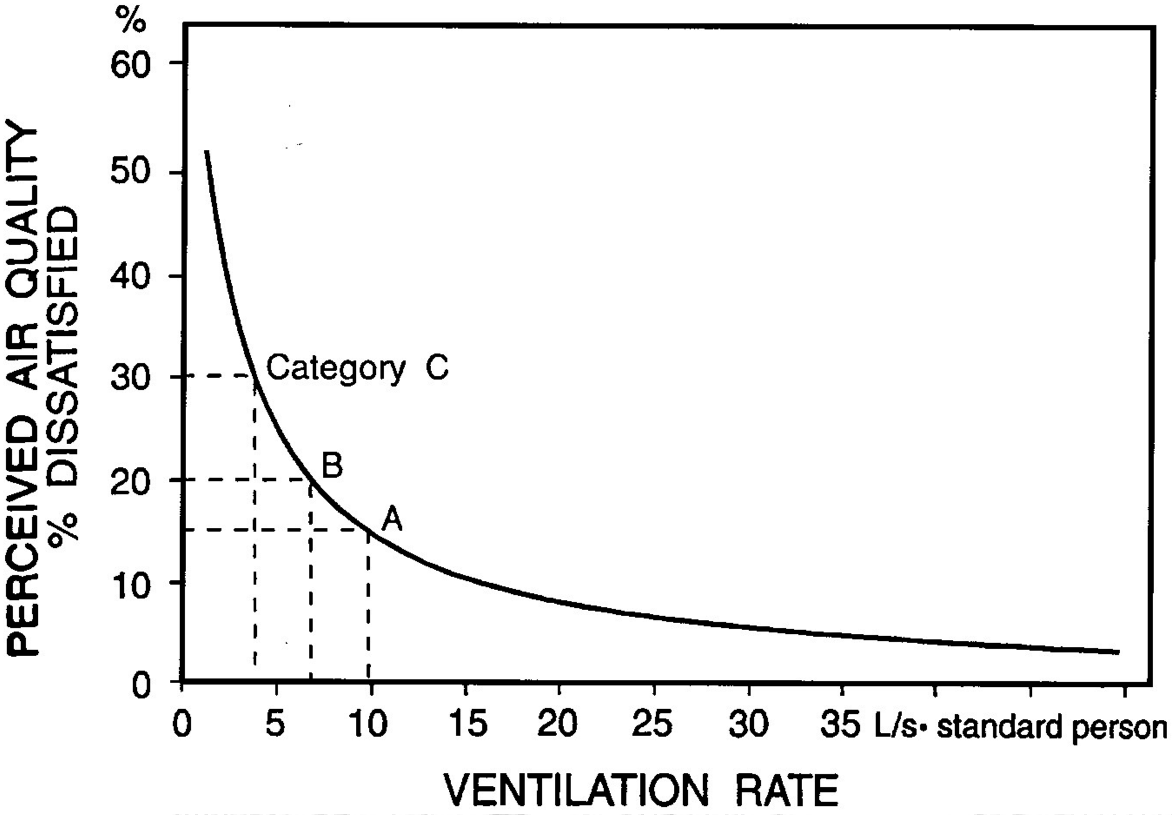
Current practical definition of IAQ – perceived air quality

Acceptable Indoor Air Quality: *air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction.*

(ASHRAE Standard 62.1-2016 *Ventilation for Acceptable Indoor Air Quality)*

Current approach to IAQ control

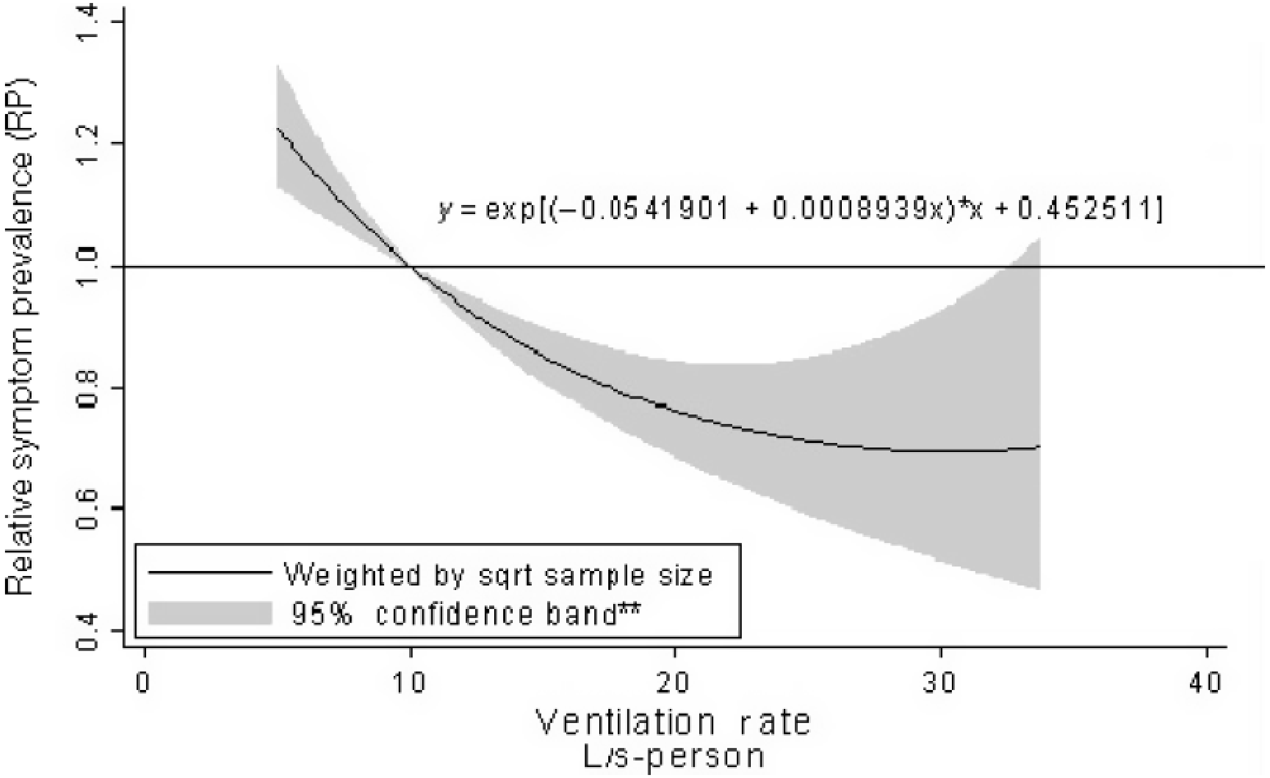
- Reduce/remove known sources of contaminants
- Manage moisture
- Ventilate to achieve subjective satisfaction
  - ASHRAE 62.1 - ~5-10 L/s-pers
- Moderate level of particulate filtration
  - ASHRAE 62.1 - MERV 8: 70-85% for > 3 µm, NR for $PM_{2.5}$



Fanger, P. O. (2008) "Perceived Air Quality and Ventilation Requirements" in Indoor Air Quality Handbook, J. Spengler, J. McCarthy and J. Samet eds.

Current ventilation standards set a low bar for health and productivity

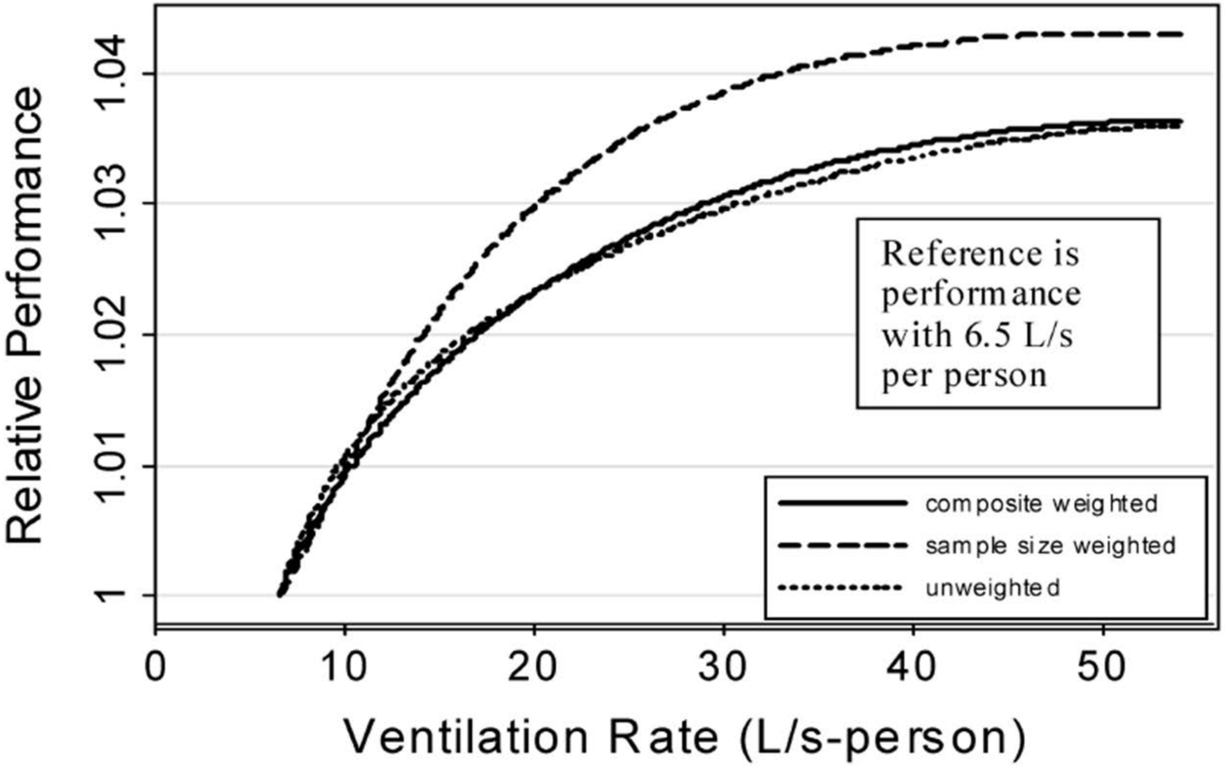
Sick building syndrome symptoms



Source: W. Fisk, A Mirer, M. Mendell. 2009. Quantitative relationship of sick building syndrome symptoms with ventilation rates. Indoor Air

Ventilation, health & productivity

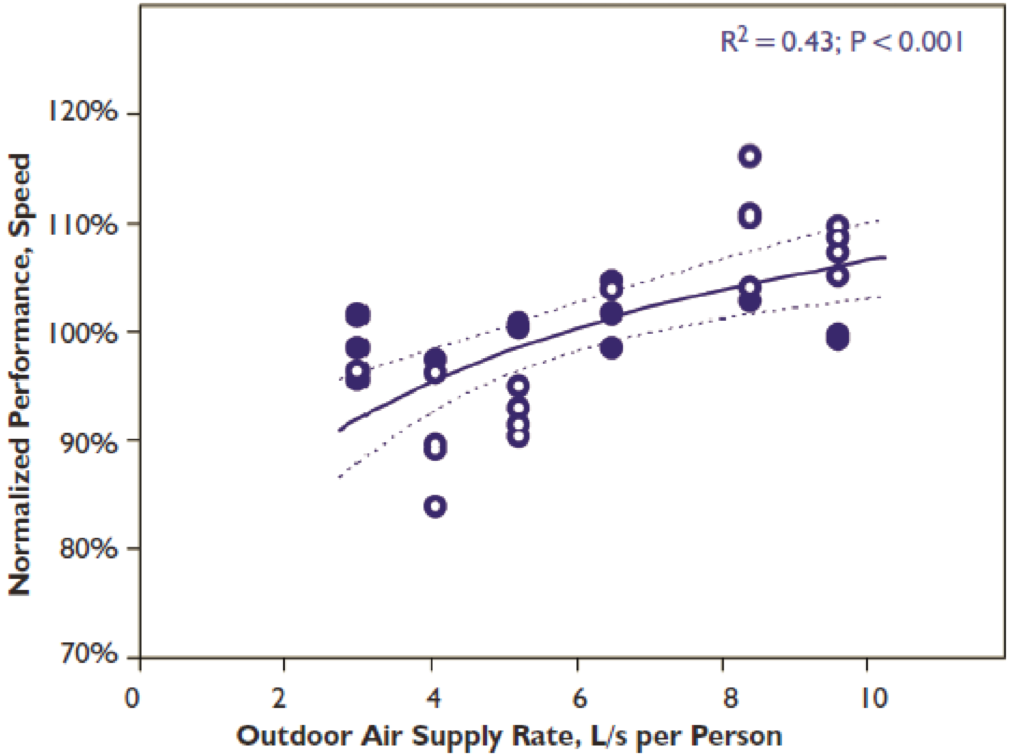
Task performance

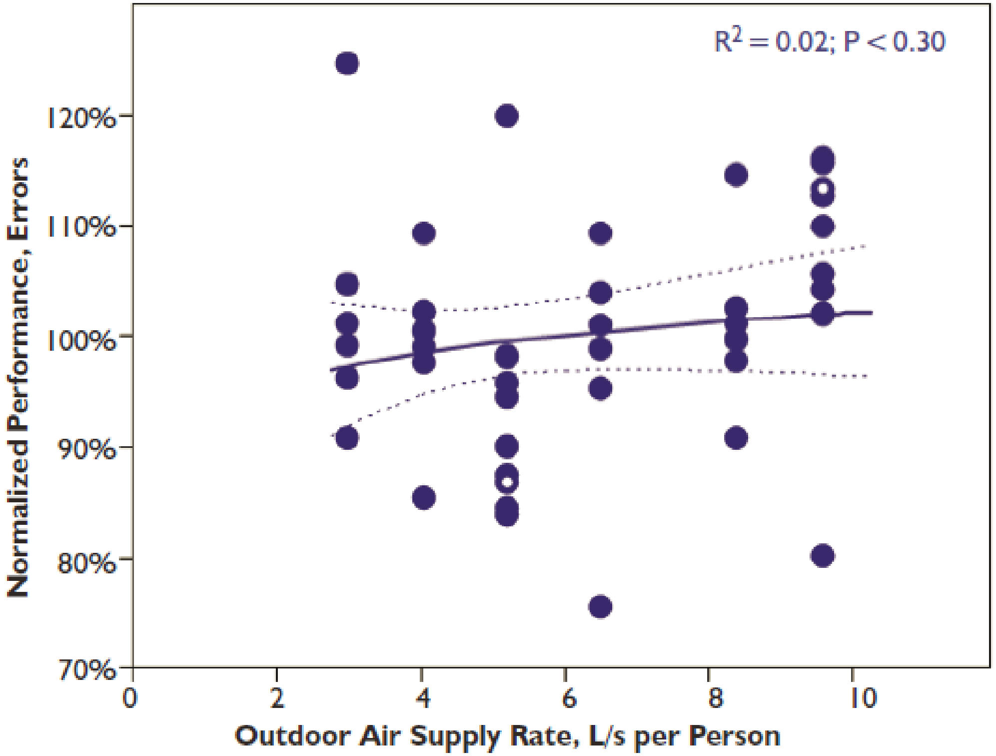


Source: Seppänen, O. and W. Fisk. 2006. Some Quantitative Relations between Indoor Environmental Quality and Work Performance or Health. HVAC&R Research.

Ventilation, health & productivity

Schoolwork performance





Source: P. Wargocki and D. Wyon. 2006. Effects of HVAC on Student Performance. ASHRAE Journal. (Summarizing ASHRAE RP-1257)

Ventilation, health & productivity

Infectious disease transmission

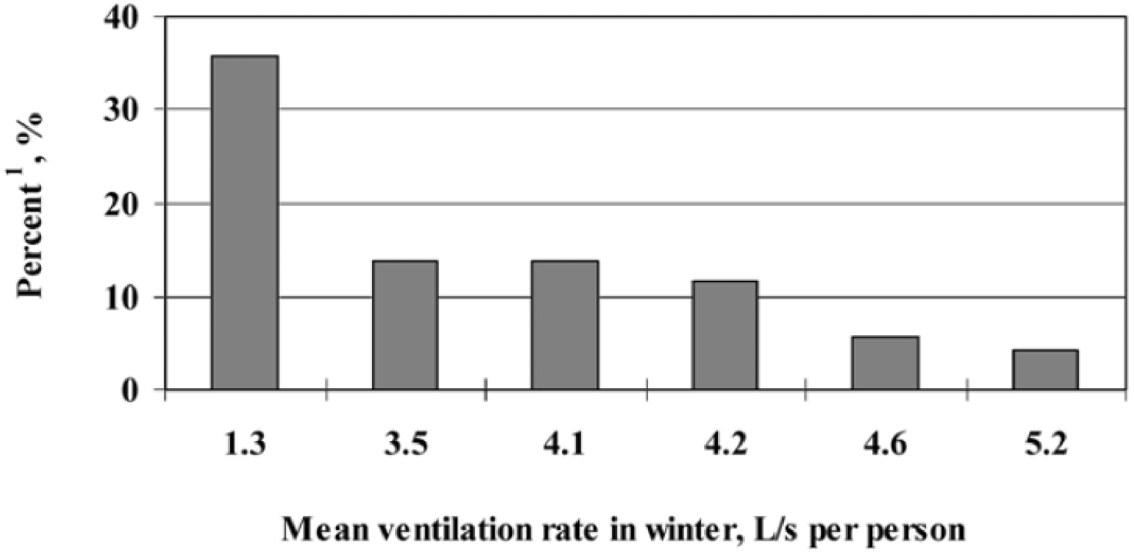


Figure 4. Associations between common cold infection rates and mean ventilation rate in winter in buildings constructed after year 1993. [1] Proportion of occupants with ≥6 common colds in the previous 12 months.

Source: Sun, Y., Z. Wang, Y. Zhang, J. Sundell. 2011, In China, Students in Crowded Dormitories with a Low Ventilation Rate Have More Common Colds: Evidence for Airborne Transmission. PLoS ONE 6(11) e27140.

Ventilation, health & productivity

Recent studies on cognitive effects of CO_2 with fixed and proportional bioeffluent

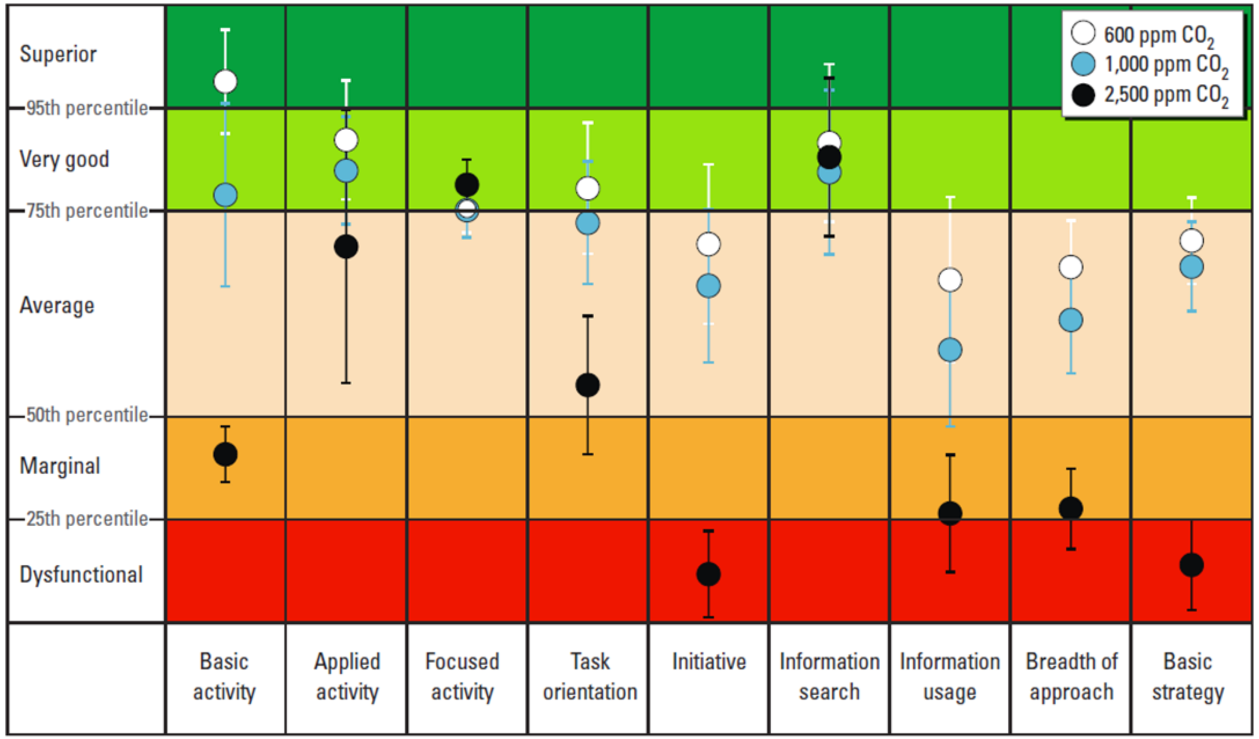


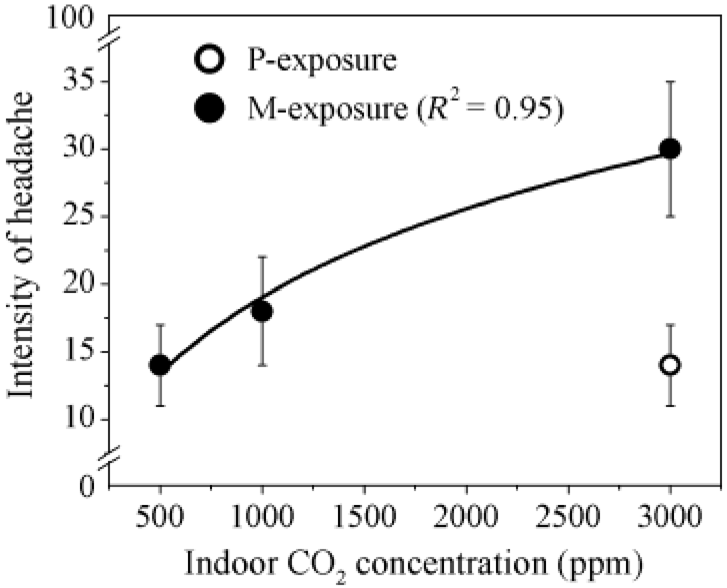
Figure 2. Impact of CO_2 on human decision-making performance. Error bars indicate 1 SD.

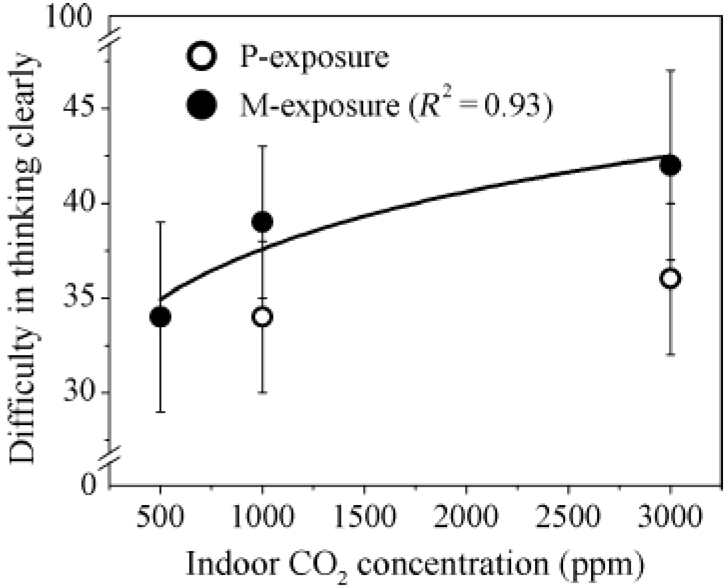
Satish, et al. – cognitive effects of CO_2 alone at concentrations compliant with current ventilation minimum standards

Source: Satish, U., M. Mendell, K. Shekhar, T. Hotchi, D. Sullivan, S. Streufert, and W. Fisk. 2013. Is CO_2 an Indoor Pollutant? Direct Effects of Low-to-Moderate CO_2 Concentrations on Human Decision-Making Performance. Env. Health Perspectives 20(12):1671-1677.

Ventilation, health & productivity

Recent studies on cognitive effects of CO_2 with fixed and proportional bioeffluent





Zhang, et al – cognitive deficit, but only with proportional bioeffluent at lower CO_2 concentrations

Source: Zhang, X., P. Wargocki, Z. Lian, C. Thyregod. 2017. Effects of exposure to carbon dioxide and bioeffluents on perceived air quality, self-assessed acute health symptoms, and cognitive performance. Indoor Air 27:47-64.

Energy efficiency and IAQ are in conflict and energy usually wins

Energy

- Measured accurately
- Monetized
- Efficiency has positive environmental impact
- Existing design process focused on optimizing energy cost and capital cost

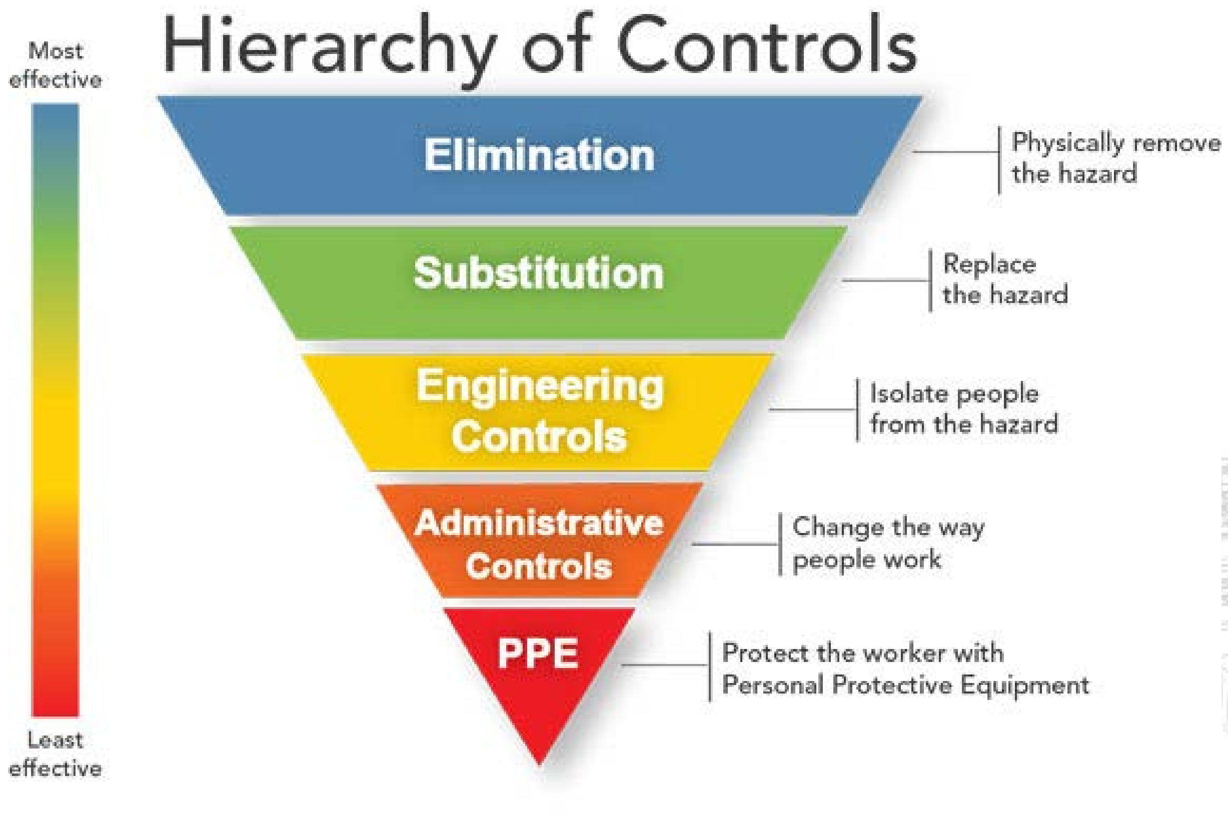
Indoor Air Quality

- Prescriptive – perceived air quality approach
- Not accurately monetized
- Without attention to energy use, IAQ improvements may increase energy
- Ventilation stands in for IAQ and is a design constraint

Agenda for integrating IAQ and energy efficiency

- Translational research: science → application
- Education and training
- *Deploy efficient technology to improve IAQ*
- *Design process changes*

Building technology is not the first priority



Source: US National Institute of Occupational Safety and Health (NIOSH)

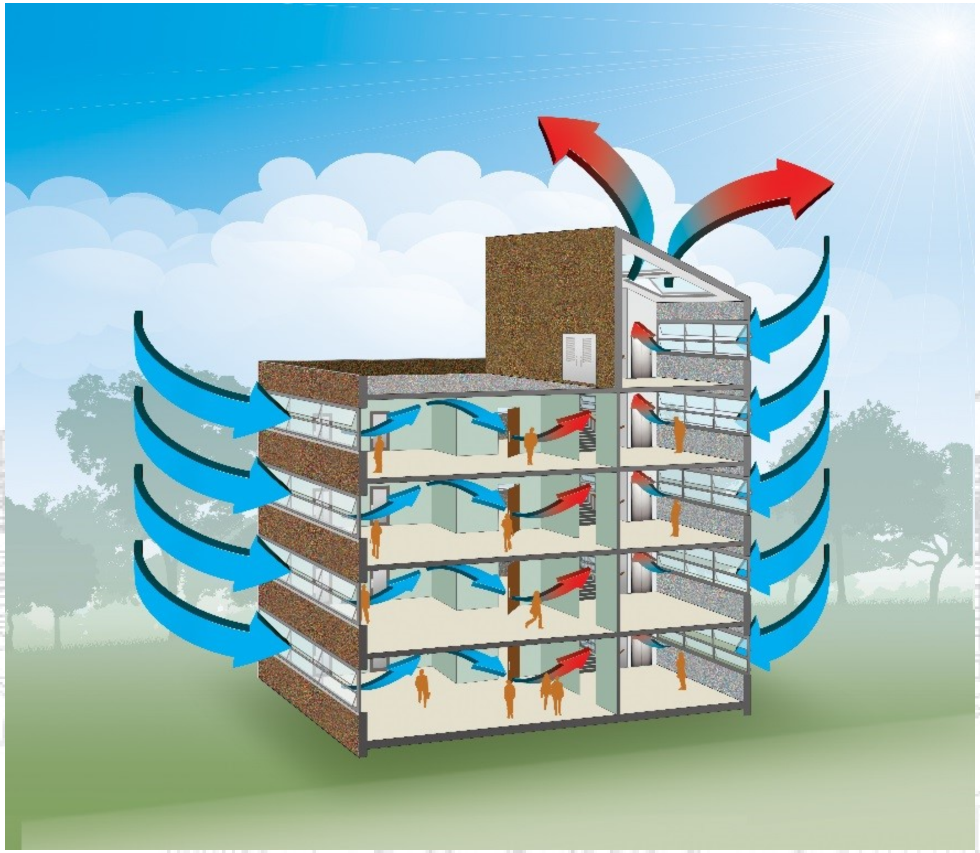
- Engineering controls limit exposure
- Exposure $\propto$ source strength
- Smaller sources require less treatment

Ventilation

- Dilute contaminants and remove them in exhaust air
- Methods for providing ventilation with low energy demand
  - Natural ventilation
  - Air-to-air energy recovery
  - Demand-controlled ventilation
  - Air-side economizer
  - Dedicated outdoor air supply (DOAS)
  - Improved ventilation air delivery methods

Ventilation – Natural Ventilation

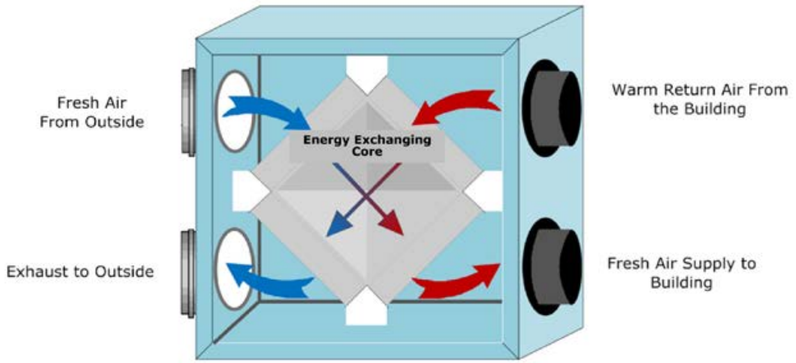
- Effectiveness varies with climate and thermal comfort estimate ~20 – 50% cooling for US
- Applicability in urban environments compromised by outdoor air quality
- As applied, concerns about seasonal effectiveness, occupant use
- ASHRAE Standard 62.1 requires most NV systems be backed up by mechanical ventilation
- Requires acceptance of adaptive model of comfort



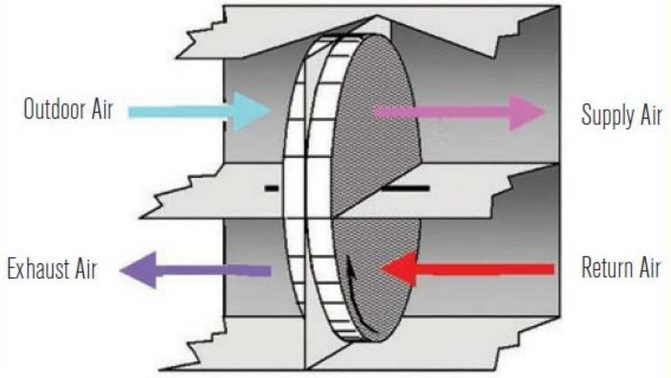
Source: Construction Canada

Ventilation – Air-Air Heat Recovery

- Should be considered for all systems
- “Total energy” recovery replacing sensible for cooling systems
- ASHRAE Standard 90.1 requires exhaust air energy recovery with enthalpy recovery ratio ≥ 50% for covered systems

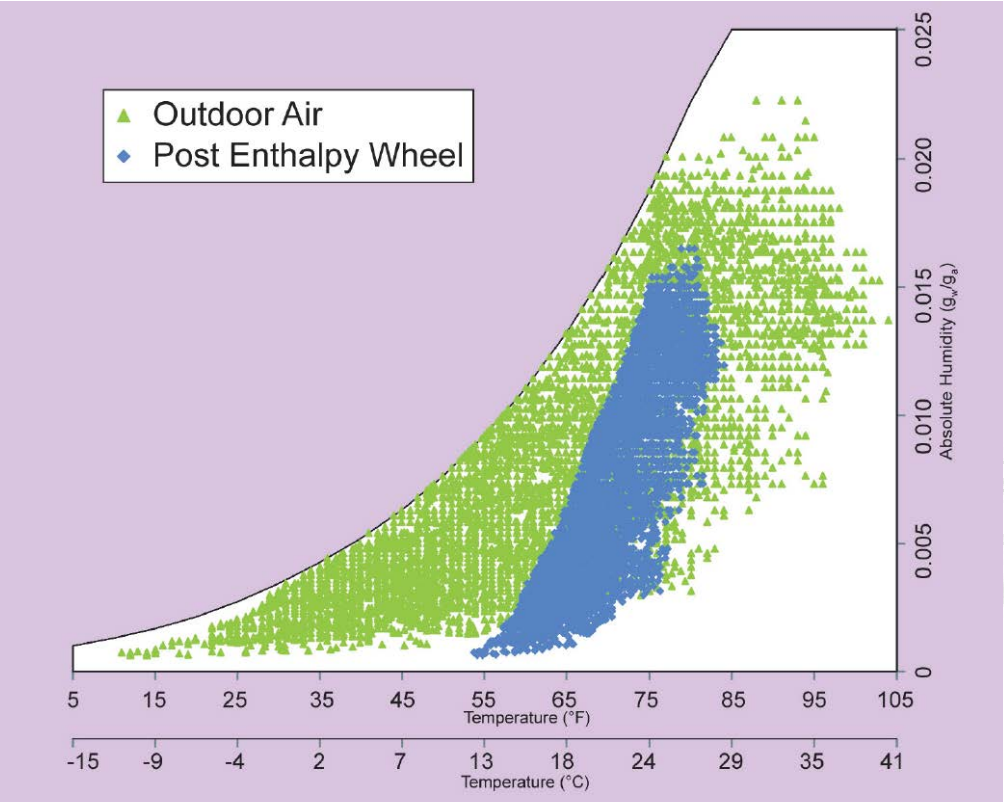


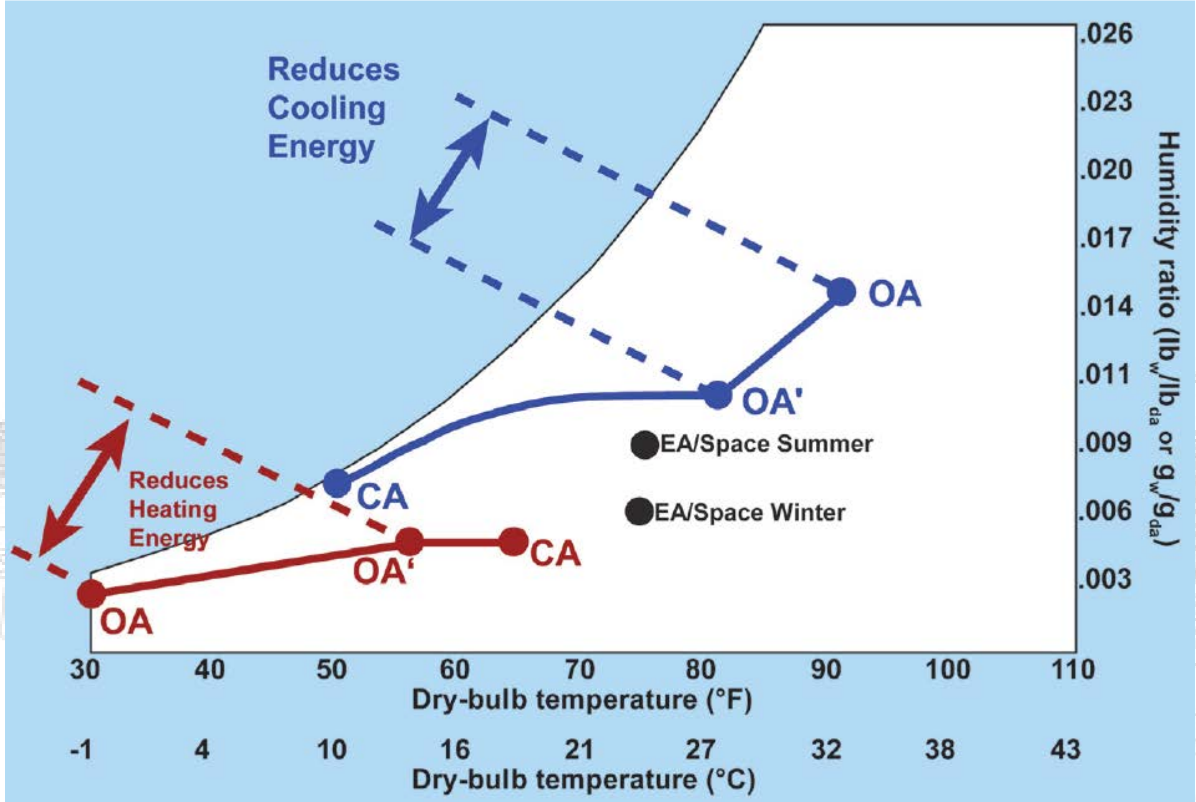
Source: Clark, L. 2017. HPAC Engineering



Source: Flow Tech

Ventilation – Air-Air Heat Recovery





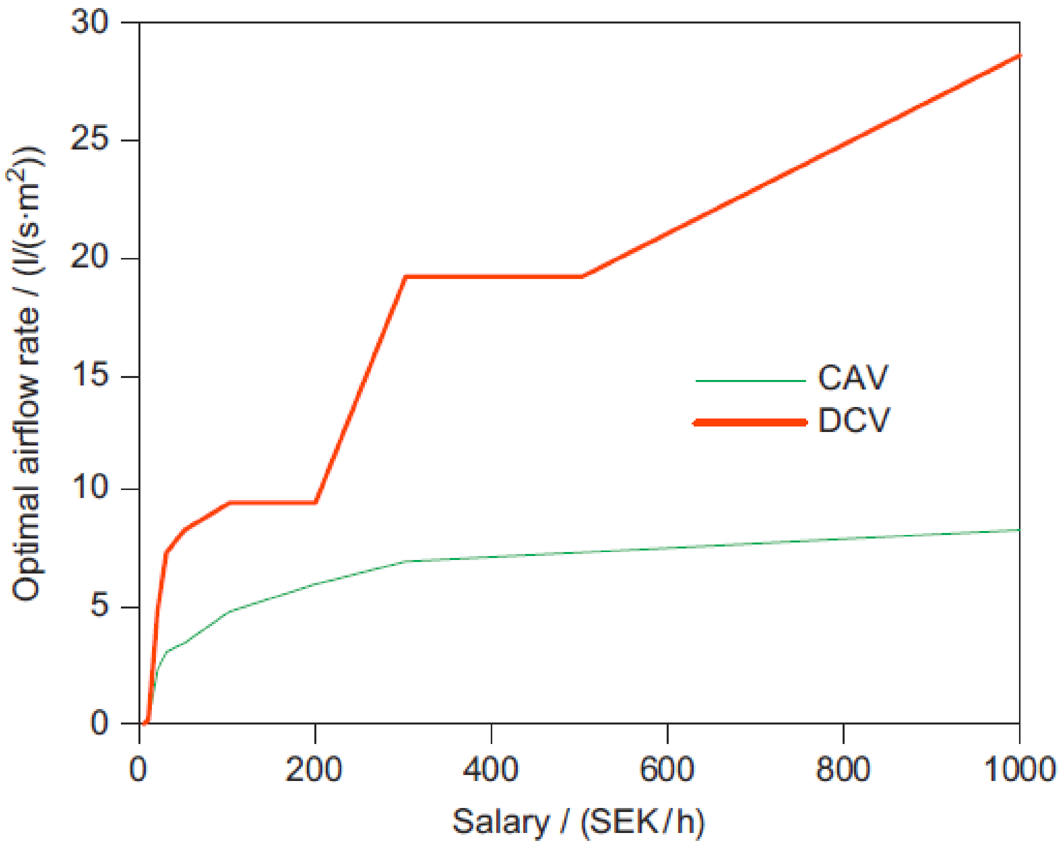
Source: ASHRAE. 2017. Design Guide for Dedicated Outdoor Air Systems

Ventilation – Demand Controlled (DCV)

- Ventilation standards specify OA requirements based on area and occupancy
- DCV limits allows reduction based on actual occupancy
- Advanced strategies may also consider PM, VOCs, humidity
- May be required by energy standards like ASHRAE 90.1 for some spaces
- Issues
  - Difficulty/cost of accurate occupant counts – CO_2 most common
  - Control to minimum standards – increased health/performance deficits
  - Could improve IAQ if per-person ventilation rate is correspondingly increased

Ventilation – Demand Controlled

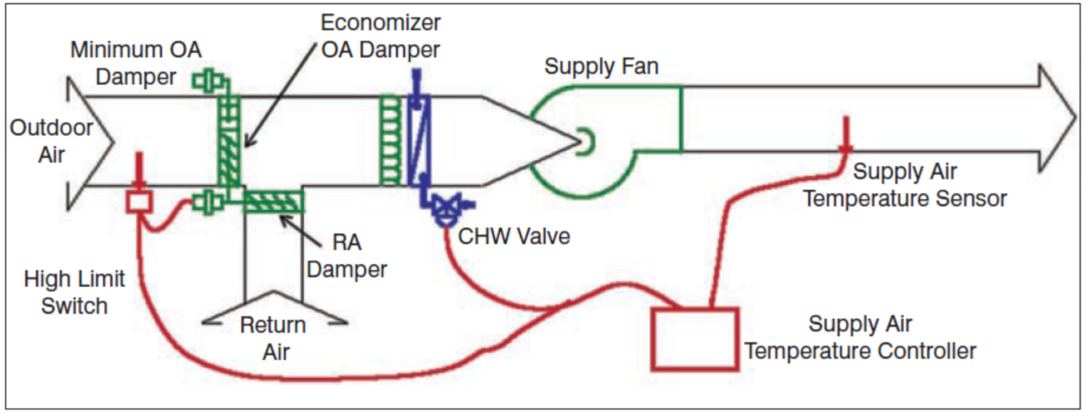
- Life-cycle cost analysis including health and productivity effects shows that higher ventilation rates can be cost optimal

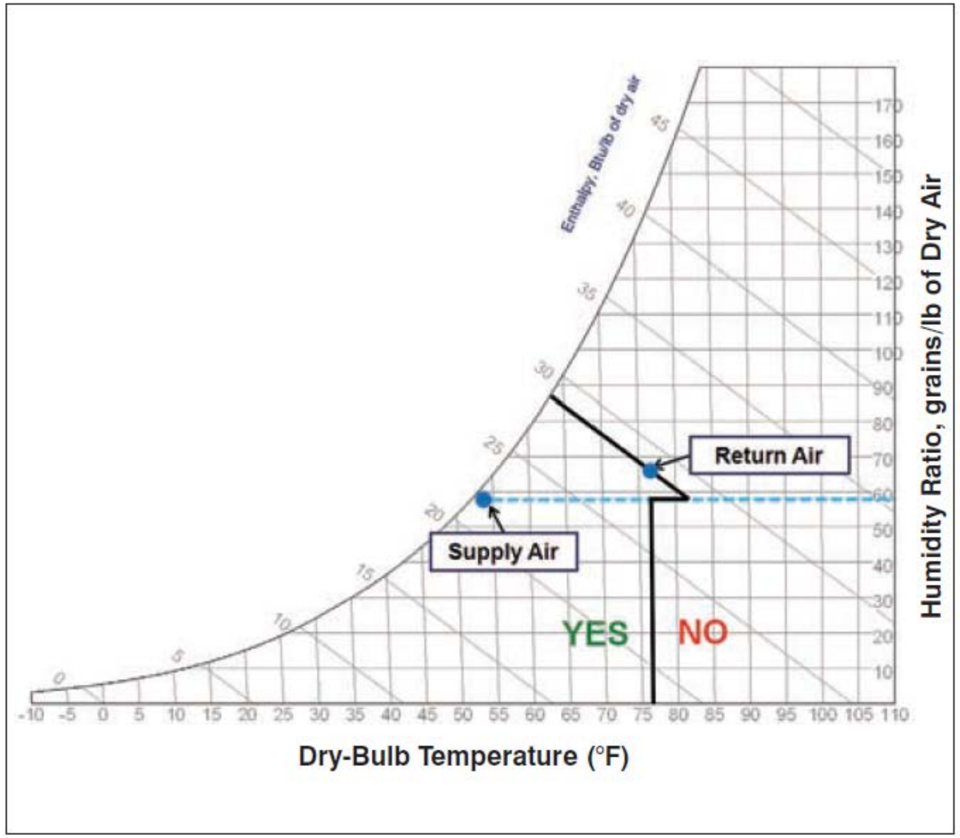


Source: Johansson, D. 2009. The life cycle costs of indoor climate systems in dwellings and offices taking into account system choice, airflow rate, health and productivity. Building and Environment (44):368-376.

Ventilation – Air-Side Economizer

- Increase OA to reduce coil cooling load based on T or h
- Saves energy and increases ventilation
- Required for some systems by ASHRAE Standard 90.1





Source: Taylor and Cheng. 2010. ASHRAE Journal.

Ventilation – Air-Side Economizer

- Monetized IAQ benefit of economizer can exceed energy cost savings
- Example:
  - Fisk, W., D. Faulkner, O. Seppänen, J. Huang. 2005. Economic Benefits of an Economizer System: Energy Savings and Reduced Sick Leave. ASHRAE Transactions 111(2).
  - Combines energy modeling with Wells-Riley based sick leave analysis for two-story office in Washington DC.

Ventilation – Air-Side Economizer

Table 2. Predicted Annual HVAC Energy Use, Ventilation Rates, and Sick Leave

Min Vent*	Vent Rate†	Economizer	Annual HVAC Energy			Lower and Upper Estimate of Annual Sick Leave			
L s^{-1}	h^{-1}	Y or N	Elec. MWh	Gas Therm (GJ)	Total $US	Lower Days	Lower $	Upper Days	Upper $
10	0.74	N	298	6390 (674)	30000	264	53000	340	68000
10	1.46	Y	269	6690 (706)	28000	186	37000	274	55000
10	Savings from economizer				**1900**	**78**	**16000**	**66**	**13000**
15	0.96	N	303	6630(699)	31000	216	43000	321	64000
15	1.56	Y	272	6850 (723)	29000	162	32000	267	53000
15	Savings from economizer				**2100**	**54**	**11000**	**54**	**11000**
20	1.18	N	308	6960 (734)	31000	180	36000	298	60000
20	1.67	Y	276	7130 (752)	29000	150	30000	259	52000
20	Savings from economizer				**2200**	**30**	**6000**	**39**	**7700**

* Per person
† Yearly average
Note: Numbers may not add precisely due to rounding.

Source: Fisk, et al. 2005. ASHRAE Trans.

Health benefit is 3 – 8 times greater than energy savings

Ventilation – DOAS

- “Dual-path”
  - 100% OA system – latent load, ventilation, partial sensible
  - Parallel sensible system
- Energy recovery
- Many parallel system options
  - Fan coil units
  - Chilled beams
  - Radiant panels
  - Variable air volume

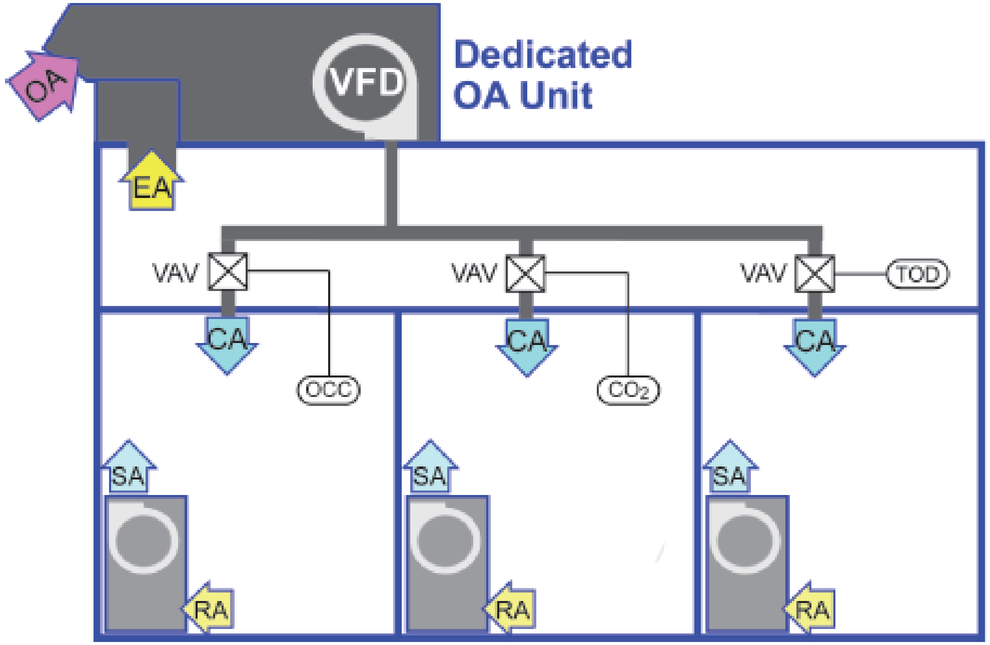


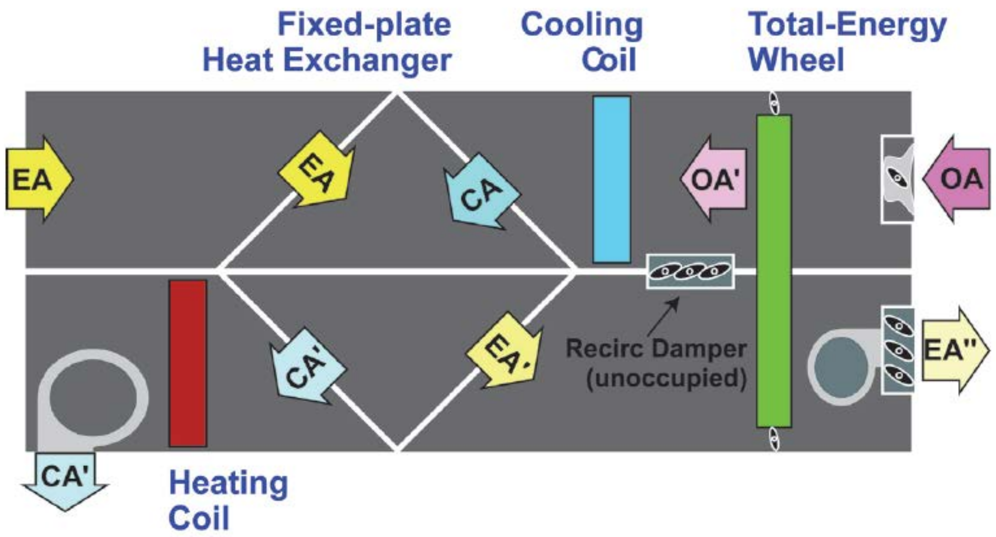
Figure 4.2 Demand-controlled ventilation with a DOAS.

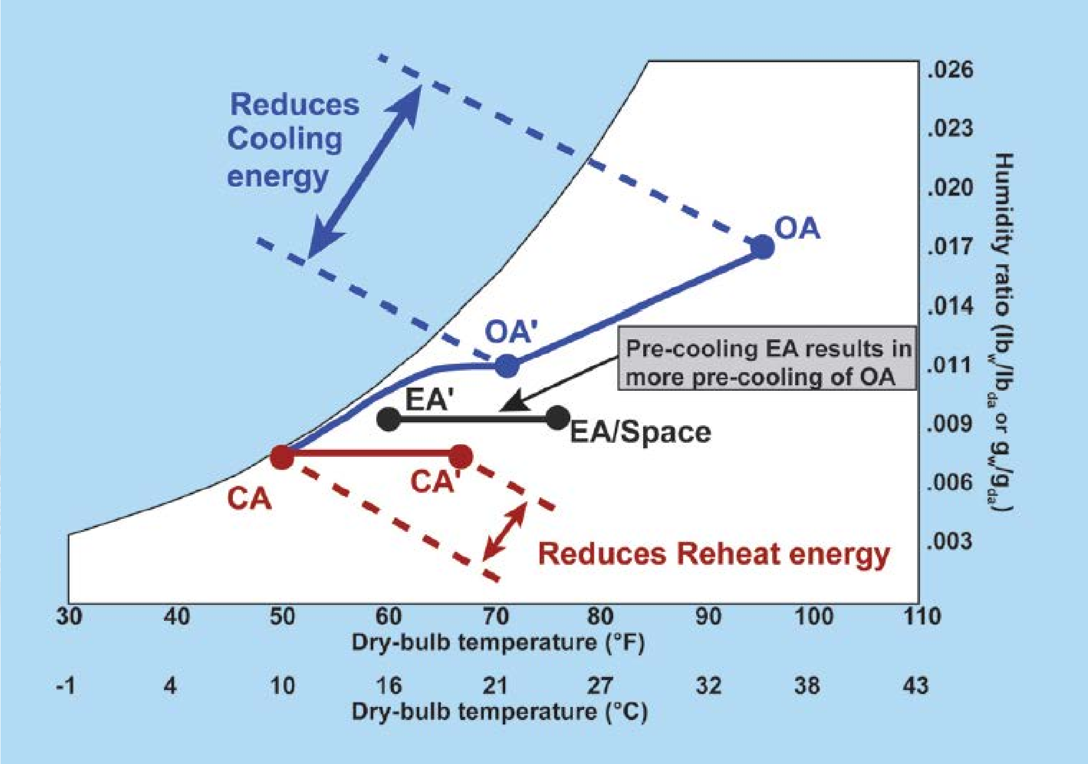
OA = outdoor air CA = conditioned outdoor air RA = recirculated air
EA = exhaust air SA = conditioned supply air

Sustainable Engineering Group, LLC

Source: ASHRAE. 2017. Design Guide for Dedicated Outdoor Air Systems

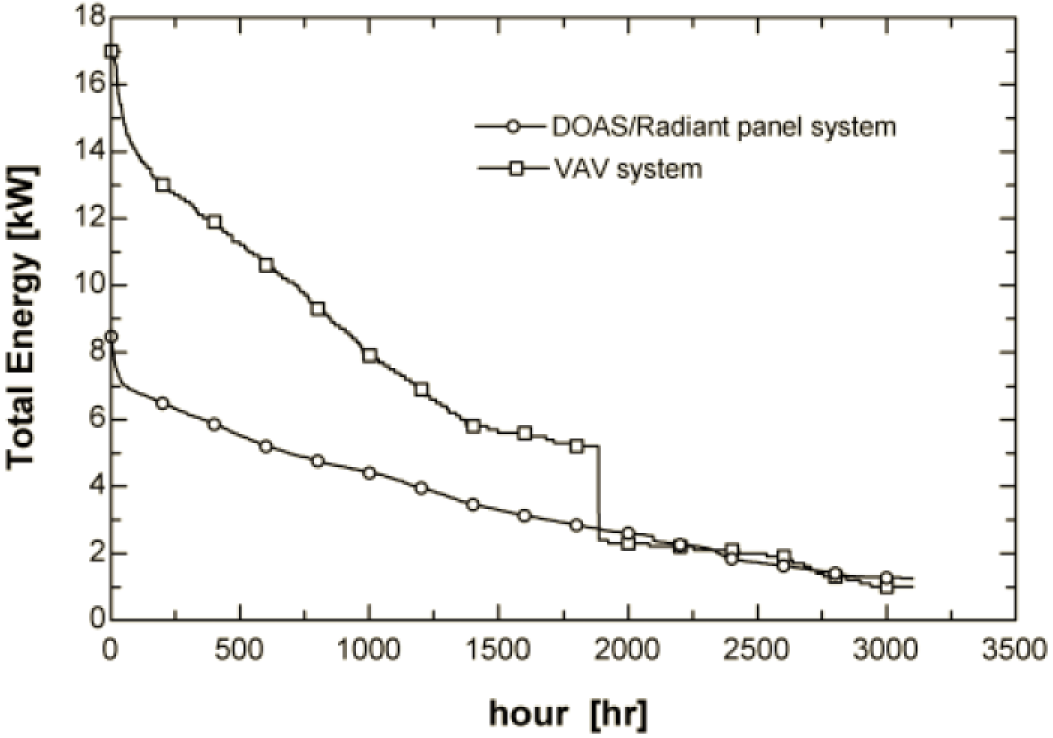
Ventilation – DOAS

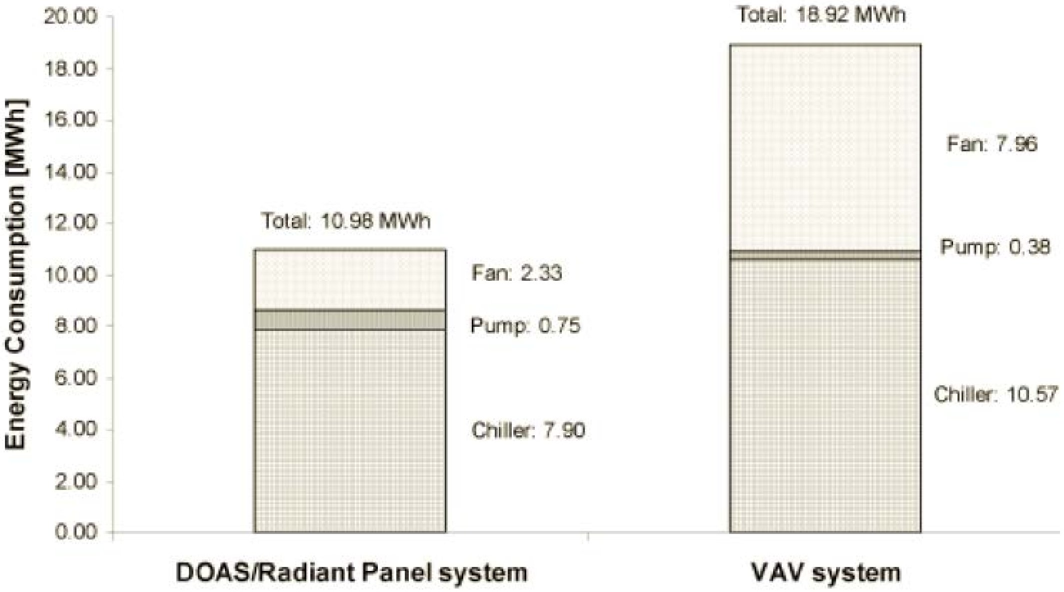




Source: ASHRAE. 2017. Design Guide for Dedicated Outdoor Air Systems

Ventilation – DOAS

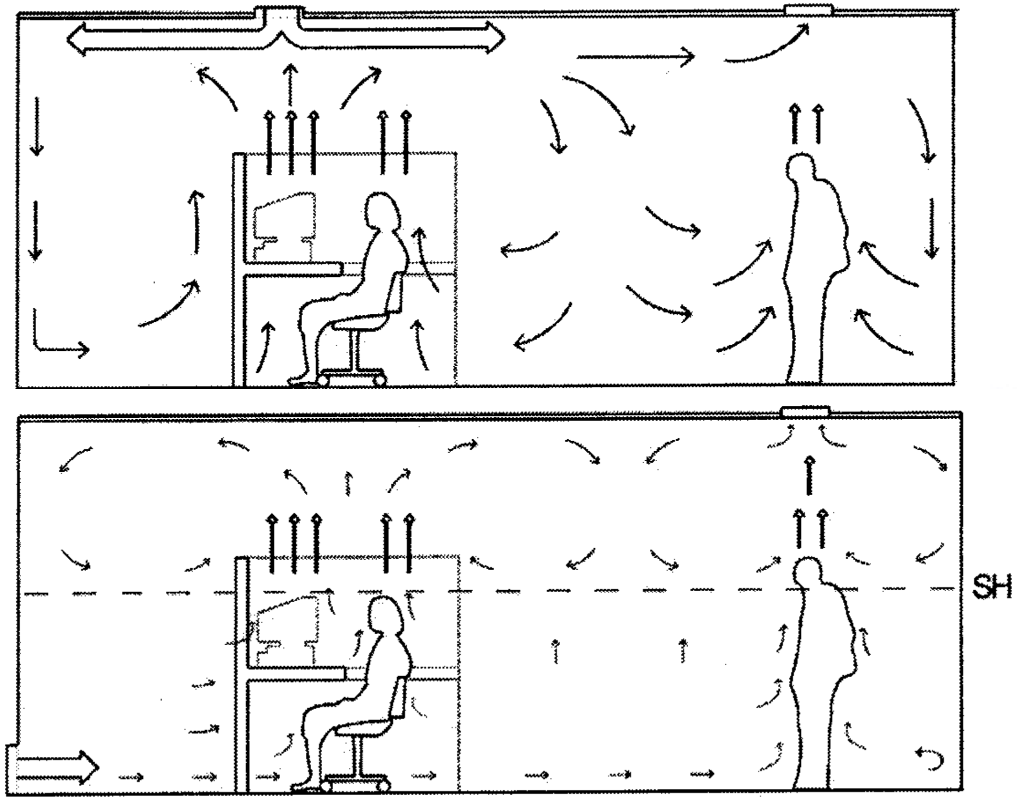




Source: Jeong, Mumma, and Bahnfleth. 2003. Energy Conservation Benefits of a Dedicated Outdoor Air System with Parallel Sensible Cooling by Ceiling Radiant Panels ASHRAE Trans.

Ventilation – Improved Air Delivery

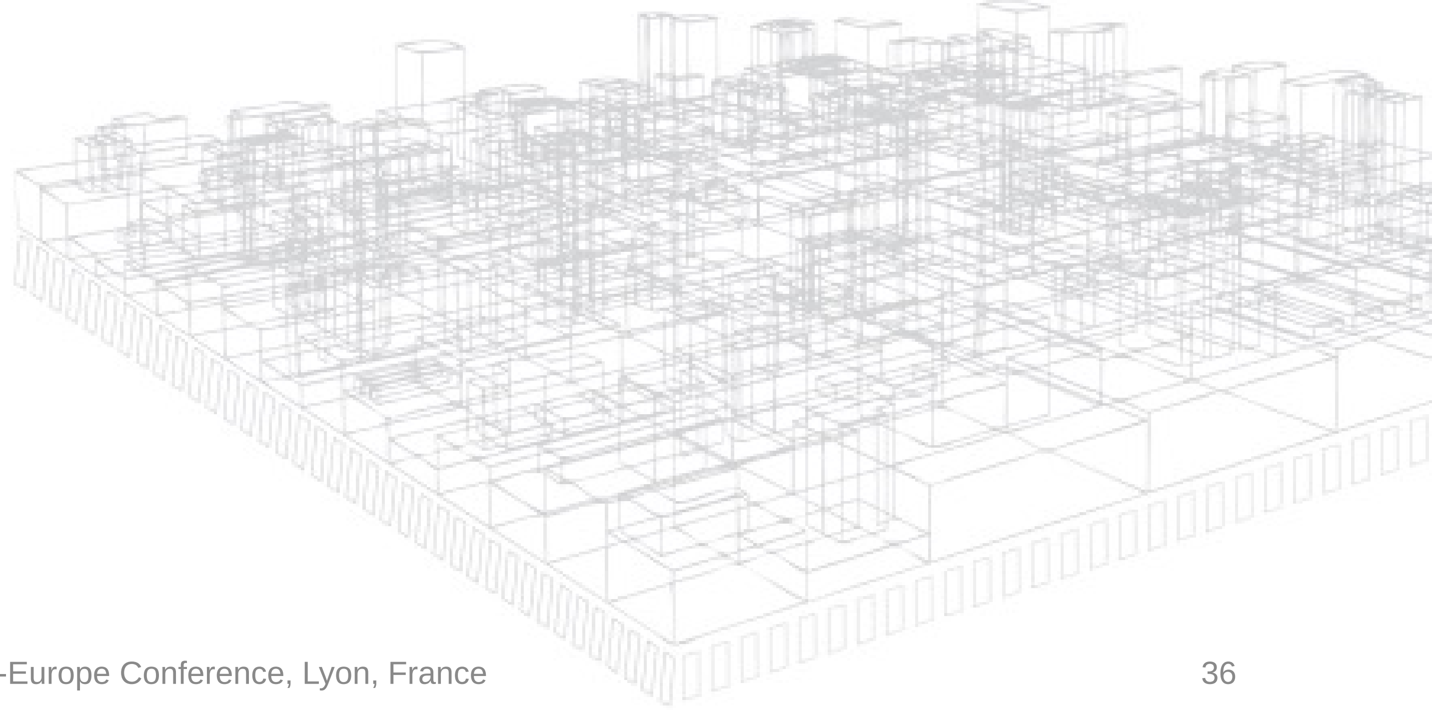
- Alternatives to overhead mixing ventilation
  - Underfloor air distribution
  - Displacement ventilation
  - Personal ventilation
- All have the effect of increasing contaminant removal effectiveness
- Lower total ventilation requirement for same IAQ



Source: Chen and Glicksman. 2003. System Performance Evaluation and Design Guidelines for Displacement Ventilation. ASHRAE.

Air Cleaners

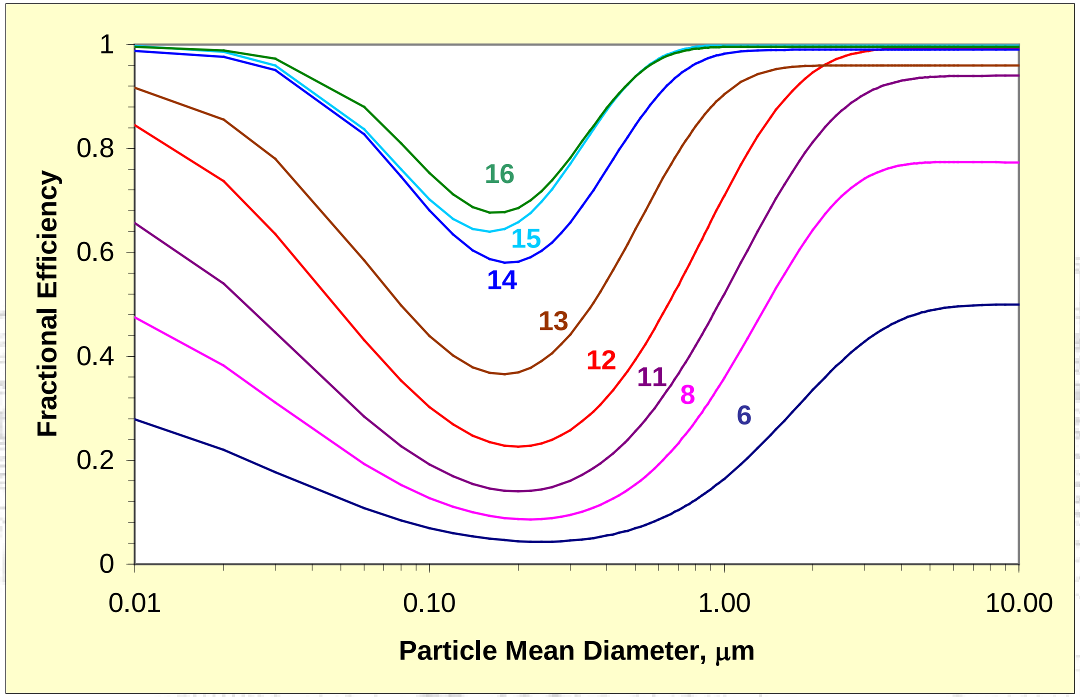
- Role of air cleaners – remove contaminants not easily removed by ventilation, reduce need for ventilation
- Major classes
  - Particulate filtration
  - Gas phase filtration
  - Microbial control



Air Cleaners – Particulate

- Well-developed technology (fiber filters)
- Older minimum requirements in standards minimally address size ranges with health effects – but improving
- HEPA filters not needed to add significant value
- Higher η filters can have minimal energy impact if integrated in original design

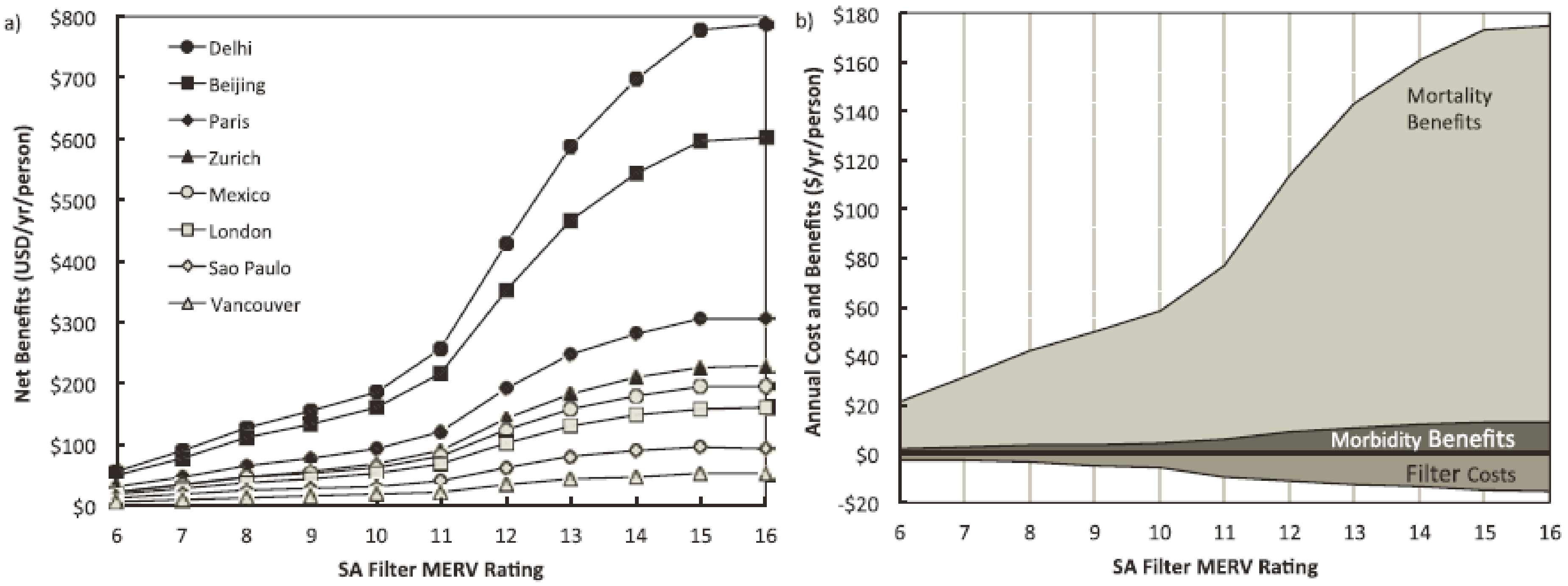
Typical filter performance by MERV rating
ASHRAE Standard 52.2



Source: Kowalski and Bahnfleth. 2002. HPAC

Air Cleaners - Particulate

- Major benefits for reduced indoor PM, especially when outdoor air levels are high



Source: Montgomery, J., C. Reynolds, S. Rogak, S. Green. 2015. Financial implications of modifications to building filtration systems. Building and Environment 85:17-28.

Air Cleaners – Gas phase

- Not required by minimum prescriptive standards
- Sorbent media (activated carbon, permanganates) are best established
- Photocatalysis has promise and problems
- Many issues
  - What to control
  - Can it be measured accurately
  - What are control levels
  - Secondary contaminant generation
  - Reliability

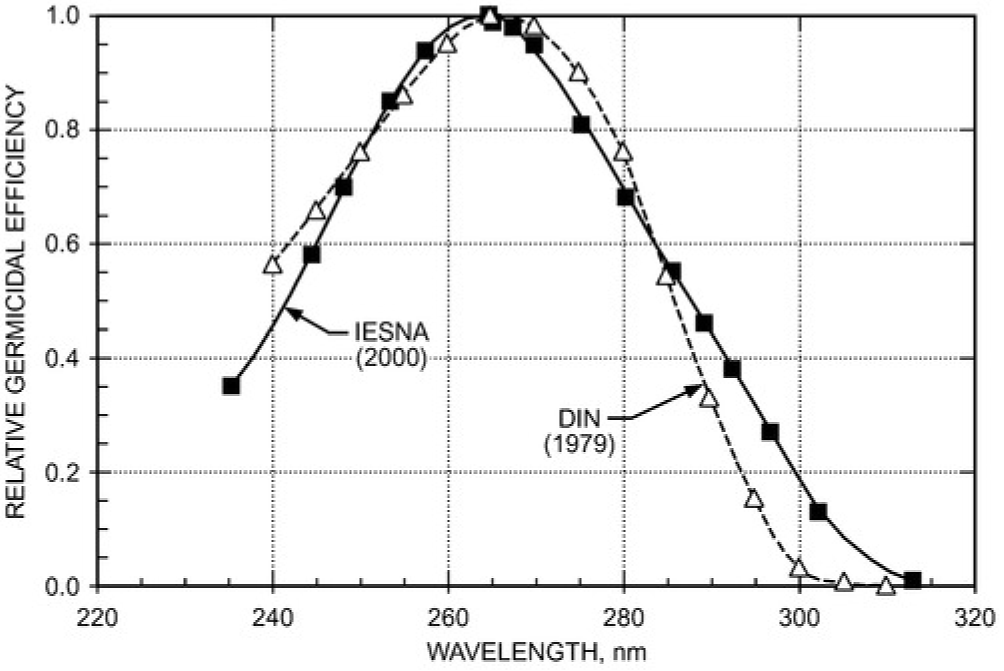
Air Cleaners – Microbial

- Particle filtration can be effective but costly and energy intensive for high efficiency at small particle sizes
- Ultraviolet germicidal irradiation (UVGI) is a low energy alternative/adjunct ventilation rates and particle filtration
  - High effectiveness when applied appropriately
  - Low lamp energy consumption
  - Low pressure drop
  - Peer reviewed effectiveness in reducing airborne infections
- Other methods

Microbial Air Cleaners - UVGI

- UVC damages microbial DNA and RNA
- 254 nm UVC produced by Hg vapor lamps
- UVC LED technology developing
- Exponential dose-response relationship

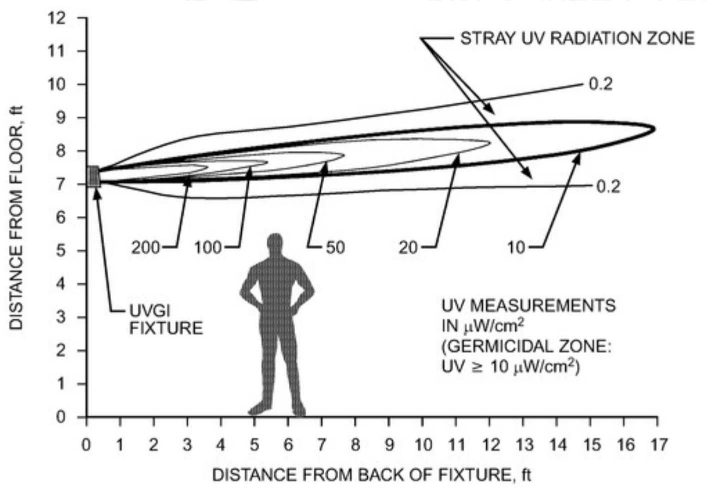
$$S = \exp\left(-kIt\right)$$



Source: 2015 *ASHRAE Handbook—HVAC Applications*, Ch. 60, Fig. 3

Microbial Air Cleaners - UVGI

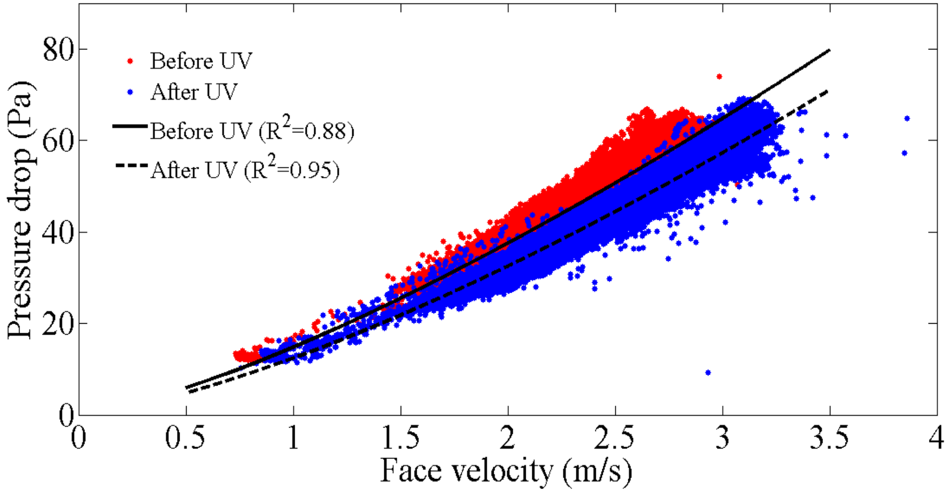
- Typical applications
  - “In-duct” in air handling unit
  - Upper-air in occupied spaces

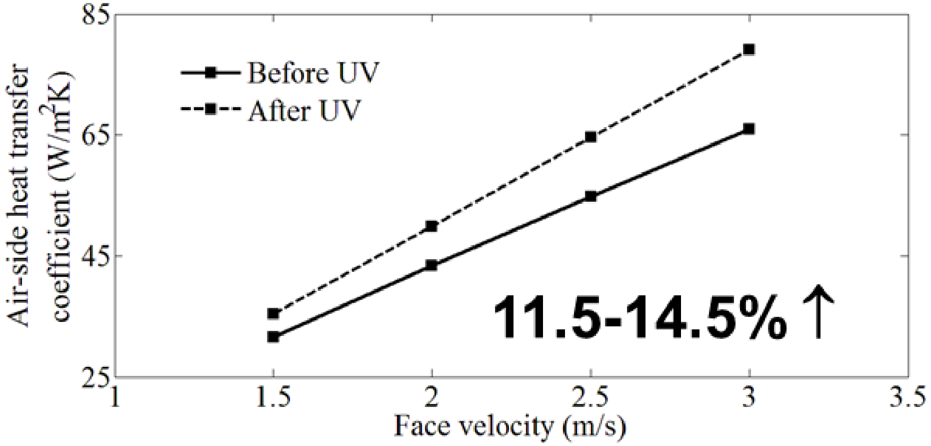


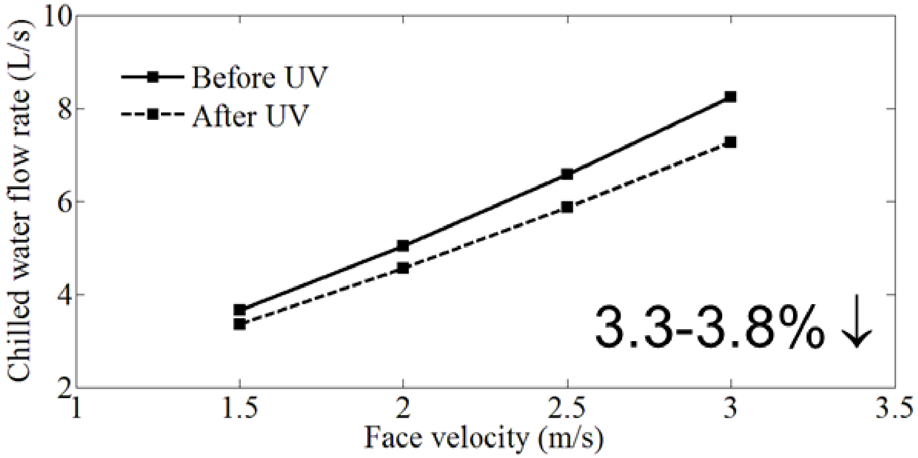
Source: 2015 *ASHRAE Handbook—HVAC Applications*, Ch. 60, Fig. 6

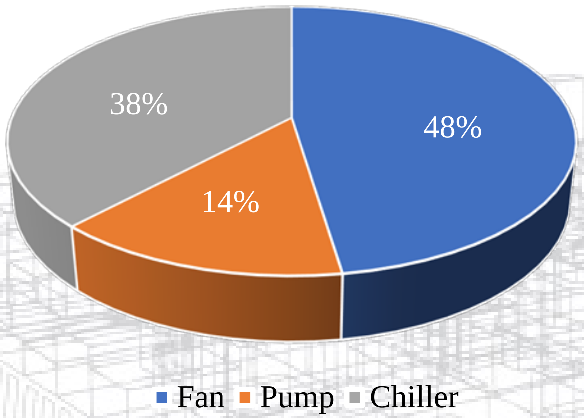
Microbial Air Cleaners - UVGI

- Coil UVGI
  - Irradiation of coil surfaces to control biological growth
  - Reduces air-side flow resistance
  - Increases air-side heat transfer coefficient
  - Saves energy and maintenance cost
- Recent studies in US and Singapore
  - Ability to reduce energy use
  - Significant impact on airborne microbial load and expected impact on air quality
  - Cost-effective in high latent-load climates where cooling is needed









Annual simulation - Singapore

- Fan energy ↓ 9.1%
- Pump energy ↓ 6.2%
- Chiller energy ↓ 0.41 %

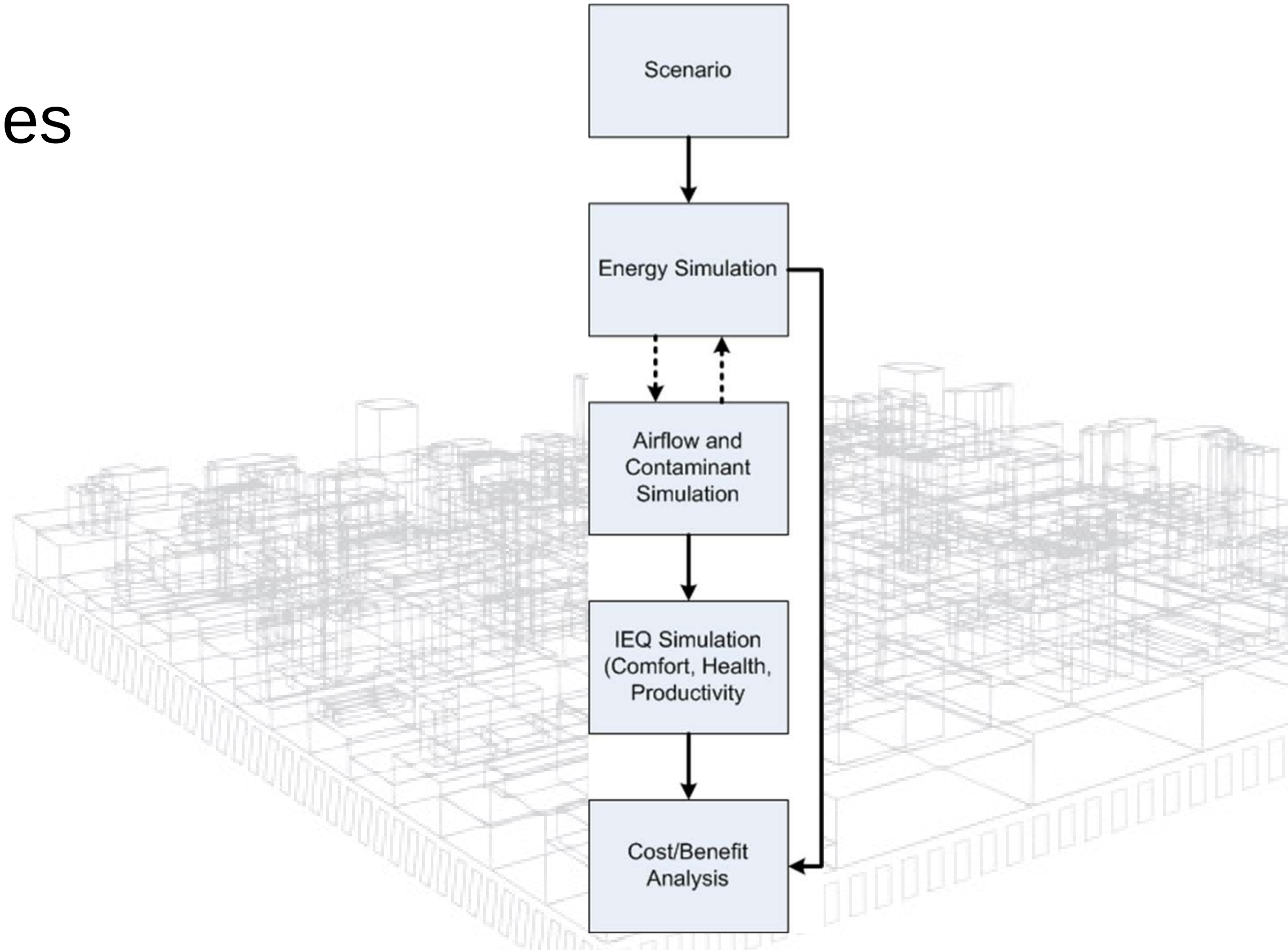
Wang, Y., C. Sekhar, W. Bahnfleth, D. Cheong, J. Firrantello. 2017. Effects of Ultraviolet Coil Irradiation Systems on Air-side Heat Transfer Coefficient and Low △T Syndrome in a Hot and Humid Climate. Science and Technology for the Built Environment 23(4):582-593.

Renewable energy supply changes the equation

- Energy efficiency is still a virtue,…however
  - IAQ benefits do not create environmental hazard
  - IAQ benefits do not further deplete a non-renewable resource
  - Refocuses decision-making process on economics

Process change – Monetize IAQ properly

- Current optimization includes
  - Construction cost
  - Energy and water cost
  - Maintenance cost
- IAQ = ventilation, an input parameter
- Better process would evaluate exposures and monetize consequences



Conclusion

- Energy use of buildings and its consequence is an important societal issue and technological challenge
- Good indoor air quality is a fundamental goal of building design and operation…and consumes a lot of energy
- Based on the consequences of poor IAQ, which is common, it needs to be addressed differently in standards and design
- Technologies are available today to promote better IAQ that are energy neutral or better, and new technologies are emerging

Questions?

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