Defining the metrics to assess the IAQ in low-energy residential buildings: results from IEA EBC Annex 68 Subtask 1

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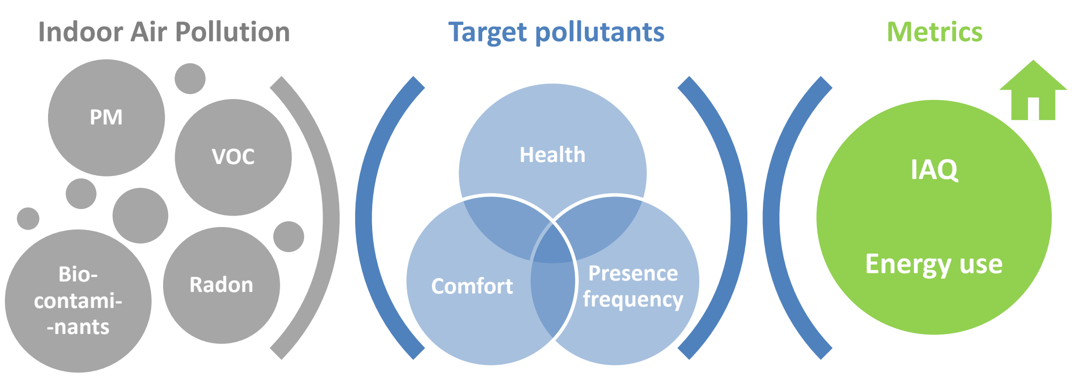

AIVC 2017 Workshop on IAQ metrics, Brussels, Belgium March 14-15 2017

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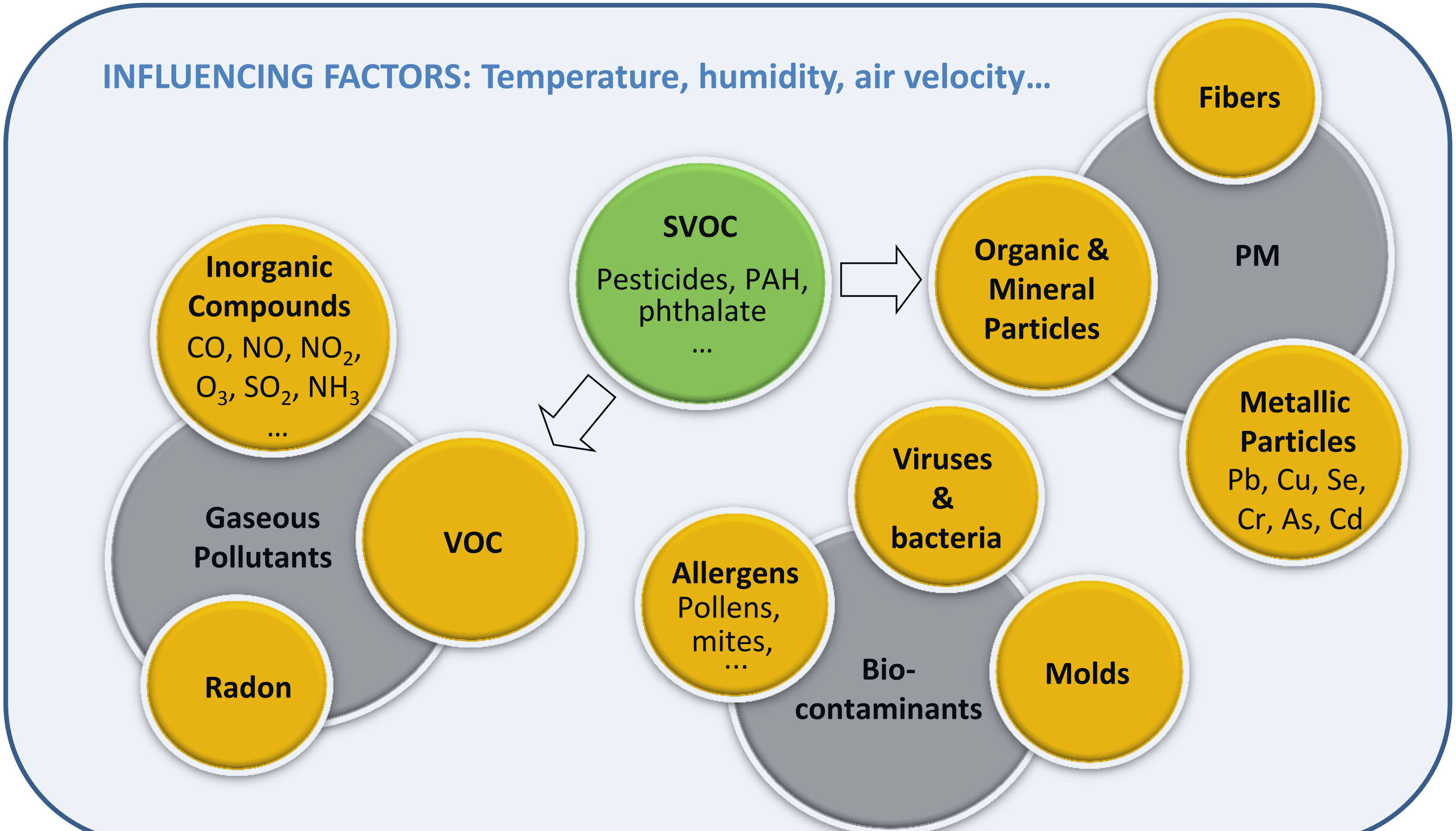
Indoor Air Pollutants



GOAL → To identify pollutants of interest for (low-energy) **residential buildings**

Pollution levels in residential buildings

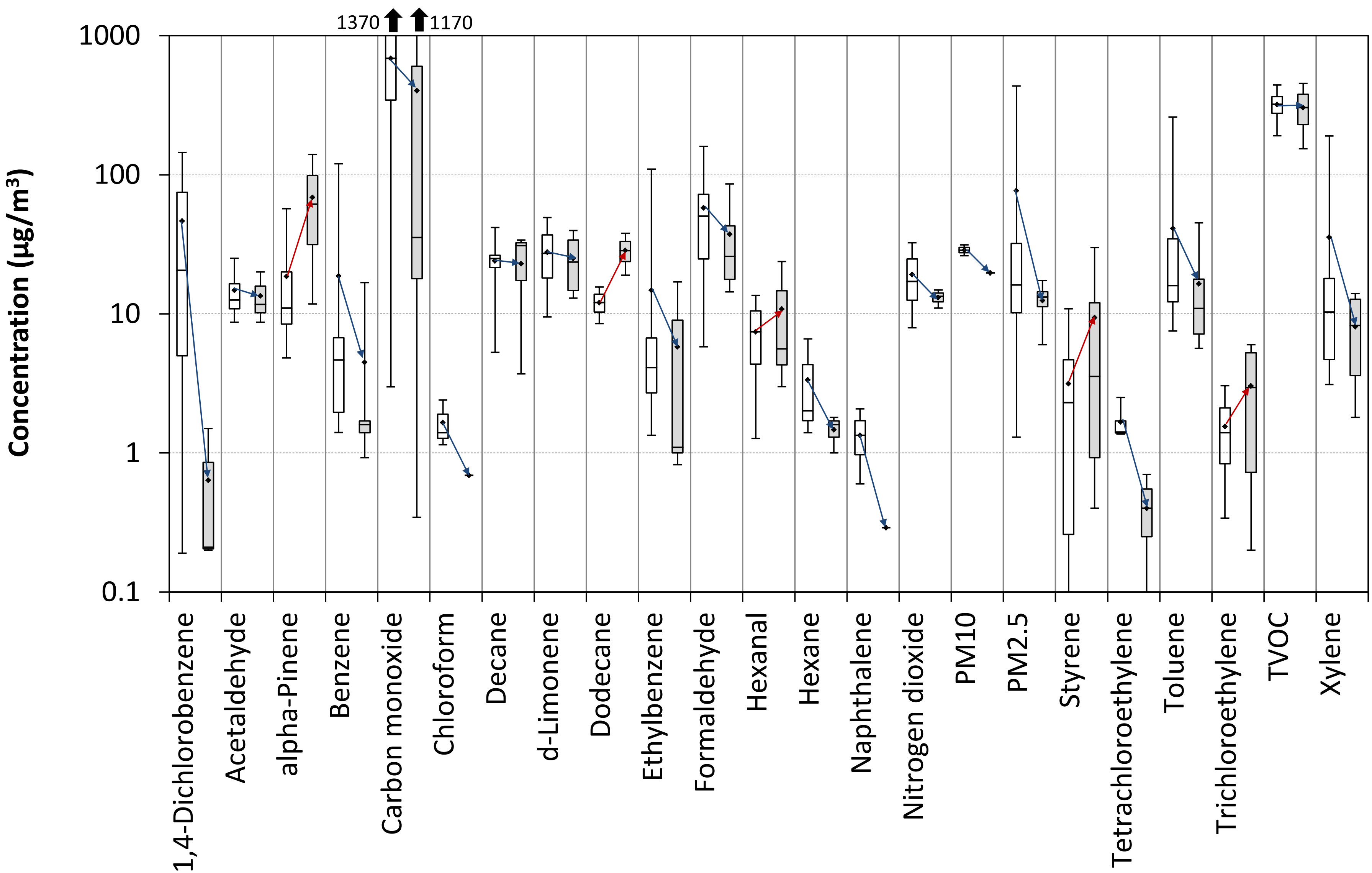
- Objectives:
  - To provide an overview of the indoor pollutants and their concentration levels measured in residential buildings
  - To identify differences, if any, between the pollutants measured in buildings constructed using the standard building practice and the recent low-energy residential buildings
- Methodology:
  - To collect both peak and average concentration levels to distinguish long- and short-term exposure issues
- Notes:
  - The literature review has been limited to peer-reviewed articles and national research projects in the period from 2006 to 2016
  - The causes of good/bad air quality in residential buildings are not the purpose of this section and they are not discussed here.

Pollution levels in residential buildings

- Non low-energy residential buildings:
  - Cheng et al. (2010) for **Australia**,
  - Stranger et al. (2012) for **Belgium**,
  - Zhang et al. (2013), Du et al. (2014) and Liang et al. (2014) for **China**,
  - Guo et al. (2009) for **China, Hong-Kong, Japan, Korea and Taiwan**,
  - Kirchner et al. (2006) for **France**,
  - Park and Ikeda (2006), Azuma et al. (2007) for **Japan**,
  - Langer and Beko (2013) for **Sweden**, and
  - Logue et al. (2011) for **USA** – about 50% of exposure levels come from US non-low-energy buildings and 9% from low-energy buildings; the other data come from other industrialized countries (Canada, Germany, France Spain, UK, Denmark, Finland, Japan, Hong-Kong, South Korea…).

- Low-energy residential buildings:
  - Cheng et al. (2010) for **Australia**,
  - Stranger et al. (2012) for **Belgium**,
  - Du et al. (2014) for **China**,
  - Derbez et al. (2015) for **France**,
  - Park and Ikeda (2006) for **Japan**, and
  - Logue et al. (2011) for **USA.**

Pollution levels in residential buildings



Exposure Limit Values

Exposure Limit Values (ELV)
Long-term (Chronic) and Short-term (Acute) exposures

Epidemiological studies

Animal experiments
(Toxicity Reference Values - TRV)

1

2

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ALL INDOOR ENVIRONMENTS

Indoor Air Guideline Value (IAGV)

- World: GV – WHO
- EU: GV – INDEX
- France: VGAI (Valeurs Guide de l'Air Intérieur) – ANSES
- Germany: RW (Richtwerte) – UBA
- Netherlands: TCA (Tolerable Concentration in Air) – RIVM
- USA: NAAQS (National Ambient Air Quality Standards) – USEPA
- Canada: RIAQG (Residential IAQ Guideline) – Health Canada
- California (USA): REL (Reference Exposure Levels) – OEHHA
- …

WORK ENVIRONMENT

Occupational Exposure Limits (OEL)

- World: TLV (Threshold Limit Values)
- EU: IOELV (Indicative Occupational Exposure Limit Values) and BOELV (Binding Occupational Exposure Limit Values)
- France, Belgique: VLEP (Valeurs Limites d'Exposition Professionnelle)
- Germany: AGW (Arbeitsplatzgrenzwert)
- Denmark: GV (Grænseværdier for luftforurening)
- Netherlands: OEL (Occupational Exposure Limits)
- Poland: MAC (Maximum Admissible Concentrations)
- Spain: VLA (Valores Límite Ambientales)
- UK: WEL (Workplace Exposure Limit)
- USA, Canada: TLV (Threshold Limit Values)
- California (USA): PEL (Permissible Exposure Limit)
- …

MATERIAL CHARACTERIZATION

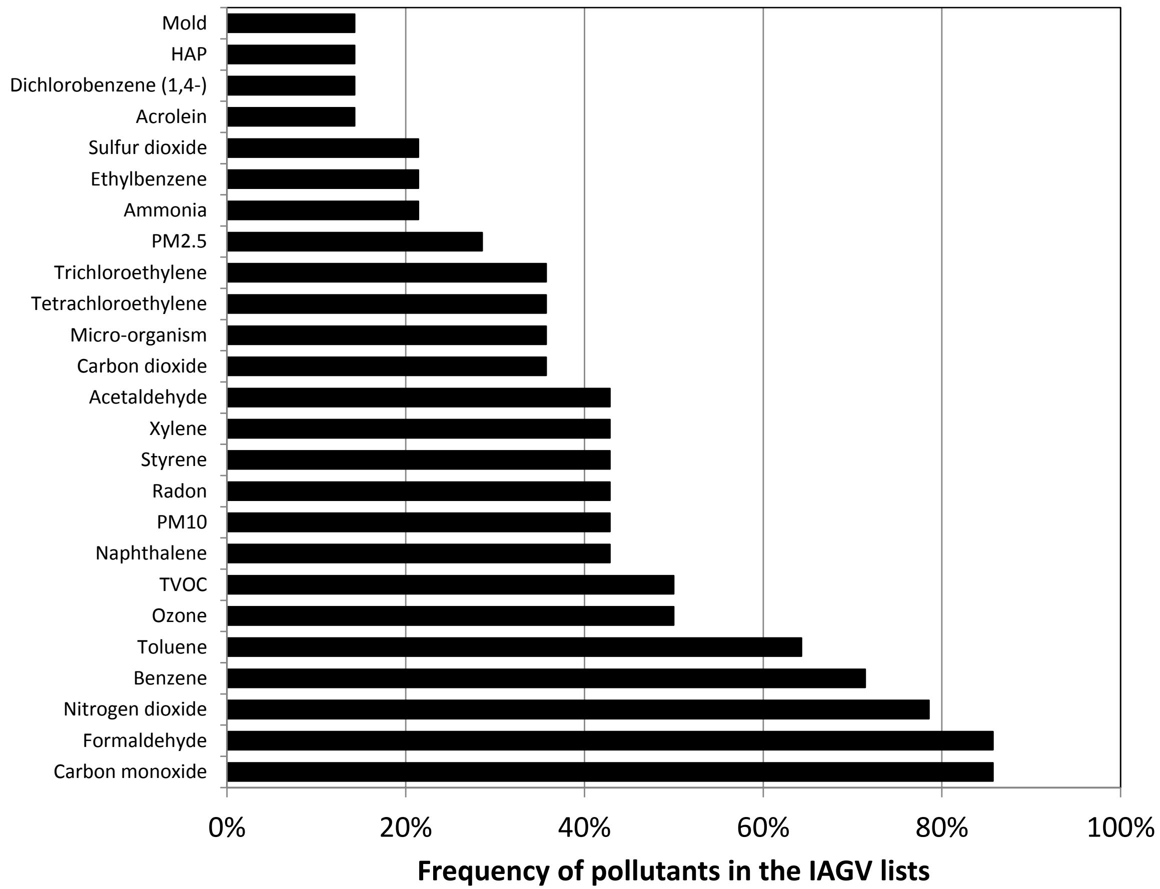
Lowest Concentration of Interest (LCI)

- World: none
- EU: EU-LCI – DG JRC
- France: CLI (Concentration Limite d'intérêt) – ANSES
- Germany: NIK (Niedrigste Interessierende Konzentration) – AgBB
- …

- Factor 10: more sensitive population.
- Factor 10: longer exposure duration.
- Factor 10: for suspected carcinogens.
- Proven carcinogens not to be emitted.

Exposure Limit Values

- ELV database:
  - World Health Organization, Europe, Austria, Belgium, USA – California, Canada, China, France, Germany, Hong-Kong, Japan, Korea, Portugal and United Kingdom (UK)

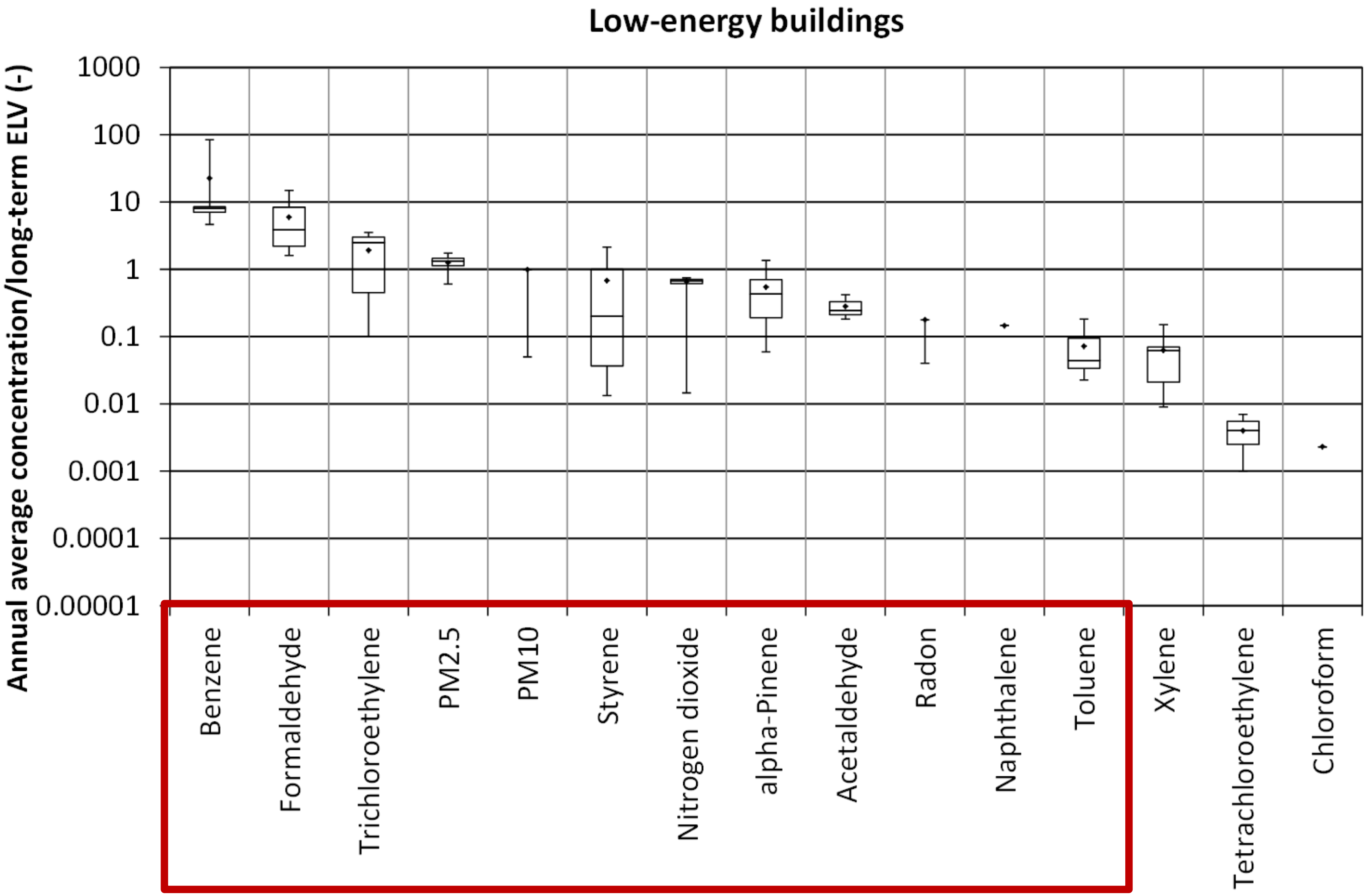


List of pollutants of concern for Annex68

- Methodology:
  - For each pollutant, all data compiled previously was used to calculate **annual or maximum** minimum, 1st quartile, median, 3rd quartile, maximum and average concentrations of pollutants,
  - For each pollutant, the **minimum value** of available **ELVs** for **long-term or short-term exposure** was used,
  - 3rd quartile (75% percentile) concentration was compared with ELV. Pollutants with ratios higher than 0.1 were kept and considered to be pollutants with potential risk for health and relevant to Annex 68 (low-energy buildings).

List of pollutants of concern for Annex68

- Illustration for long-term exposure

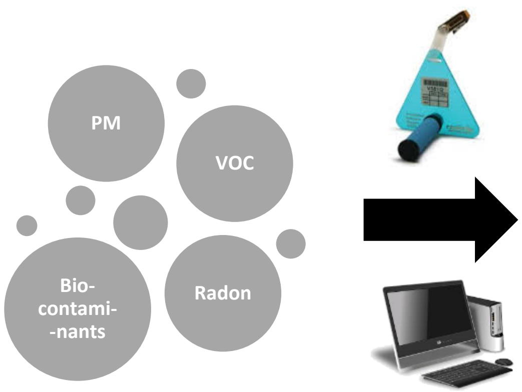


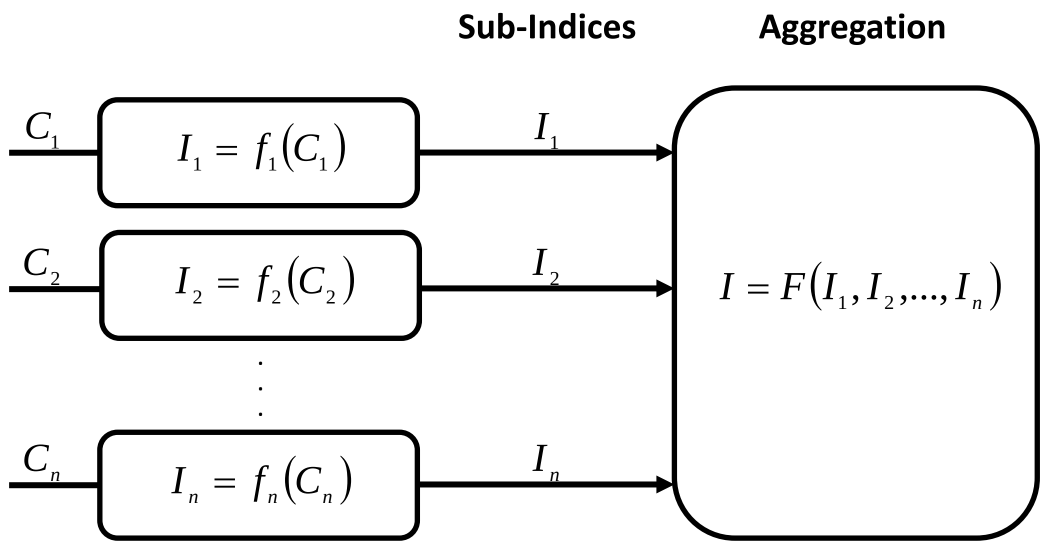
+ pollutants according to previous studies on pollutant prioritization (WHO, INDEX, ...)

List of pollutants of concern for Annex68

	Long-term Exposure			Short-term Exposure		
	ELV	Averaging period	Source	ELV	Averaging period	Source
Acetaldehyde	48	1 year	Japan	-	-	-
Acrolein	0.35	1 year	USA-California	6.9	1 h	France
α-pinene	200	1 year	Germany	-	-	-
Benzene	0.2	whole life (carcinogenic risk level: 10^{-6})	France	-	-	-
Carbon dioxide	-	-	-	1250	8 h	Portugal
Formaldehyde	9	1 year	USA-California	123	1 h	Canada
Naphthalene	2	1 year	Germany	-	-	-
Nitrogen dioxide	20	1 year	France, Canada	470	1 h	USA-California
PM10	20	1 year	WHO	50	24 h	WHO
PM2.5	10	1 year	WHO	25	24 h	WHO
Radon	200	1 year	Austria, Canada, Hong-Kong	400	8 h	Austria, China, Portugal
Styrene	30	1 year	Germany	-	-	-
Toluene	250	1 year	Portugal	-	-	-
Trichloroethylene	2	whole life (carcinogenic risk level: 10^{-6})	France	-	-	-
TVOC	-	-		600	8 h	China, Hong-Kong, Portugal
Mold	200	1 year	EU	-	-	-

IAQ indices: the problematic





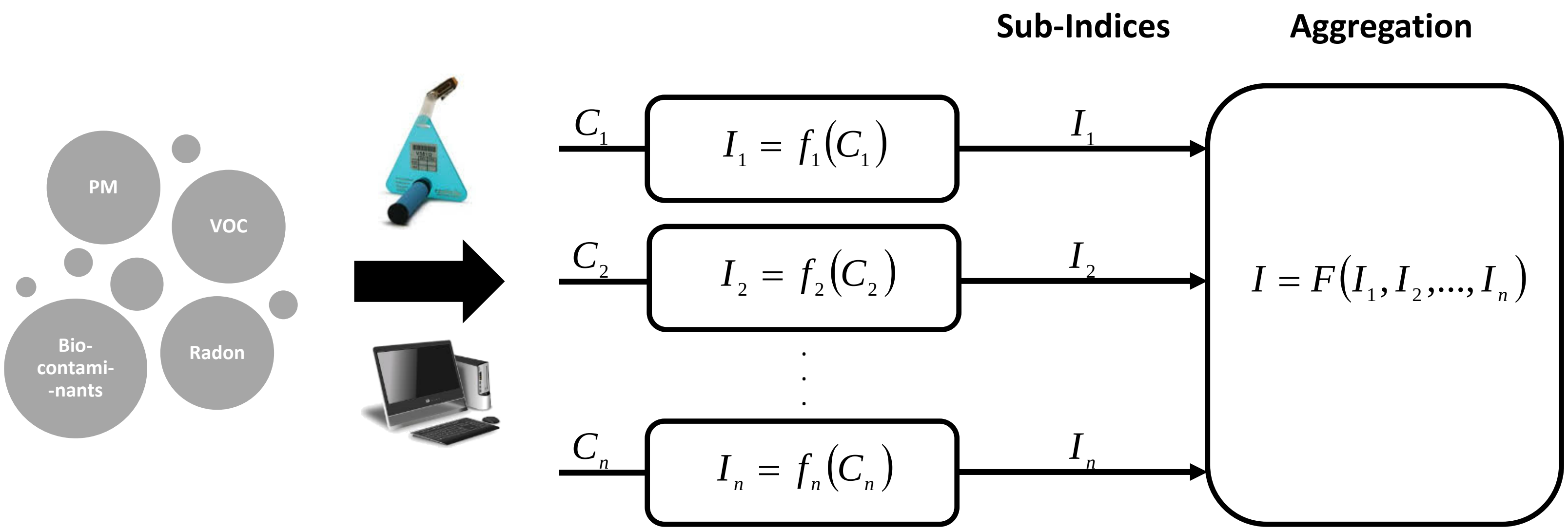
adapted from IND-QAI (Sharma and Bhattacharya, 2012)

Step 1: Sub-indices

- $$I_i = \frac{C_i}{ELV_i}$$
- $$I_i = f_i(C_i) \; or \; f_i\left(\frac{C_i}{ELV_i}\right)$$

	Grade for PM_{10} (µg/m^3, 24h) - Chiang and Lai (2002)								
Grade	20		40		60		80		100
C_i		>350≥	X	>150≥		>50≥		>25≥	

IAQ indices: the problematic



Step 2: Aggregation of Sub-indices

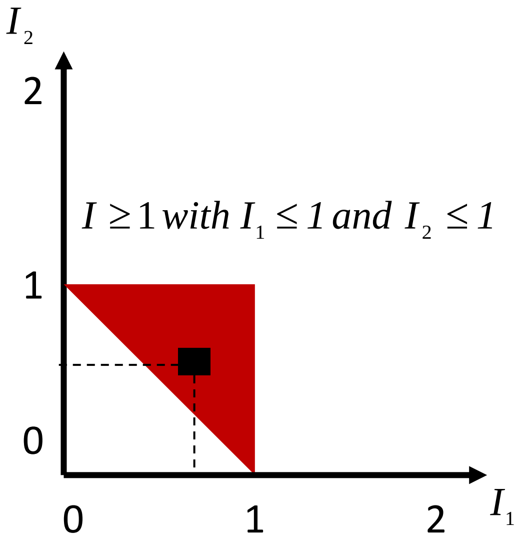
- **Weighted Additive Form** $$I = \sum w_i I_i$$
- **Root-Sum-Power Form (non-linear aggregation form)** $$I = \left(\sum_{i=1}^{n} I_i^p \right)^{1/p}$$
- **Root-Mean-Square Form** $$I = \left(\frac{1}{n} \sum_{i=1}^{n} I_i^2 \right)^{1/2}$$
- **Max Operator** $$I = \max(I_1, I_2, \ldots, I_n)$$

IAQ indices: the problematic

Aggregation limitations (Sharma and Bhattacharya, 2012):

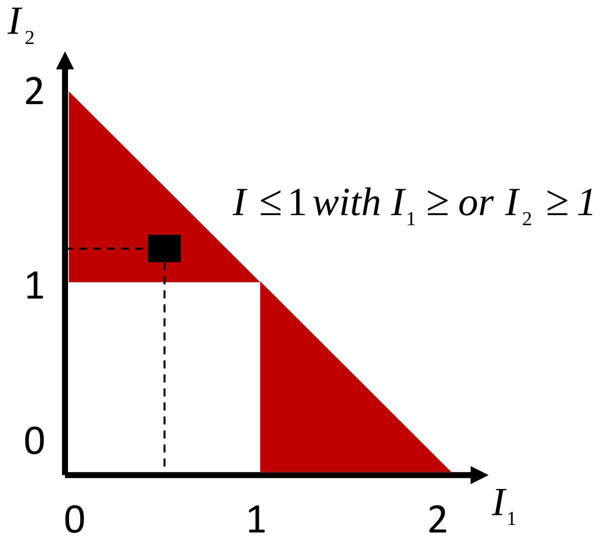
Ambiguity

$$I = I_1 + I_2$$



Eclipsing

$$I = \frac{1}{2}\left(I_1 + I_2\right)$$



Non-ambiguous and non-eclipsing aggregation = Max (sub-indices)

IAQ indices from literature

(based on Kirchner, Jédor and Mandin, 2006)

Max. operator

Cohas (1996)
any pollutant

$$I_{BILGA} = \begin{cases} \max\left(\dfrac{C_i^{obs} - ELVc_i}{ELVa_i - ELVc_i}\right) si\ C_i^{obs} > ELVc_i \\ \max\left(\dfrac{C_i^{obs} - ELVc_i}{ELVc_i}\right) si\ C_i^{obs} \leq ELVc_i \end{cases}$$

Weighted Additive Form

Gadeau (1996)
CO, CO_2, NO_2, HCHO

$$I_{CLIM2000} = \frac{1}{4}\left(\frac{[CO]}{30} + \frac{[CO_2]}{4500} + \frac{[NO_2]}{0.4} + \frac{[HCHO]}{0.06}\right)$$

Castanet (1998)
CO, CO_2, Bacteria

$$I_{LHVP} = \frac{[CO]}{5} + \frac{[CO_2]}{1000} + \frac{[Bacteria]}{1000}$$

Chiang and Lai (2002)
CO, CO_2, HCHO, TVOC, PM_{10}

$$I_{IEI\_IAQ} = \frac{1}{p}\sum_{i=1}^{p} Grade_i$$

QUAD-BBC (2012)
CO_2, NO_2, SO_2, O_3, CO, HCHO, Acetaldehyde, Ethylbenzene, Styrene, Toluene, o-Xylene, Acetone, $PM_{2.5}$, PM_{10}

$$I_{QUAD-BBC} = \sum_{i=1}^{p} \frac{C_i^{obs}}{ELV_i}$$

Sofuoglu and Moschandreas (2003)
Formaldehyde, TVOC, CO, CO_2, $PM_{2.5}$, PM_{10}, Fungi, Bacteria

$$I_{IAPI} = \frac{1}{8}\sum_{i=1}^{8} 10 \times \left[1 - \frac{C_i^{\max} - C_i^{obs}}{C_i^{\max} - C_i^{\min}}\left(\frac{ELVc_i - C_i^{obs}}{ELVc_i}\right)\right]$$

The DALY approach

(Logue et al., 2011)

Disability-Adjusted Life-Years (DALY):

WHO definition: *One DALY can be thought of as one lost year of "healthy" life. The sum of these DALYs across the population, or the burden of disease, can be thought of as a measurement of the* ***gap between current health status and an ideal health situation*** *where the entire population lives to an advanced age, free of disease and disability.*

$$DALY_{disease} = YLL_{disease} + YLD_{disease}$$

$YLL_{disease}$: Years of Life Lost due to premature death from the disease,
$YLD_{disease}$: Years of Life Disability, weighted from 0 to 1 depending on disease severity.

The DALY approach – Calculation

(Logue et al., 2011)

- **Intake-Incidence-DALY** method:

  Epidemiology based concentration-response (CR) functions to quantify disease incidence rates + estimates of DALYs per disease incidence reported in the literature.

$$DALY = \frac{\partial DALY}{\partial disease\ incidence} \times disease\ incidence = \frac{\partial DALY}{\partial disease\ incidence} \times pop \times y_0 \times \left(1 - e^{-\beta \times 0.7 \times C_i}\right)$$

  pop: number of persons exposed (usually 100,000),
  y_0: baseline prevalence of illness per year,
  β: coefficient of the concentration change (natural logarithm of the relative risk divided by the change in mean/median exposure),
  C_i: exposure-related concentration (μg/m³),
  Pollutants: **PM2.5, CO, NO2, SO2, O3**

- **Intake-DALY** approach:

  Used the work of Huijbregts et al. (2005) to calculate the health impact associated with intake of pollutants based on animal toxicity literature.

$$DALY = \frac{\partial DALY}{\partial intake} \times intake = \left[\left(\frac{\partial DALY}{\partial intake}\right)_{cancer} \times ADAF + \left(\frac{\partial DALY}{\partial intake}\right)_{non-cancer}\right] \times \left[Q_{intake} \times C_i \times \Delta t\right]$$

  $ADAF$: Age-Dependent Adjustment Factor (-),
  Q_{intake}: volume rate of air intake (m³/day),
  Δt: considered period of time (day, usually 365),
  C_i: exposure-related concentration (μg/m³).

$$\Rightarrow \quad DALY^p = \sum_{j=1}^{n_{disease}} DALY_j = \sum_{j=1}^{n_{disease}} f_j(C_i)$$

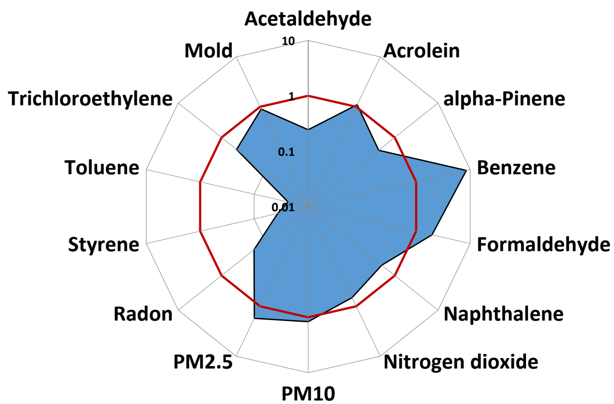
Metrics for Annex68

- IAQ:
  - Sub-indices per pollutant
    - Long-term exposure:
      - ELV-based approach: simple detection of the potential risks that is easy to comprehend by designers i.e. *"to stay below the ELV level for each pollutant!"*
      - DALY approach: effects on health, tool for decision makers, "*which efforts should be made and for which pollutants to achieve the largest effects on the population health"*
    - Short-term exposure:
      - ELV-based approach: frequency of exceedance of ELV over the occupation period
  - Indices = max(ELV sub-indices) and = sum(DALY sub-indices)
- Energy:
  - Primary energy consumption of the building

Metrics for Annex68 – Dashboard

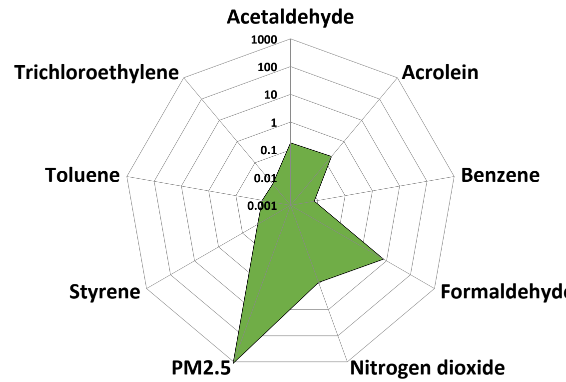
Long-term effects

ELV indices



Maximal value: **8.5** – Pollutant: **BENZENE**

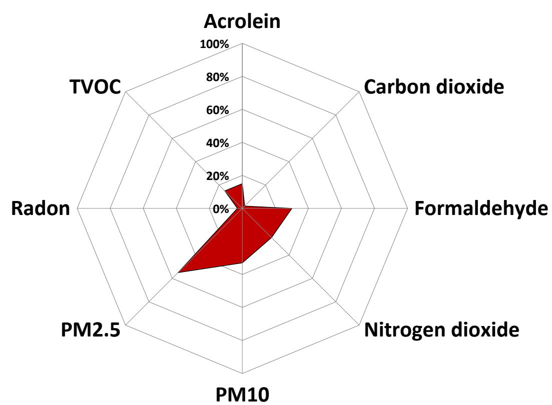
DALY



Total : **1166 DALYs lost**/(year.100,000 persons)

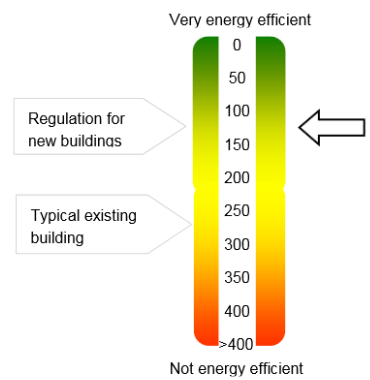
Short-term effects

ELV indices



Maximal value: **55%** – Pollutant: **PM2.5**

Energy Consumption



Energy consumption: **130 kWh_{pe}/m^2.year**

Data represented here are just for display and do not represent actual situation

Conclusions

- Pollutants of interest:
  - List of 16 pollutants: acetaldehyde, acrolein, α-pinene, benzene, carbon dioxide, formaldehyde, naphthalene, nitrogen dioxide, PM10, PM2.5, radon, styrene, toluene, trichloroethylene, TVOC and mold.

- Quantification of IAQ:
  - ELV-based approach for both long- and short-term exposure
  - DALY approach for long-term exposure

- Use of Annex68 metrics: to evaluate solutions for a better IAQ in low-energy residential buildings
  - ELV-based approach: % of reduction of the max related to variation of kWh_{PE}/m^2.year
  - DALY approach: % of reduction of the total DALY related to variation of kWh_{PE}/m^2.year


рахмат
danke
謝謝
ngiyabonga
teşekkür ederim
Баярлалаа
спасибо
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misaotra
matondo
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mahalo
tapadh leat
thank you
gracias
хвала
asante
manana
obrigada
tenki
murakoze
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blagodaram
спасибі
nanni
nandri
dhanyavad
maururu
hvala
köszönöm
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bayarlalaa
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তোমাকে ধন্যবাদ
감사합니다
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