VEOLIA INSTITUTE

THE VEOLIA INSTITUTE REVIEW

FACTS REPORTS

2020

INDOOR AIR QUALITY: TACKLING THE CHALLENGES OF THE INVISIBLE

In partnership with

nomadéis

THINKING TOGETHER TO ILLUMINATE THE FUTURE

THE VEOLIA INSTITUTE

Designed as a platform for discussion and collective thinking, the Veolia Institute has been exploring the future at the crossroads between society and the environment since it was set up in 2001. Its mission is to think together to illuminate the future.

Working with the global academic community, it facilitates multi-stakeholder analysis to explore emerging trends, particularly the environmental and societal challenges of the coming decades. It focuses on a wide range of issues related to the future of urban living as well as sustainable production and consumption (cities, urban services, environment, energy, health, agriculture, etc.).

Over the years, the Veolia Institute has built up a high-level international network of academic and scientific experts, universities and research bodies, policymakers, NGOs and international organizations. The Institute pursues its mission through publications and conferences, as well as foresight working groups.

Internationally recognized as a legitimate platform for exploring global issues, the Veolia Institute has official NGO observer status under the terms of the United Nations Framework Convention on climate change.

THE FORESIGHT COMMITTEE

Drawing on the expertise and international reputation of its members, the Foresight Committee guides the work of the Veolia Institute and steers its development.

The current members of the Foresight Committee are: **Harvey Fineberg**, President of the Gordon and Betty Moore Foundation and former President of the American Institute of Medicine; **Pierre-Marc Johnson**, international lawyer and former Premier of Quebec; **Philippe Kourilsky**, Honorary Director General of the Pasteur Institute; **Mamphela Ramphele**, former Managing Director of the World Bank; **Amartya Sen**, Nobel Prize-winning economist and Professor at Harvard University; and **Nicholas Stern**, Professor of Economics at the London School of Economics, Fellow of the British Academy and the Royal Society.

Review coordinated by Cédric Baecher, Fanny Sohui, Leah Ball and Octave Masson, Nomadéis

THE REVIEW

The Veolia Institute Review - FACTS Reports is a high-level international publication compiling diverse perspectives on topics at the crossroads between society and the environment.

The review was launched in 2007 with the aim of sharing best practices from the field, to help find solutions to problems in the economy, development, healthcare, environment, agriculture and education, in both developing and developed countries.

The interdisciplinary review is a vehicle for sharing the experiences and expertise of different stakeholders (researchers, academic experts, policymakers, companies, NGOs, international organizations, etc.), with the aim of taking advantage of a diversity of perspectives on a given topic, by combining feedback on best practices from the field and expert analysis.

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FOREWORD

Philippe Kourilsky - Honorary Director-General of the Institut Pasteur, Biologist, Professor Emeritus at the Collège de France, Member of the Veolia Institute Foresight Committee

Back in 1975, I was a young academic who, thanks to a fortunate mix-up, ended up accompanying a group of eminent figures as a member of the first delegation of French scientists to be officially welcomed to China. Mao Zedong still ruled over a country that was just beginning to open up. It was a fascinating trip during which, to illustrate the merits of traditional Chinese medicine, we were given a demonstration of surgery under acupuncture anesthesia. It was very impressive – a single needle was inserted in the foot of a male patient who continued to speak calmly as doctors sawed open his thorax. The window in the rudimentary operating room was opened between operations to let "pure" air in and let out microbes and miasma.

Reading this remarkable issue of the Veolia Institute's FACTS Reports, my memories of the event resurfaced because it illustrates the volatility of what we perceive to be "pure" air. This issue invites us to look afresh at the fundamentals of the quality of the air that we breathe, whether indoors or outdoors.

On the surface, what could be simpler than air? What could be easier to share? More essential and vital? Yet the truth is that air is varied and complex. Air is seen as so fundamentally elementary as to be of interest only to poets, not to chemists. This is far from the case. We should speak of "airs" not of air. In this, air is the same as water. Air is made singular and diverse by its impurities: molecular pollutants, microparticles, microbes, etc. Their sources are as numerous as their effects: polluted air dirties building façades, annoying city-dwellers who have to renew them often; it is harmful to health, causing the loss of countless days of life; and again, it is a form of air pollution that induces global warming.

We seek the causes: here, cars, diesel fuel, tire wear; elsewhere, methane produced by cows and rice paddies. We need solutions for everywhere we live and work, including cities, factories, aircraft, offices, fields, and garbage dumps. We also seek the culprits: all too quickly we point fingers at manufacturers that know the harm they cause in search of making a profit, at incompetent or complacent politicians who close their eyes out of self-interest or lust for power, and so on. But this is something that concerns every single one of us. We have to become more conscious of the problems and challenges associated with air quality. This is the subject of the first part of this issue.

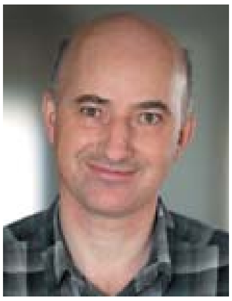
Part two looks at several areas of research and explores possible solutions. Science is advancing. The digital era is here and massive data gathering using ever more powerful sensors gives us the ability to analyze problems that are increasingly complex, preventing us from applying solutions that are at once simple and universal. Biology has a role, too, because plants and microorganisms have considerable and as yet under-explored capacities for regeneration. Architecture too: suitably designed constructions are themselves instruments for prevention and improvement.

The last part of this issue looks at the future, discussing possible changes to standards and regulations, with a focus on public health, and how to spread and harmonize best practices at the global level.

Our future will be what we make of it. Air is one of the most fundamental global commons. It is so ubiquitous that all too often we take it for granted. This issue invites us to pay much closer attention to it – and not just in a superficial way. This core component of our environment raises countless problems that demand we address them head-on, individually as well as collectively, in an ongoing process to improve our knowledge, understanding, and actions.

INTRODUCTION

Nicolas Renard - Director of Foresight, Veolia Institute



Although invisible, air pollution is one of the world's main environmental risks. Its global human cost is jaw-dropping: with 8 million premature deaths annually, it is the fourth largest mortality risk on the planet. While it is necessary to act to protect outdoor air quality, looking after indoor air is equally vital. Why? Because we spend most of our lives in buildings and almost half of the 8 million deaths due to poor air quality are caused by indoor pollution.

Many people are unaware that indoor air is generally more polluted than outdoor air. What lies behind this paradox? In addition to any pollution in the outdoor air, you also have to consider pollution from products used indoors for cleaning or cooking, contaminants emanating from paints, walls, floor coverings, and so on. The list of known indoor pollutants is seemingly endless: xylenes, benzene, volatile organic compounds, formaldehyde, ozone, particulates, allergens, etc. Another paradox: we're more exposed to pollutants underground in the metro than we are at street level when traveling on foot or by car. Whether in Barcelona, Hong Kong, Mexico City, Istanbul or Santiago, someone making a journey by metro will inhale more particulates than if they travel by bus or on foot.

And yet, the crux of the matter lies elsewhere. Three billion people, 40% of the world's population, still lack access to clean fuels and technologies for cooking, heating and lighting. In terms of public health, the priority is to provide access to clean household energy for all. There are two types of hurdles to overcome: economic, because clean energies and technologies are more expensive; and political, because, in some countries, providing electricity in villages is not legally required.

The bitter arithmetic of poor air quality and the deaths it causes should not blind us to recent advances. In developed economies, governments and businesses alike have fully taken on board the problem of emissions from industries, which has led to massive falls in pollution. Progress is also evident in terms of lower emissions and petrol consumption by private cars (albeit partial offset by rising traffic volumes), and the promising rise of electric vehicles.

Today, air pollution is a more potent killer than tobacco, with one major difference – people can stop smoking but they cannot stop breathing polluted air. All around the world, combating this form of pollution has become a major issue in terms of public health and quality of life. The task is vast, even immense, when you consider that three-quarters of the global population breathe indoor or outdoor air that fails to meet WHO recommendations. This is why efforts need to focus initially on those who are most exposed and vulnerable, especially children. The first step in this battle involves measuring indoor air quality, thus making the invisible visible and identifying where problems that need addressing are located. Every building is unique in terms of its structure and equipment, and depending on whether it is purely residential or used for other purposes. Once the sources of indoor air pollution are identified, they must be neutralized. In parallel, it is necessary to improve airflow in the building, using a high-tech process, perhaps AI-based, or a low-tech one such as phytoremediation. At the same time, it has to be remembered that outdoor air quality is a key driver for better indoor air quality. In the long run, the real solution lies in generalized pollution prevention.

Effective solutions exist to ensure that the right to breathe healthy air becomes a reality for all

Just like the oceans, the air is a common good that knows no frontiers. It is open to everybody and many can be tempted to release their pollutants in it. As is also the case for oceans, air protection is hampered by an absence of governance. Who does air belong to? Which body is responsible for safeguarding air quality? Which standards apply? Although ambitious action plans exist to tackle outdoor air quality, indoor air quality is a major blind spot in environmental policies. Very few countries have enacted regulations in this field. But times are changing and this insidious and poorly understood form of pollution is subject to increasing attention. Sales of home air purifiers are skyrocketing in the polluted cities of many emerging economies, China has launched an ambitious Blue Sky plan, schools are beginning to fit sensors, and so on. And as regulations are enacted, litigation is also becoming more common. Lawsuits have been filed against governments, cities and schools, challenging them on the basis of their incapacity to remedy poor air quality.

Purifying the air means protecting the present and the future. In this, as in every other environmental field, nothing is set in stone: effective solutions exist to ensure that the right to breathe healthy air becomes a reality for all.

Paradigm change is needed to answer the indoor air quality challenge

Cédric Baecher
Nomadéis co-founder

Nicolas Dutreix
Nomadéis co-founder

For many years, issues relating to climate and air quality have been addressed separately. However, several scientific studies have clearly shown that atmospheric pollution and climate are indissociable and that each influences the other. People all around the world are growing increasingly aware of their impacts on health and human society. A glance at the news is enough to confirm this: in early November 2019, the Indian megacity of New Delhi was hit by an extreme spike in air pollution caused by a combination of vehicle traffic, industrial emissions and smoke from agricultural land clearance in neighboring regions. Fine particle concentrations per cubic meter reached levels 32 times higher[1] than those recommended by the World Health Organization. One particularly symbolic consequence has been the emergence of oxygen bars, where locals can pay to breathe pure air for 15 minutes[2]. Another example took place in France, where the Lubrizol factory[3] in Rouen caught fire in September 2019, rekindling debates on the impacts air quality has on human health and the environment[4].

Events such as these trigger multiple reactions from a wide range of actors. On June 5th, the UN held the 2019 World Environment Day around the topic of air pollution, with a statement on the issue from Secretary General Antonio Guterres: "*On World Environment Day, I ask that each and every one of us acts so that we can breathe better. From pressuring politicians and businesses to changing our own habits, we can reduce pollution and overcome climate change*"[5]. Scientists and academics have published baseline surveys that help bring this issue and its causes to public attention. We are also seeing the emergence and spread of civil society protest movements. In London in March 2018, members of a group called Stop Killing Londoners were arrested after spraying the walls of the mayor's office with slogans denouncing air pollution and calling for urgent political action.[6] Growing distrust, caused by a lack of information and transparency, has forced civil society to organize into networks, collectives and nonprofits, which have become vital actors in attempts to address the issue of air quality. Founded in the 1970s in France to protect the collective interest, accredited air quality nonprofits (AASQA) operate in every region and take daily measurements of pollution in all major cities. The association for the promotion of indoor air quality (AQPAI) and the "Rouen Respire" collective formed recently in response to the Lubrizol fire are just two examples of French nonprofits focused on this issue and speaking out on behalf of a general public which is very keen to see concrete measures put in place. The political fallout is increasing: on October 24th, 2019, France was convicted by the Court of Justice of the European Union (CJEU) for failing to meet its obligations under the 2008 air quality directive and for its inability to protect its citizens from air pollution. France is not the only guilty party: other member states, including Germany and the United Kingdom, have been charged by the CJEU. In parallel, the main branches of the private sector (manufacturing, transportation, agriculture, construction, etc.) have begun to get to grips with this issue. The market for air quality has thus been penetrated by numerous actors, from major corporations to startups, and is seeing ever more technical and technological innovations, including the rise of connected sensors, apps and remediation systems. Corporate social responsibility

1 On November 3, 2019 the US embassy in the Indian capital recorded a concentration of 810 micrograms of PM2.5 (fine particles) per cubic meter, a level 32 times higher than recommended. https://www.lemonde.fr/planete/article/2019/11/03/a-new-delhi-un-brouillard-de-pollution-si-dense-que-les-avions-ne-peuvent-plus-atterrir_6017863_3244.html

2 https://www.liberation.fr/checknews/2019/11/18/pollution-de-l-air-qu-est-ce-que-le-bar-a-oxygene-lance-a-new-delhi_1764051

3 The Rouen fire broke out on September 26, 2019, at a chemical factory with a Seveso high-risk classification owned by Lubrizol. The factory synthesized and stocked chemicals used as additives in lubricants.

4 https://www.lemonde.fr/idees/article/2019/10/18/incendie-de-rouen-l-autre-risque-de-pollution-potentiellement-bien-plus-dangereux-concerne-les-emissions-quotidiennes-de-ces-industries_6015949_3232.html

5 https://www.un.org/en/events/environmentday/sgmessage.shtml

6 https://www.theguardian.com/environment/2018/mar/19/london-air-pollution-activists-prepared-to-go-to-prison-to-force-action

policies too are evolving to embrace the challenges of air quality and help trigger behavioral change.

In recent years, it is through the renewed support that Nomadéis has been providing to this diversity of actors that it has incrementally developed its expertise in the field of air quality.

At first, the missions entrusted to us focused on outdoor air pollution. In 2015, in collaboration with a team of teacher-researchers from the University of La Rochelle, we carried out a market study on behalf of the Agency for Food, Environmental and Occupational Health & Safety (ANSES) with the aim of defining, in technical and economic terms, a set of techniques aiming to protect individuals against outdoor air pollution, targeting both the general public and professionals.[7] We have also been tasked with examining the complex issue of governance applied to air quality. In 2018, with the goal of promoting exchanges and generating synergies between actors, we worked with the ATMO Normandie nonprofit to carry out a preparatory study for setting up an "Air Lab" designed to foster the emergence of a regional ecosystem around air quality[8].

We have also been solicited to conduct surveys on indoor air quality. This market, whose health, social and environmental challenges are every bit as important as those of outdoor air, offers real opportunities for action and remediation because indoor environments, although particularly complex, are also more controlled. One of the key challenges in this market lies in the sheer number of solutions and devices claiming to improve or purify indoor air, with numerous question marks remaining regarding their true effectiveness and efficiency. We have contributed to a number of ANSES studies seeking to map these solutions and assess the available knowledge. This work has identified the need to consolidate and demonstrate the real-world efficiency of many of the solutions currently available on the market. Progress is also needed in regulatory frameworks to ensure that the various devices perform correctly and are suitable for the uses they are put to. Similarly, and with a few questions about the potential as well as the conditions for the deployment and success of air quality initiatives, we have provided support to Urban Lab, the experimental laboratory run by Paris&Co (Paris City Council's economic development and innovation agency), to assess 10 innovative solutions, ranging from connected windshield badges to microsensors and air pollution treatment using biofiltration. We provided support to entrepreneurs seeking to test their solutions across the Paris region, identifying the most promising configurations, conducting quantitative and qualitative analyses of the impacts observed, and identifying a series of key factors for success, as well as hindrances, to the deployment of these experiments. Again with the aim of helping public authorities design and apply effective public policies for air quality, we were tasked by ADEME (France's environment and energy management agency) and the health and environment ministries to conduct a comparative study of public policies for protecting and improving indoor air quality in Europe and around the world. The conclusions fed into the decision-making process for application of the third national and regional health and environment plans (PNSE/PRSE III)[9].

All these experiences have led us to conceive air quality, indoor in particular, as a multifactorial challenge that demands a cross-disciplinary approach. Although most of the responses to these problems necessarily involve technological innovation, this alone cannot suffice – measuring air quality is not an end in itself. It must have a precise purpose, and serve to reinforce the awareness of all actors, as well as provide objective feedback on the impact of corrective actions. In the same vein, remedial devices can only be truly effective if accompanied by measures to bring about behavioral change. Indoor air quality must therefore (and above all?) become a central issue for all stakeholders, one that has to be addressed through knowledge and education. There is also an imperative to provide actors — businesses, nonprofits and public bodies — with specialist contacts and appropriate common analytical and conceptual frameworks, to avoid diluting responsibilities and failing to grasp the challenges correctly.

No measurement or remedial device must obstruct the overarching challenge for air quality: the reduction of polluting emissions. This global challenge implies transforming our production, consumption and travel habits, as well as our lifestyles in general, to align them with the greatest stake of the millennium: achieving the energy, environmental and social transitions.

We trust that this latest edition of FACTS, produced in a partnership between the Veolia Institute and Nomadéis, will help bring the challenges into better focus, to the benefit of all stakeholders.

7 http://www.nomadeis.com/2016/10/qualite-air-exterieur-anses/

8 http://www.nomadeis.com/2018/09/air-lab-normandie/

9 http://www.nomadeis.com/2016/01/qualite-air-interieur-ademe/

1. INDOOR AIR QUALITY: A MULTIFACETED PUBLIC HEALTH PROBLEM

Indoor air pollution is an issue that impacts a wide range of enclosed spaces such as houses, offices, schools and public transports, in which we spend 80% of our time on average. Whether caused by fuels used in the home or the presence of toxic materials, chemicals and pollutants in the ambient air, the effects on health can be extremely severe: the WHO estimates that poor indoor air quality is responsible for 3.8 million deaths worldwide each year.

FROM LIVING SPACES TO TRANSPORT SYSTEMS: A WIDE RANGE OF DIFFERENT POLLUTIONS

Indoor air pollution results from the interaction of multiple factors. Corinne Mandin, head of French Indoor Air Quality Observatory, underlines the complexity of this sort of pollution: over 2,700 potentially toxic substances have been identified, varying according to the type of space considered. Chemical, biological or physical pollutants may come from outdoor ambient air, ground pollution linked to industrial activities, components used in building materials or equipment, or even activities performed by the occupants themselves. This means that specific surveys have to be undertaken for each source and site. Regarding transportation, ESTACA researcher Amine Mehel presents a methodology to quantify and analyze types of pollution present in car interiors. Underground metro systems, in which some cities register fine particle concentrations that far exceed recommended safe levels, are also analyzed by Teresa Moreno and Fulvio Amato from the Institute of Environmental Assessment and Water Research in Barcelona.

VARIABLE HEALTH IMPACTS: FROM INCONVENIENCE TO INTOXICATION

The health effects of air pollution, which are as varied as the pollutants themselves, have been demonstrated by many studies. Dr. Fabien Squinazi, expert advisor to several commissions under the authority of the French Health Ministry, explains that stale indoor air is often responsible for a wide range of symptoms that include eye, nose and lung soreness, headaches, nausea and fatigue. In France alone, it is estimated that almost half the population could be affected. Daily exposure to highly polluted indoor air also increases the probability of developing more serious illnesses such as pneumonia and other respiratory pathologies, cardiovascular diseases and cancers. Some studies also highlight the social and economic impacts of stale air, which can affect productivity and students' ability to concentrate.

INDOOR AIR QUALITY AND ENERGY TRANSITION

Although indoor air pollution concerns every country in the world, the specific challenges it poses vary according to economic and energy contexts. Countries with low or intermediate income face the urgent issue of reducing fine particle pollution, which is highly toxic to the respiratory tract. This sort of pollution is most often due to the use of dirty energy sources for heating and cooking, affecting those most vulnerable (women and children) disproportionately. Maria Neira, head of the WHO's Department of Public Health, Environmental and Social Determinants of Health, stresses the importance of promoting access to sources of energy that are less dangerous to health and the environment.

Cédric Baecher, Fanny Sohui,
Leah Ball and Octave Masson,
Coordinators,
Nomadéis

MANAGING INDOOR AIR QUALITY TO PROTECT OCCUPANT HEALTH

Docteur Fabien Squinazi,
Former director of the Paris Hygiene Laboratory
Member of the French Public Health Council (HCSP)
Member of the scientific board of the French Observatory on Indoor Air Quality (OQAI)
Medical biologist

Replacement of a ventilation filter

Fabien Squinazi is a medical biologist, former hospital biologist, former director of the Paris Hygiene Laboratory and former head of the Environmental Health and Hygiene Bureau at Paris City Hall. He is a member of various commissions at the French Ministry of Health (French High Council for Public Hygiene, Living Environments section, Buildings group – health; technical panel on lead; expert panel on clinical waste) and at the French Health and Safety Agency (expert panel on air environments and working groups). Dr. Squinazi also sits on the scientific board of the French Observatory on Indoor Air Quality (OQAI) and the "Environmental Risks" commission of the French Public Health Council (HCSP), and is a corresponding member of the National Academy of Pharmacy (6th environmental health section) and of several non-profits involved in the following areas: environmental health, High Environmental Quality (HQE) for buildings, asthma and allergies, prevention of atmospheric pollution, prevention and study of clean room contamination, air environment occupations. He has published several articles and books on air quality and water quality.

Deterioration in indoor air quality can lead to various diseases linked to the growth of microorganisms or the presence of pollutants and allergens. Other collective non-specific symptoms affecting various bodily functions (ENT, ocular, respiratory, dermal, neurological) can occur in a building, then disappear when the people affected leave the building. In both cases, a medical and environmental investigation may identify clinical aspects and search for sources of pollution or faults in the ventilation system. The audit results and interpretation of the observed concentrations compared with reference values may provide information to help understand the problems encountered. Various tools are currently available to control and assess indoor air quality during the construction or renovation of a building, and while it is operational. Three main categories may be identified: 1/ preventative measures taking account of sources of pollution from both inside and outside the building and the ventilation system, 2/ protocols for measuring various parameters on at the delivery stage and in operation, and 3/ measurement tools providing continuous information on indoor air quality.

THE EMERGENCE OF SICK BUILDING SYNDROME

Indoor air refers to non-industrial closed indoor environments, including dwellings, establishments open to the public, care and education settings, health care and medical-social establishments, and means of transportation. Living, staying, visiting, studying or working in these indoor environments can lead users or occupants to report discomfort or health issues.

The French health authorities are increasingly faced with "epidemics of unexplained symptoms" occurring in workplaces and public buildings such as schools and hospitals. These collective non-specific syndromes, commonly known as "Sick Building Syndrome," are distinct from specific illnesses linked directly to the building (building-related illnesses), which form a uniform clinical picture of objective clinical or biological abnormalities for which a doctor can identify one or multiple agents[1]: infectious diseases (legionellosis, colds and flu, tuberculosis), immunological diseases (hypersensitivity pneumonitis) and allergic disorders (allergic rhinitis, asthma, eczema, contact urticaria). The agents concerned are bacteria, viruses, fungi, actinomycetes, molds and allergens from dust mites, cockroaches, pets, etc.

Sick building syndrome differs from building-related illness in that it causes various non-specific symptoms, which may differ from one person to another, even during the same episode. People may present multiple relapses, especially upon returning to the place where their symptoms began. Symptoms are generally subjective, in that clinical examination of affected people reveals no objective abnormality and the results of any additional examinations are normal. Complaints may involve different organs and are often polymorphic. Each person may present different clinical signs, which fall into five categories:

1. Symptoms affecting the mucous membranes and upper respiratory tract: eyes (irritation, dryness, tingling, itching, burning sensation, watering), nose (irritation, dryness, congestion, sneezing, nosebleeds), or throat (irritation, dryness, husky or altered voice, coughing);
2. Symptoms affecting the lower respiratory system: tightness in the chest, wheezing, shortness of breath, asthma attacks, etc.;
3. Symptoms affecting the skin, such as dryness, itching, eruptions, sensations of burning or pressure on the face, dry or red facial skin;
4. Symptoms affecting the central nervous system, causing fatigue, difficulty in concentrating, drowsiness, heavy head, headaches, light-headedness, dizziness or nausea;
5. Symptoms of external discomfort (unpleasant odors, altered taste).

1 Institut de Veille Sanitaire. Diagnostic et prise en charge des syndromes collectifs inexpliqués. Technical guide. 2010

The signs of discomfort or symptoms experienced inside a building characteristically improve after leaving the location concerned, primarily affect vulnerable people, and promote clinical exacerbations in people already affected by allergic, respiratory, ocular or dermal disorders.

THE MULTIFACTORIAL ORIGIN OF SICK BUILDING SYNDROME

Numerous scientific publications[2,3] record associations between certain environmental or psychosocial factors and the onset of these symptoms. However, several authors[4,5] agree that all these factors may play a role without any single factor being sufficient to explain the health phenomena observed. Therefore, we speak of "multifactorial pathology"[6] that combines:

- Environmental factors: the presence of indoor pollutants such as volatile organic compounds including aldehydes, particulates and fibers, nitrogen dioxide, ozone, and molds associated with damp; ventilation defects, uncomfortable temperature, insufficient humidity, inappropriate lighting, overcrowding, etc.
- Individual risk factors: immune system predisposition, pre-existing skin dryness, wearing of contact lenses;
- Psychosocial factors: overly distant management or overly controlling management that restricts employee autonomy, workload-related stress, difficult relationships with line managers or colleagues, boring work, lack of privacy.
- The relative influence of these different factors may change over time, especially if the initial problem brings on an attack when the first attempts at management fail to relieve the reported symptoms. Numerous social factors are likely to make the attack worse.

Aside from consequences that can be highly detrimental to health, sick building syndrome also causes a deterioration in performance, not only in office staff, but also in children in the school setting.

2 Burge P.S. Sick building syndrome. **Occup Environ Med**. 2004;61:185-190

3 WHO. Indoor air quality: biological contaminants. WHO regional publications. European series no. 3. WHO, 1990:1-54.

4 Mendell M.J., Fisk W.J. Is health in office buildings related only to psychosocial factors? *Occup Environ Med*. 2007;64(1):69-70.

5 Baker D.B. Social and organizational factors in office building-associated illness. *Occup Med*. 1989;4(4):607-24.

6 Lahtinen M., Huuhtanen, Reijula. Sick Building syndrome and psychosocial factors – a literature review. *Indoor Air*. 1998;4;71-80.

COMFORT, HEALTH AND PERFORMANCE AT WORK IN OFFICE BUILDINGS

An audit carried out in office blocks in the Île-de-France region by the Society of Occupational Medicine of western Île-de-France and the Paris Hygiene Laboratory[7] enabled improved definition of employee complaints, based on a self-completed medical questionnaire distributed to employees when they visited the occupational physician. Two studies performed in 1994 and 1995 collected 4,276 questionnaires in winter and 2,152 in summer. The results were as follows: half the people surveyed complained of symptoms linked to their building: nose (25%), eyes (24%), throat (19%), headaches (17%), skin (12%), difficulties in concentrating (10%), abnormal fatigue (8%). The study also revealed several sources of dissatisfaction: building temperature (complained of by 60% of respondents), air quality (58%), noise (42%) and lighting (35%). A second study, using the same format, but this time performed at the national level over the winter of 1996-1997 with 3,953 employees, confirmed these results.

The European OFFICAIR project[8], which ran from 2010 to 2014 and involved 1,190 respondents, highlighted the same sources of dissatisfaction, but in different proportions: temperature (35%), air quality (38%), noise (44%) and lighting (27%). In a subsample of five buildings[9], the relationships between indoor air quality and work performance testing were studied. It was shown that individual variables such as age and being in receipt of medical treatment remained the main determinants of performance at work. It was also found that indoor concentrations of xylenes and ozone could influence employees' reaction times during the summer. Additionally, in both summer and winter, satisfaction in terms of noise and the ability to control the indoor temperature increased the occupants' self-reported productivity.

In the United States, the study by Professor Fisk and colleagues[10] compared the costs of a non-optimal indoor environment (in terms of absenteeism, for example) with the costs of improving that environment. According to the different scenarios considered, the benefits could be as high as $17 billion per year for American offices as a whole.

7 Squinazi F., Lanfranconi I., Giard A.M. Confort et santé dans les bâtiments climatisés. Proposition d'un auto-questionnaire à utiliser par le médecin du travail. Documents pour le Médecin du Travail. 1994 ;60(4):341-352.

8 Bartzis J. et al. European collaborative project OFFICAIR. On the reduction of health effects from combined exposure to indoor air pollutants in modern offices. 2014

9 Mandin C., Boerstra A., Le Ponner E., et al. Qualité de l'air intérieur et confort dans les espaces de bureaux, et relations avec la performance au travail. French section of OFFICAIR project, Part 2. Environnement, Risques & Santé. 2017;16(6):565-74.

10 Fisk W.J., Black D., Brunner G. Benefits and costs of improved IEQ in U.S. offices. Indoor Air. 2011;21:357-67.

CLASSROOM AIR QUALITY AND CHILDREN'S SCHOLASTIC PERFORMANCE

In 2007, Pawel Wargocki and David Wyon[11] carried out two summer interventional studies of the environment in two classrooms in a Danish school occupied by children aged between 10 and 12 years.

The authors observed that reducing the temperature from 25 °C to 20 °C improved performance in two arithmetical exercises and two language-based exercises similar to school work. The performance improvement was mainly due to the increase in the children's response speed. Other positive impacts were that the students' perception of the temperature changed from "slightly too hot" to "neutral" and they reported significantly fewer headaches at the lower temperature. A panel of adults entering the classrooms just after the children had left also noted a cooler and more acceptable environment at the lower temperature.

In addition, doubling the flow rate of fresh air per person from 5 to 10 liters per second improved students' performance by 15% for four arithmetical exercises, increasing response speed while generating almost no errors.

A similar European study[12] in 1996, involving 800 students in eight schools, showed that students' scores in concentration tests dropped as confinement (measured by carbon dioxide level) increased.

These results show that introducing the means to avoid rises in temperature and increase ventilation could improve students' school results.

11 Wargocki P., Wyon D.P. The effects of moderately raised classroom temperatures and classroom ventilation rate on the performance of schoolwork by children. *HVAC&R Research*. 2007;13(2):193-220

12 Myhrvold A.N., Olsen E., Lauridsen O. Indoor Environment in Schools—Pupils' Health and Performance in regard to CO_2 Concentrations. *Indoor Air. The Seventh International Conference on Indoor Air Quality and Climate.* 1996;4:369-371.

THE ENVIRONMENTAL AUDIT: A MEANS OF IDENTIFYING AND DEFINING ISSUES RELATED TO INDOOR AIR QUALITY IN BUILDINGS

An environmental audit is initiated when the nature of building or redevelopment work makes it likely to affect the environment. The environmental audit is rooted in a double approach[13].

- **A medical approach,** identifying non-specific symptoms or diseases associated with the presence of agents in the affected premises. Meeting with medical experts, managers, clerical and technical staff, followed by chronological analysis of the facts, should allow identification of the factor causing the symptoms, the timing of the symptoms (duration and frequency) and the number of people affected. There may be perception of a particular odor, disruption of the environment by the work (noise, dust, alterations regarded as harmful), general concern triggered by a sick person in the group, etc. Certain contextual factors can also promote reporting: an environment perceived as having deteriorated (for example, a nearby building site or poor workstation ergonomics), a strained sociological situation (underlying social conflicts, poor working conditions, difficult reporting relationships, defective management structures, etc.), unusual physical or psychological stress (relocation, performance reviews, restructuring, difficult economic situation, the prospect of downsizing, etc.).
- **A technical approach,** including a visit to the premises concerned and any annexes, looking for potential sources of pollution. The assessment must take into account potential emissions from construction materials; wall, floor and ceiling coverings; technical equipment (furniture, fuel-burning appliances, heating and air-conditioning systems, computing equipment); products for cleaning, personal hygiene, DIY, deodorizing, etc. It will involve searching for any damp stains, damaged surfaces or the presence of mold. The effectiveness of the building's air recirculation system will be checked (windows and doors, natural or mechanical ventilation system). Potential external sources in the vicinity should also be identified, such as a cooling tower, parking lot, industrial or artisanal activity, or even a building constructed on a potentially polluted site.

Based on the information gathered during the environmental audit and on medical advice received, a strategy is defined for measuring physical, chemical or microbial agents in the air, materials or surfaces. An external reference measurement and/or control environment near the affected premises may provide useful points for comparison.

13 French standard PR NF X 43-406: December 2018. Air quality – Strategy for environmental audit following a report. Building in residential, educational or office use.

For example, the following parameters will be measured, depending on the suspected sources of pollution:

Carbon monoxide	Faulty heating and hot water appliances, tobacco smoke, external urban pollution including from nearby road traffic
Volatile organic compounds	Construction or decorating products (wood-derived products; floor, wall and ceiling coverings; primary installation products, fillers and adhesives; paints and varnishes), furnishings, cleaning and dry-cleaning products, tobacco and e-cigarette smoke, external urban pollution including from nearby road traffic (fuel, service stations, parking lots), proximity to industry and incinerators, possible earlier soil pollution on the site, asphalt or bitumen, fires
Benzene	Tobacco smoke, burning of scented candles and incense, fuel-burning heating, fuel (proximity to a service station or parking lot)
Formaldehyde	Smoking and vaping, rough timber and wood-derived boards with formaldehyde-based binder (particle board, fiberboard, OSB, etc.), solvent based paints, materials containing formaldehyde without diffusion barrier treatment, cleaning and treatment products (phytosanitary or for pest control), burning of incense and scented candles, tobacco smoke
Ozone	Laser printers, photocopiers, electrostatic air purifiers
Nitrogen dioxide	Various types of fuel burning including gas burning; poorly sealed fume extraction ducts; urban pollution including from road traffic; air intake near road traffic, parking lot or garage
Particulates	Dirty or deteriorated ventilation system, fuel burning, tobacco smoke, proximity to a construction site, external urban pollution including from road traffic, proximity to industry, polluted outdoor air (including with pollen)
Artificial mineral fibers	Glass wool, rock wool, slag wool
Radon	Construction materials, soil in potential radon zones (fissures, porosity, joints, pipeline paths)
Airborne fungal flora	Indicator of the quality of air filtration by air treatment systems, internal source of damp (water damage, leaks, condensation) or mold growth
Airborne bacterial flora	Environmental indicator of the effectiveness of air recirculation, cleanliness of the premises and ventilation/air conditioning systems
Dust mite allergens (for allergic patients)	Bedding, box spring, textile floor and wall coverings, curtains, sofas, plush toys
Legionella pneumophila	Internal water and air-cooling distribution systems

Sensors can continuously measure some types of indoor air pollutants

Systematic measurements are also taken of temperature, humidity and carbon dioxide:

- Measurements of temperature and relative humidity over a period of at least 24 hours (eight days if possible) provide information on ambient conditions in the environment under investigation. These parameters demonstrate both the building's comfort conditions for occupants and the level of chemical emissions from the various materials and products present within the building.
- Carbon monoxide measurements give an indication of air recirculation in the building. Depending on the occupancy and non-occupancy patterns of the premises, this may bring to light any nychthemeral fluctuations[14] and variations between weekdays and the weekend.

In interpreting the measurement results, it is useful to compare them with reference values. Several factors must be considered when selecting the reference value for a given substance: the type of environment in which the measurements were taken, the length of time for which people mentioned in the report were exposed (was it acute exposure for a short time, or continuous, chronic, long-term exposure?) and the duration of measurement.

In a context where the aim of the investigations is to protect the health of occupants, the selection of reference values for the environment under investigation should initially be made as follows: 1/ regulatory values, if any have been defined; 2/ air quality reference values (VRAI) suggested by the French Public Health Council; or 3/ indoor air guideline values (VGAI) from the French Environmental and Occupational Health & Safety Agency (ANSES) or WHO guideline values or toxicity reference values (TRVs). For substances for which no reference values are available, informative values from studies representative of the environment under investigation may be used.

Ultimately, the audit must provide details of suggested actions.

ACTION LEVERS FOR PREVENTION AND REMEDIAL MEASURES

Given the health issues, but also environmental and economic challenges it represents, management of indoor air quality has become a major prevention issue for organizations involved in the construction, renovation and operation of buildings.

Different action levers for prevention and remedial measures have emerged in response to these challenges.

1. NEW OR RENOVATED BUILDING: PROJECTS BY ALLIANCE HQE-GBC FRANCE

In 2013, Alliance HQE-GBC France[15] published a document concerning the rules for evaluating indoor air quality on acceptance of a new or renovated building (that is, at the moment ownership passes to the contracting client, before the occupants move into the building)[16]. A practical guide[17], published in June 2017, presents the five key stages for integrating, completing and enhancing indoor air quality measurements on acceptance: program planning, building design, tender document preparation, construction and handover.

Several other works focus on the worksite phase, a sensitive stage in the process of constructing or renovating a building.

On the subject of regular monitoring of indoor air quality in buildings at every stage of their life cycle, in a 2018 methodology report, Alliance HQE-GBC France proposed a set of rules for evaluating indoor air quality in an operational building[18]. This report forms part of the organization's commitment to quality of life in a sustainable built environment. The parameters measured, whether physical, chemical or microbial in nature, are compared with reference values to detect any technical faults within the operational building.

14 Variations that occur within a period of 24 hours, especially those relating to day and night.

15 Alliance HQE-GBC is the professional alliance for a sustainable built environment. It brings together unions, trade federations, companies, local authorities and individuals from the construction, development and infrastructure sectors.

16 Alliance HQE-GBC. Protocole HQE PERFORMANCE : Règles d'application pour l'évaluation de la qualité de l'air intérieur d'un bâtiment neuf ou rénové à réception. 25 pages. June 2015 edition.

17 Alliance HQE-GBC France. Mesurer la qualité de l'air intérieur des bâtiments neufs ou rénovés : 5 étapes clés pour intégrer, réaliser et valoriser des mesures à réception. Practical guide. 36 pages. June 2017.

18 Alliance HQE-GBC France. Le bâtiment durable pour tous. Règles d'application pour l'évaluation de la qualité de l'air intérieur d'un bâtiment en exploitation. 29 pages. 2018

The basic on-acceptance protocol and priority parameters when in operation may be supplemented by additional parameters if the preliminary survey reveals other potential sources of pollution, such as damp problems, a potentially polluted site, or changes to the external environment (for example, new high-rise construction or changes in traffic flows).

2. CONTINUOUS MEASUREMENT SENSORS

Recent years have brought the development of continuous measurement sensors for some types of pollutants (particulates and volatile organic compounds, including formaldehyde and nitrogen dioxide), carbon dioxide, temperature and relative humidity. This development allows us to envision progress along three major lines:

- Improved study of the dynamics of concentrations;
- Better understanding of occupants' exposure to different pollutants;
- Appraisal of emissions-producing activities and/or aeration practices and/or ventilation system function.

The information obtained may enable detection of a pollution event (significant variation in the concentration of a parameter, either over an extended period – 1 to 2 hours – or temporary, but chronic and repetitive) and/or monitoring of its concentrations over time (trend monitoring) linked with emissions-producing activity and/or air recirculation in the premises (aeration and/or ventilation).

However, it should be remembered that the information obtained from these sensors has its limits: sensors provide socalled "indicative" measurements, or an "objective estimate" of indoor air quality. The use of sensors to manage indoor air quality within a building or raise awareness among its occupants cannot therefore be a measuring tool in isolation; it must be combined with technical information on the ventilation systems, occupancy of the premises and occupants' activities during the measuring period[19]. The considerable quantity of data accumulated over time must be interpreted in light of this information to enable decisions that are useful and effective for the occupants.

3. VENTILATION: A LINK TO BE STRENGTHENED

The importance of air recirculation appropriate to the occupancy of the premises should be emphasized. An effective and well-maintained ventilation system brings in fresh air and provides occupants with the oxygen they need, supplies fuel-burning appliances with the oxygen required to work properly, regulates the building's humidity and prevents the growth of unwanted microorganisms and pests (mold, dust mites, cockroaches), reduces the transmission of infective agents, eliminates odors and the physical and chemical pollutants that accumulate, limits exposure to soil pollutants (radon, volatile chemical substances) and, ultimately, improves human performance.

Feedback received highlights certain failings in the design, realization and/or operation of ventilation systems, which cause deterioration in indoor air quality and excessive humidity, which in turn leads to mold growth. The design phase of a new or renovated building must take account of the external environment's impact and adapt the ventilation system to the occupants and their activities. The expertise of a ventilation specialist is valuable during the design and construction of the ventilation system. In the building acceptance phase, inspection of the ventilation system ensures it has been installed correctly. Lastly, in the operational phase, the assurance of controlled ventilation flow rates guarantees the effective recirculation of air.

Feedback highlights certain failings in the design, realization and/or operation of ventilation systems, which cause deterioration in indoor air quality

It would be worthwhile reopening the debate on regulatory ventilation flow rates, which were defined in the 1980s in France (through regulations on dwellings, the standard regional health regulations for public buildings or the labor law on office buildings), with regard to occupants' expectations of comfort and the air quality in buildings.

4. INDOOR AIR PURIFICATION SYSTEMS

In recent years, technical air purification solutions have appeared on the market. These are either air purification appliances based on the filtration or destruction of indoor air pollutants (by photocatalysis, ionization, etc.), or functionalized materials that trap and neutralize pollutants such as formaldehyde or use photocatalysis.

Precautions should be taken with certain technologies; the French national health and safety agency recommends carrying out tests of their effectiveness and safety (given the potential emission of by-products resulting from the incomplete decomposition of pollutants) in real-world conditions to raise awareness, especially among asthma patients, of the potential risks from reduced air quality when using certain purification appliances[20]. Asthmatic patients in particular should be made aware of the possible worsening of their condition when using such appliances, especially those that use essential oils and those that may produce ozone.

It would be worth compiling all medical, technical and metrological data on these appliances in a national database as an aid to health care professionals and organizations involved in construction.

19 Alliance HQE GBC France. Place des capteurs de mesure en continu de la qualité de l'air intérieur lors de la réception ou l'exploitation d'un bâtiment. Framework paper

20 French Agency for Food, Environmental and Occupational Health & Safety (ANSES). Identification et analyse des différentes techniques d'épuration d'air intérieur émergentes. 2017

ENERGY TRANSITION FOR BETTER AIR QUALITY: A PUBLIC HEALTH ISSUE

Maria P. Neira
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Woman cooking indoors on a wood stove

Dr. Maria P. Neira is a Spanish physician who specializes in endocrinology, metabolic disorders and public health. She started her medical career as a doctor with Médecins Sans Frontières (Doctors Without Borders), working in refugee camps in El Salvador and Honduras. Her career then took her to Africa, including a stint in Rwanda with the United Nations Development Program. She joined the WHO in 1993, serving as Coordinator of the Global Task Force on Cholera Control until 1998, when she was appointed Director of the Department of Disease Control and Prevention (1999-2002). From 2002-2005 she was Head of the Spanish Food Safety Agency as well as Vice-Minister of Health and Consumer Affairs. Since 2005 she has headed the WHO's Department of Public Health, Environmental and Social Determinants of Health, steering its policy on environmental health. Dr. Neira was awarded the national order of merit by the government of France as well as the "extraordinary woman" award by the queen of Spain. In 2019 she was named among the 100 most influential people for health and climate change policy.

The World Health Organization is a specialized agency of the United Nations concerned with international public health. Problems raised by indoor air quality are at the heart of its mission and action. Causing over 3.3 million deaths every year, domestic air pollution is particularly prevalent in regions where income is low or modest, as households will often use highly polluting energy sources for heating and cooking. It is estimated that over half of the world's population uses sources of energy for heating and cooking whose fumes are toxic to human health and the environment. Soot particle pollution is extremely toxic for the airways and is something that women and children are particularly exposed to. Indoor air pollution is responsible for serious illnesses like pneumonia and heart disease. There are innumerable political and economic obstacles to energy transition in such regions. It is essential to initiate dialogue and cooperation between politicians and public health specialists to alert public opinion to the relationship between air quality and climate change and to enact public health policies that will anticipate and prevent pollution rather than remedy it subsequently. It is equally essential to stress the importance of cooperation between public health actors and those sectors of the economy that generate the most pollution, in order to bring about meaningful changes in public health.

What is the WHO's role in relation to air quality issues, particularly in the home?

Maria P. Neira: The WHO is a specialized agency of the United Nations concerned with international public health. Problems raised by indoor air quality are central to its mission and action. The WHO distinguishes between two concepts in terms of indoor air quality: 'domestic air pollution', caused mostly by fuels used in the home; and 'indoor air pollution', which includes domestic air pollution as well as other sources of pollution such as lead, asbestos, radon, molds and so.

The WHO bolsters national and regional capacities for combating indoor air pollution by providing tools to help prevent and anticipate this form of pollution, and by providing information on the relationship between domestic fuels and public health.

The WHO has published domestic air quality guidelines intended to provide advice about minimizing health risks. The guidelines provide technical assistance for organizing interventions and assessments centered on domestic fuel. They also offer advice about existing schemes to encourage rapid and lasting take-up of low-emission technologies and fuels by households. The WHO has produced the Clean Household Energy Solutions Toolkit (CHEST) to help promote implementation of these guidelines and associated public policies. Other tools include a guide outlining the acceptable and recommended daily and annual concentration levels for various categories of indoor pollutants.

In 2016, 3.8 million people died from causes related to indoor air pollution. In poorly ventilated homes, particulate concentration in smoke from domestic cooking can reach levels 100 times higher than acceptable limits

Beyond such actions, the WHO leads the way among international institutions in matters of health, energy and climate. The organization seeks to highlight to governments, international cooperation agencies and the general public the importance of switching to less polluting types of domestic fuels and the impacts that indoor air pollution has on people's health, in particular for women and children. For the WHO, one of the major challenges lies in persuading countries to set in motion ambitious energy transition plans. In October 2018, in collaboration with the UN Environment Program, the World Meteorological Organization, the Secretariat of the United Nations Framework Convention on Climate Change (UNFCCC), the Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants (CCAC) and the United Nations Economic Commission for Europe (UNECE), it organized the first WHO Global Conference on Air Pollution and Health. The conference focused on air quality, fighting climate change and saving lives. The WHO's lobbying efforts targeting major international bodies and forums are supported and relayed by its partners, such as the Climate and Clean Air Coalition. The pressure exerted is beginning to gain momentum, with an increasing number of international conferences, working groups and alliances focused on air quality. These include the World Health Assembly[1], the Global Platform on Air Quality and Health[2] and so on.

Which regions are most exposed or most vulnerable to indoor air pollution problems?

M. P. N.: Countries in Africa and Asia are disproportionally affected by indoor air quality problems for reasons that are essentially economic. For the most part, these are countries with lower or intermediate income in which households have no choice but to heat and cook using very polluting fuels.

Close to half of the world's population, some 3 billion people living mostly in rural areas, still have no access to clean fuels and technologies for cooking, heating and lighting. They rely on wood, agricultural by-products, animal manure, coal and charcoal, use kerosene in open fireplaces and generally have very inefficient cooking facilities. The fuels and cooking methods used lead to a high pollutant concentration within dwellings, which can be very harmful to health, particularly in the case of soot particulates that can penetrate deep into the lungs. Particulate concentration in smoke from domestic cooking can reach levels 100 times higher than acceptable limits. Women and children, who spend the most time at home, are especially at risk.

What consequences do these practices have on health?

M. P. N.: In 2016, 3.8 million people died from causes related to indoor air pollution. The most common illnesses are pneumonia, ischemic cardiomyopathy, chronic obstructive bronchopneumopathy, cardiovascular strokes and lung cancers. More generally speaking, particulates and other pollutants in domestic smoke emissions provoke inflammation in airways and lungs that leads to impaired immune responses and a reduced oxygen-carrying capacity of the blood. Additional data[3] points to the existence of a relationship between domestic air pollution and a wide range of ailments such as tuberculosis, cataracts and nasopharyngeal and laryngeal cancers. Indoor air pollution can also have consequences such as low birth weight for newborns.

1 https://www.who.int/fr/news-room/fact-sheets/detail/household-air-pollution-and-health
2 https://www.who.int/airpollution/global-platform/en/
3 https://www.who.int/phe/health_topics/outdoorair/databases/en/

Access to non-polluting fuels for cooking and heating is a major challenge for half the world's population

How would you rate air quality compared to other public health challenges (food, lack of exercise, etc.)?

M. P. N.: From a public health perspective, attempting to compare causes of death is always problematic. No death should ever be taken lightly. Having said this, it is still important to point out that air pollution is a bigger killer than HIV, malaria and tuberculosis combined; over 7 million deaths each year if you combine indoor and outdoor air pollution, which is almost as many as tobacco. The most frightening aspect is that these deaths have an anthropic origin: we humans deteriorate the quality of the air that we breathe. Urgent action is needed.

These [political and economic] obstacles can only be overcome once governments acknowledge that indoor air quality is a major public health issue

What are the economic and legislative hurdles that emerging economies in particular have to face? What levers can be used to overcome them?

M. P. N.: The problem is twofold: economic and political. Firstly, economic, because electricity and clean fuels, such as liquefied petroleum gas, biogas and natural gas, are all expensive. Secondly, political, because the legislation in some countries with low and intermediate income does not require electrification for rural communities. The challenge in these cases is to encourage governments to take the necessary political decisions, invest in non-polluting energy sources and roll out investment plans for electricity grids to serve rural areas. These obstacles can only be overcome once governments acknowledge that indoor air quality is a major public health issue and once the health risks associated with certain cooking and heating practices are fully factored in.

This is why it is so important to create dialogue opportunities via programs like the Transport, Health and

Environment Pan-European Program[4] that is co-sponsored by the WHO. Initiatives such as these facilitate the design of regional cooperation models between member states in a number of sectors, seeking to limit air pollution and other health-risk factors in the transportation sector and develop tools to assess the health benefits of adopted measures. The Convention on Long-Range Transboundary Air Pollution (CLRTAP)[5] is yet another example of an international framework through which signatory parties put in place policies and strategies to cut atmospheric pollutant emissions. The Convention specifically recognizes the need for cooperation and transparency in inter-state communications.

It is more important than ever that people realize and understand that to combat climate change is also to promote better public health

The need to raise awareness is just as critical in industrialized countries. For instance, Swedes are extremely sensitive to environmental and climate issues, but their culture and traditions encourage them to continue burning wood in open fireplaces, which generates smoke that is highly toxic and polluting. The biggest challenge centers on the need to alter people's social behavior patterns. In the United Kingdom, the latest air pollution plan clearly sets out to tackle this problem by presenting open fireplaces as major sources of air pollution.

What do you think about new technologies that let people measure, or even treat the quality of their indoor air?

M. P. N.: We don't think that remediation is the answer. What is needed is prevention, avoiding the air becoming polluted in the first place. It's not enough to treat the symptoms, you need to identify the root causes behind pollution and poor air quality, such as transportation, fuel, industry, waste incineration and so on, then take these on directly. There can be no justifying the unjustifiable.

New technologies for improving air quality, such as indoor air purifiers, can have a preventive role in reducing the concentrations of certain pollutants, particularly for those most vulnerable. But data on possible health benefits remains incomplete.

Another possibility revolves around sensor technologies to measure air quality. These technologies can alert people and help raise awareness about the importance of indoor air quality. However, they are not solutions that can reduce pollution in the long run.

Can highlighting links between air quality and climate change be used to raise awareness?

M. P. N.: The link between climate change and air quality is extremely important. Black carbon (soot particulates) and methane emitted by inefficient cooking stoves are highly polluting and contribute to the climate emergency. It is more important than ever that people realize and understand that to combat climate change is also to promote better public health. Our studies show that the causes of these two issues are 70% linked, they overlap. It is truly a public health war that must be fought. Just like the destruction of biodiversity, the melting of icecaps etc., air quality is a global public health issue. The most recent major international gathering in New York during the 2019 Climate Action Summit, on September 23, was an opportunity for the WHO to highlight to the public the links between air quality and climate change, and to continue to push for a coherent international roadmap on this topic.

4 https://solidarites-sante.gouv.fr/sante-et-environnement/activites-humaines/article/programme-paneuropeen-sur-les-transports-la-sante-et-l-environnement

5 International convention set up under the aegis of the United Nations on November 17, 1979. Signatories include states that are members of the United Nations Economic Commission for Europe (UNECE), states that have consultative status with this commission, and regional economic integration organizations empowered to negotiate, sign and apply international agreements in domains covered by the convention, at the UN office in Geneva.

THE INDOOR AIR QUALITY OBSERVATORY (OQAI): a unique project to understand air pollution in our living spaces

Corinne Mandin
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Combustion deodorizers contribute to indoor air pollution
©OQAI-CSTB

Head of the Indoor Air Quality Observatory (OQAI) in the Health & Comfort directorate of the Scientific and Technical Center for Building (CSTB) in France, Corinne Mandin has a background in chemical engineering and holds a doctorate in biology and health sciences. She works in the field of human exposure to chemicals, especially in buildings.

The OQAI was formed in 2001 to research air quality and comfort in living spaces. Its work is financed by the French ministries responsible for housing, the environment and health, the Environment and Energy Management Agency (ADEME) and the Agency for Food, Environmental and Occupational Health & Safety (ANSES).

The mission of the CSTB, which has scientific and technical oversight of the OQAI, is to ensure the quality and safety of buildings. It supports stakeholders in the transformation of buildings, together with environmental, energy and digital transformation. It is active in five key areas: research and consulting, assessment, certification, testing, and the dissemination of knowledge. Its areas of expertise cover construction products, buildings, and their integration into the town and district.

Over the past 10 years, indoor air quality has become a major component of environmental health. In France, the Indoor Air Quality Observatory (OQAI) runs national campaigns to measure indoor air pollution in homes, schools, office spaces and health care or medical-social establishments. After presenting the pollutants concerned and their health effects, this article summarizes the main outcomes of the OQAI's national campaigns in three types of environments: dwellings, classrooms and offices. It then focuses more specifically on the relationships between indoor air quality and energy performance, as making the building envelope more airtight to reduce energy loss can lead to reduced air exchange, resulting in a deterioration in indoor air quality. Although further research is necessary to improve our understanding of the airborne substances present in buildings and of their health effects, there are already good practices and tools that can be implemented to improve indoor air quality in our living spaces.

INTRODUCTION

That indoor air quality represents a health issue is no longer in question. In 2014, the French National Agency for Food, Environmental and Occupational Health & Safety (ANSES) and the Indoor Air Quality Observatory (OQAI) estimated the number of new cases of illness and deaths per year in France linked with six indoor air pollutants at around 28,000 and more than 20,000 respectively. This represents a cost of around €19 billion. Modern lifestyles effectively lead the population to spend the majority of their time in indoor environments where a large number of pollutants may be present.

In response to the need for deeper understanding and to better direct government policies and improvement solutions, the OQAI conducts research on new pollutants and investigates new problems.

POLLUTANTS THAT DEGRADE INDOOR AIR QUALITY AND THEIR EFFECT ON HEALTH

The sources of air pollution in buildings are numerous. Typically, indoor pollutants are categorized by type: chemical (semi-volatile and volatile organic compounds or VOCs, inorganic gases), biological (viruses, bacteria, molds, pet allergens, mite allergens) or physical (particulates, asbestos fibers, artificial mineral fibers, electromagnetic fields). Indoor pollution may also be described according to the three types of sources typically recognized: i) external pollution (air or ground in the case of radon, or soil contaminated by past or present industrial activity), ii) building constituents (construction materials and floor, wall and ceiling coverings) and fixtures, and iii) the occupants themselves (bioeffluents, smoking, cleaning, DIY, personal hygiene, etc.).

The respective contribution of each of these sources to indoor concentrations is difficult to determine, due not only to the specific characteristics of each space and its occupants' habits, but also to the variability over time of indoor concentrations and chemical reactivity phenomena leading to the formation of secondary pollutants. For example, terpenes are chemical substances mainly used in indoor cleaning and deodorizing products, which can react with ozone from outside and lead to the formation of formaldehyde and ultrafine particulates. Temperature and relative humidity also play a role by encouraging materials to release emissions into the indoor air.

Indoor air pollution constantly changes over time. New practices such as electronic cigarettes or 3D printing generate new forms of pollution. Additionally, some substances now banned from sale may still be present in buildings. This is the case with polychlorinated biphenyls (PCBs), for example, which were used in sealants in the 1970s and are frequently detected in the air in buildings constructed during that period. The same may be said of lindane, which was used as an insecticide in timber frames and head lice treatment shampoo, and is still often detected in indoor air. Ahead of the next national campaign to measure indoor air quality in French dwellings starting in 2020, the OQAI has updated its directory[1] of substances that may be present in indoor air. The list includes substances that have either: i) previously been detected in air or dust deposited on the ground, ii) previously been measured in an environmental chamber in emissions from construction materials or consumer products, or iii) been recorded in the composition of materials and products used in buildings. In total, 2,741 substances have been collated, including 1,715 new substances compared with the OQAI's last compilation of indoor air pollutants in 2010.[2]

The health effects of indoor air pollutants are just as varied as the pollutants that cause them. They range from mild annoyance linked to odors to serious effects such as lethal poisoning due to carbon monoxide, asthma, cancer, cardiovascular illnesses and reproductive problems. Poor indoor air quality may also be associated with headaches, nausea, and irritation of the eyes, nose and respiratory tract.

While some associations between substances present in indoor air and health effects are well established (as is the case with asbestos fibers and mesothelioma, or radon and lung cancer), the effects of a large number of other pollutants have not been clearly identified and remain merely suspected. Moreover, determining health effects can be made more complex by several features: effects are sometimes delayed; exposure is often to weak doses or occurs through various routes, including the ingestion of dust deposited on surfaces and skin contact, as well as inhalation; and these effects may be cumulative, synergic or antagonistic due to the mix of substances present.

Currently, concerns regarding indoor pollution are centered on endocrine disruptors, pesticides (especially near crops), biocontamination (for example, the dispersion of viruses in buildings in the case of flu pandemics) and nanoparticulates. These particulates are less than 100 nm in diameter and may be incorporated into construction materials and consumer products to give them particular properties, for example to strengthen or preserve. While studies are revealing the troubling implications of particulates of this size for respiratory health,[3] questions remain about how they are emitted into indoor air during use of said materials and products, or through their decomposition.

CURRENT STATE OF POPULATION EXPOSURE IN BUILDINGS

As the number-one indoor environment in terms of time spent, dwellings were the subject of the OQAI's first national campaign in 2003-2005. More than a hundred chemical, physical and biological parameters were recorded over one week, in a sample of 567 randomly selected dwellings representative of the stock of primary residences in mainland France. This campaign showed that some pollutants, such as formaldehyde, particulates, and certain phthalates and polycyclic aromatic hydrocarbons were systematically present in the dwellings. Air pollution in dwellings is not homogeneous, however, and different pollution profiles were identified. Additionally, 10% of French dwellings are multipolluted: they simultaneously present several chemical pollutants in very high concentrations. Conversely, 40% of dwellings are considered lightly polluted, as they showed concentrations lower than or equal to the median levels of the sample for almost all the pollutants studied.

1 Directory due for publication in early 2020.

2 https://www.oqai.fr/fr/campagnes/la-hierarchisation-des-polluants

3 Review of evidence on health aspects of air pollution – REVIHAAP Project. World Health Organization, Regional Office for Europe, 2013.

Indoor air quality measurement in a private home - ©OQAI-CSTB

Examination of the concentrations recorded alongside the characteristics of the buildings, their location, their occupants and their lifestyles identified factors leading to degradation of indoor air quality. For example, in single-family homes, the presence of a connecting garage increases concentrations of benzene and toluene in the rest of the dwelling. These substances are emitted by vehicles (exhaust gases and fuel tanks) and DIY products that may be stored in the garage. Cooking, care and hygiene (showers, drying laundry) activities may contribute to high humidity in the building, which favors the growth of molds. Behavior with regard to opening windows and the state of mechanical ventilation systems also play a role in indoor air quality.

Almost one in two new or recently renovated dwellings is contaminated by molds, most often invisible

After dwellings, schools are the location frequented second most often by children. In schools, the high density of furniture, use of products for activities (glues, paints, markers, etc.) and frequent cleaning of the premises may have repercussions on indoor air quality and represent distinctive features of these buildings in comparison with dwellings. In addition, the use of chalk, proximity to major highways, and children's high activity level (which causes dust deposits to become airborne) are all factors that contribute to particulate pollution in classrooms. All these distinctive features prompted a national measurement campaign, carried out by the OQAI between 2013 and 2017 in a sample of 301 randomly selected nursery and elementary schools representative of schools in mainland France.

The vast majority of schools conformed to the regulatory guideline values on indoor air quality available for formaldehyde and benzene,[4] and the threshold values requiring additional investigation and notification of the departmental prefect were never exceeded. Nitrogen dioxide, a marker of external atmospheric pollution where there are no combustion sources in the school buildings, was undetected in a quarter of schools. However, the results of this national campaign did highlight four points for consideration. Firstly, fine particulate pollution is omnipresent, with indoor concentrations higher than the World Health Organization's (WHO) guideline values in 96% of schools. Some pollutants were present in the air in 100% of classrooms, including phthalates, which are used as plasticizers; polycyclic aromatic hydrocarbons, produced by combustion, including from road traffic outside; and lindane. The presence of lead in deteriorating paint was observed in concentrations above the regulatory limit of 1 mg/cm^2 in 15% of schools. Lastly, 40% of schools had at least one classroom in which air renewal was unsatisfactory with regard to occupation, with a confinement index equal to 4 or 5 out of 5.

4 French Decree 2011-1727 of December 2, 2011 relating to indoor air guideline values for formaldehyde and benzene.

Indoor air quality measurement in a classroom
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Indoor air quality measurement in a workplace
©OQAI-CSTB

With statutory indoor air quality monitoring in place in nurseries and schools, the next step is to prepare for subsequent deadlines and identify the relevant parameters for monitoring other spaces open to the public. To this end, the public authorities have commissioned the OQAI to perform surveys in three types of establishments specifically targeted for the 2023 deadline: accommodation for senior citizens, and long-term care units and centers for disabled children and adults. Approximately 100 randomly selected establishments are currently being studied (2019-2020) to obtain preliminary data on indoor air quality and comfort in these spaces.

FOCUS ON INDOOR AIR QUALITY IN OFFICE BUILDINGS AND ITS RELATIONSHIP WITH PERFORMANCE AT WORK

In office spaces, specific sources and activities, such as the presence of printers and photocopiers and regular use of cleaning products that may produce volatile organic compounds (VOCs), raise the question of a specific kind of indoor pollution in these buildings. In this context, considering that a large part of the active population spends a significant amount of time in these spaces, the OQAI mounted a national measurement campaign between 2013 and 2017. Measurements of VOCs and aldehydes (19 compounds studied), particulates from 10 nm to 1 µm in diameter, temperature, relative humidity and carbon dioxide (CO_2) were taken in 129 office buildings, two-thirds of which were randomly selected, with the remaining third included on a voluntary basis. Five workspaces were measured in each building.

Initial data analysis showed overall weak indoor concentrations of the substances under investigation. The median concentration of formaldehyde was 14 µg/m^3, lower than the median concentrations in dwellings and schools. High concentrations of limonene (>100 µg/m^3) were recorded in 5% of offices. Similarly, concentrations of benzene above 10 µg/m^3 were occasionally observed, and were in almost every case linked to an equally high concentration in outside air in dense urban areas. Some offices (7%) were multipolluted, with all compounds under investigation present in higher concentrations than across the sample as a whole. Analysis is continuing to identify the contributory factors to poor indoor air quality in certain office spaces.

Poor indoor air quality in office spaces is associated with reduced worker performance. Numerous studies have been conducted under controlled conditions. They showed that temperature, air renewal rates, noise and lighting could have an effect on how quickly and/or accurately some tasks were performed. These factors were also associated with the number of incidents of short-term sick leave. A French study examining this relationship in real-world conditions took place as part of the European project OFFICAIR[5]. The aim of this project (2011-2014) was to study air quality and comfort in new or recently renovated office buildings in Europe. Coordinated by the OQAI in France, the study showed that while personal characteristics remained the primary factors determining performance at work, indoor concentrations of xylenes and ozone recorded during the summer could have an effect.[6] For this project, occupants of the offices surveyed were asked about their perception of their workspace, with the main causes of discontent among the 1,190 respondents in the 21 French buildings surveyed being: noise made by other occupants (54% of dissatisfied people), dry air (48%) and confined air (46%). Of health symptoms attributed to the building, headaches were most frequent (31% of respondents), followed by dry eyes (27%), watering or itching eyes (21%) and dry or irritated

5 Study cited in the article by Fabien Squinazi: Bartzis J. et al. European collaborative project OFFICAIR. On the reduction of health effects from combined exposure to indoor air pollutants in modern offices. 2014.

6 Mandin C., Boerstra A., Le Ponner E., Cattaneo A., Roda C., Fossati S., Carrer P. Qualité de l'air intérieur et confort dans les espaces de bureaux, et relations avec la performance au travail. French section of OFFICAIR project, Part 2. Environnement, Risques & Santé 2017;16;565-574.

Investigation of the links between the perception of air quality, comfort and health effects in indoor environments - ©OQAI-CSTB

throat (21%).[7] The ability to control the indoor environment (temperature, lighting, etc.) promoted a more favorable perception of it. Similarly, the existence and effectiveness of a complaint management procedure is associated with a more favorable perception of air quality and comfort, and with a reduction in perceived health effects noted inside and attributed to the building.

NECESSARY RECONCILIATION OF HEALTH AND ENERGY CHALLENGES

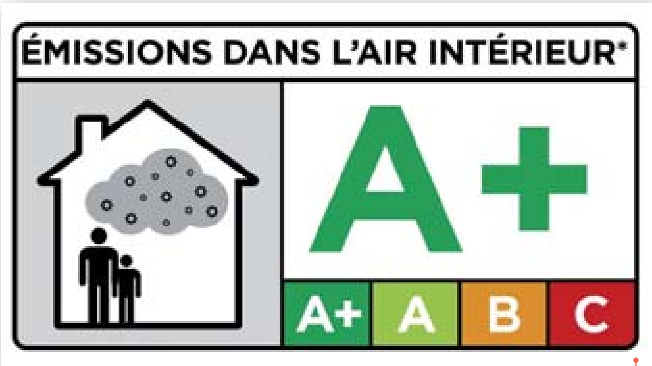
As buildings are currently among the priorities for energy savings, the OQAI is paying special attention to air quality and comfort in new and refurbished buildings. In short, improvement in the energy performance of buildings, which comes largely from making the building envelope more airtight, should not be to the detriment of indoor air quality. The OQAI therefore started a program[8] in 2012 to study indoor air quality and comfort in new or recently renovated buildings. Results so far pertain to 72 dwellings and show concentrations lower than or equivalent to those observed in French dwellings in 2003-2005, with the exception of three chemicals: hexanal, alpha-pinene and limonene. The factors associated with these higher indoor concentrations appear to be linked not to the buildings' energy performance, but to the presence of wood (frames, floors, furnishings and insulation) and cleaning products[9]. In the same sample, active fungal growth was present in 47% of dwellings, compared with 37% for housing stock in 2003-2005, which means almost one in two new or recently renovated dwellings is contaminated by molds, most often invisible. In buildings under construction, the elimination of unwanted air leakages while the mechanical ventilation system is not yet in operation and the windows are kept closed, combined with the reduction in material drying times, may explain high humidity when the building is made weatherproof/airtight[10] and the presence of molds in the acceptance phase. In renovated buildings, the failure to consider ventilation when making the building envelope more airtight limits the egress of moisture generated by the occupants and their activities, and thus encourages the growth of molds.

The increase in radon concentrations in renovated dwellings also demands attention. In France, extensive measurement campaigns in geographical areas with high ground radon emission potential showed that homes in which windows had been replaced for energy-saving purposes contained statistically significantly higher radon concentrations than homes in which windows had not been replaced[11]. Similar observations were made in other countries (Switzerland, Finland, Lithuania and the United States).

POSITIVE STEPS AND WAYS TO ACHIEVE GOOD INDOOR AIR QUALITY

Although further research is necessary to improve our understanding of the airborne substances present in buildings and of their health effects, there are already good practices and tools that can be implemented immediately to improve indoor air quality in our living spaces.

Improving indoor air quality firstly involves using low-emission products and materials. Since September 1, 2013, construction and decoration materials (wall, floor and ceiling coverings, paints and varnishes, insulating materials, etc.) marketed in France must be labeled with their potential VOC emissions. This labeling is based on emissions of 10 different VOCs and of volatile organic compounds overall ("total VOCs"). Four classes indicate the emissions level, ranging from "A+" (the product emits no or very few VOCs) to "C" (the product emits a large quantity or has not been evaluated).



Label indicating the volatile organic compound emissions class of a material or product for construction or decoration

7 Mandin C, Boerstra A, Le Ponner E, Roda C, Fossati S, Carrer P, Bluyssen P. Perception de la qualité de l'air intérieur, du confort et de la santé dans les espaces de bureaux, et relations avec les caractéristiques techniques des bâtiments. French section of OFFICAIR project, Part 1. Environnement, Risques & Santé 2017;16;553-564.

8 https://www.oqai.fr/fr/campagnes/fonctionnement-du-programme-oqai-bpe

9 Derbez M., Wyart G., Le Ponner E., Ramalho O., Ribéron J., Mandin C. Indoor air quality in energy-efficient dwellings: levels and sources of pollutants. Indoor Air. 2018;28;318-338.

10 Installing the roof, and fitting doors and windows

11 Le Ponner E., Collignan B., Ledunois B., Mandin C. Déterminants des concentrations intérieures en radon dans les logements français. Environnement, Risques & Santé 2019;18;33-40.

In the absence of labeling when choosing products, it is important to follow the usage instructions, which often call for increased ventilation of the area when using products. It is also important to avoid storing products that might emit VOCs in living spaces, ensure proper ventilation of the storage areas if necessary, and lastly, to take care when using harmful, inflammable, corrosive or toxic products (look for hazard symbols on the labels).

The large-scale observation of occupied building stock is a unique tool for developing and adjusting government policies, motivating professionals and raising awareness among the general public

Hazard pictograms on chemical products - ©INRS

Other actions are also necessary to ensure indoor air quality. Regular cleaning of the building's equipment and combustion appliances for heating and hot water production is necessary to limit the emission of pollutants such as carbon monoxide. Management of water damage, water ingress and rising damp is also essential to limit the presence of moisture and growth of molds.

The second set of actions to improve indoor air quality concerns air circulation and ventilation. As pollutants cannot be avoided completely, the air should be renewed to remove them. Ventilation systems should be properly sized, installed and maintained. Air inlets should never be blocked. The intake valves for mechanical ventilation systems should be away from any external sources of pollution (road traffic or vent from underground parking if on a wall, air cooling tower or chimney if on a roof). Filters should be cleaned and replaced regularly. A gap of 2 cm should be left under doors to allow air to circulate. The website https://www.batiment-ventilation.fr contains details in French of the standards and guides on evaluating the ventilation in residential and commercial buildings.

Lastly, the use of air purifiers is the final solution to consider. Great care is required when introducing these devices into buildings, whether as part of ventilation systems, integrated into the materials or as standalone appliances. The effectiveness of these systems and their safety (non-emission of by-products) remain to be determined. In a 2017 investigation, the French National Agency for Food, Environmental and Occupational Health & Safety (ANSES) concluded that current scientific knowledge cannot demonstrate the effectiveness and safety of indoor air purifiers that work on the principles of catalysis or photocatalysis, plasma, ozonation or ionization.[12] Traditional mechanical filtration of particulates at the ventilation system's air intake or using a standalone appliance is effective if the device is correctly and regularly maintained.

CONCLUSION

The large-scale observation of occupied building stock is a unique tool for developing and adjusting government policies, motivating professionals and raising awareness among the general public. Our knowledge of the pollutants present in indoor air has progressed greatly in recent years, and major advances have been made in reducing exposure to some chemicals. Further research is necessary, all the more so given that building techniques are constantly evolving and new questions are being raised due to new uses and products. More research is also needed in connection with climate change and the reemergence of asbestos issues as buildings are renovated to be more energy efficient. At the same time, private companies are tackling the problem to integrate it into the act of constructing and operating buildings. The increasing development of miniaturized, connected sensors to measure certain pollutants should make it possible to monitor indoor air quality on a massive scale, and thus alert people to take action in the event of pollution. As indoor air quality has become a performance indicator for buildings, it is becoming increasingly central to society's concerns and expectations around health protection.

For more information:

http://www.oqai.fr

The publication "Qualité d'air intérieur, qualité de vie : 10 ans de recherche pour mieux respirer," published by Éditions CSTB in 2011 to mark 10 years of the OQAI.

12 https://www.anses.fr/fr/content/%C3%A9purateurs-d%E2%80%99air-int%C3%A9rieur-une-efficacit%C3%A9-encore-%C3%A0-d%C3%A9montrer

COMMUTING BY SUBWAY? WHAT YOU NEED TO KNOW ABOUT AIR QUALITY*

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*Edited with *The Conversation*[1]

Subway, Tokyo, 2016. Mildiou/Flickr, © BY-SA

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Fulvio Amato is a tenured researcher at the IDAEA. He got a PhD on traffic non-exhaust emissions in 2010 and worked in the Netherlands (TNO) as post-doc research fellow. He is also an advisor for national and international organizations (WHO, EPAs, OECD, CEN, UNECE) on air quality and health.

1 https://theconversation.com/commuting-by-subway-what-you-need-to-know-about-air-quality-82859

Internationally, more than 120 million people commute by subway every day, and this number will keep increasing in the future as the United Nations predicts that 75% of the world's population will be urban by 2050. On top of being crucial to the mobility of city dwellers, subway systems can also play a pivotal role in reducing outdoor air pollution in large metropolises by helping to reduce motor-vehicle use. However, in response to increasing scientific and public awareness regarding the importance of clean air to human health, several studies have revealed unacceptably high levels of inhalable particulate matter (PM) in some subway systems. This article reviews some of these studies and puts their results in perspective, given World Health Organisation (WHO) guidelines concerning safe concentrations of particulate matter in the air. Following on from this, the authors identify some of the key factors influencing subway air pollution and put forward a number of recommendations to help city planners improve air quality in subway systems, as well as commuters protect themselves from the brunt of air pollution in the subway environment.

INTRODUCTION

Four more major Indian cities will soon have their own metro lines, the country's government has announced[2]. On the other side of the Himalayas, Shanghai is building its 15th subway line, set to open in 2020, adding 38.5 km and 32 stations to the world's largest subway network. And New Yorkers can finally enjoy their Second Avenue Subway line after waiting almost 100 years for it to arrive.

In Europe alone, commuters in more than 60 cities use rail subways. Internationally, more than 120 million people commute by subway every day. We count around 4.8 million users per day in London, 5.3 million in Paris, 6.8 million in Tokyo, 9.7 million in Moscow and 10 million in Beijing.

The use of public rather than private transport to abate urban atmospheric emissions is to be encouraged, and, in this context, subway systems are especially desirable.

2 In 2017.

Subways are vital for commuting in crowded cities, something that will become more and more important over time – according to a United Nations 2014 report, half of the world's population is now urban. They can play a part in reducing outdoor air pollution in large metropolises by helping to reduce motor-vehicle use. Large amounts of breathable particles (particulate matter, or PM) and nitrogen dioxide (NO_2), produced in part by road traffic, residential heating and industrial emissions, are responsible for shortening the lifespans of city dwellers. Public transportation systems such as subways have thus seemed like a solution to reduce air pollution in the urban environment. However, in response to increasing scientific and public awareness of the importance of clean air to human health, a number of studies have revealed unacceptably high levels of inhalable particulate matter (PM) in some subway systems.

As such, we may wonder what the air that we breathe is like underground, on rail platforms and inside trains.

MIXED AIR QUALITY

Over the last decade, several pioneering studies have monitored subway air quality across a range of cities in Europe, Asia and the Americas. The database is incomplete but is growing and is already valuable.

A number of studies have revealed unacceptably high levels of inhalable particulate matter (PM) in some subway systems

For example, comparing air quality on subway, bus, tram and walking journeys from the same origin to the same destination in Barcelona revealed that subway air had higher levels of air pollution (PM2.5 concentrations (43 µg/m^3: range, 37-49 µg/m^3)) than in trams or walking in the street (29 µg/m^3: range, 23-35 µg/m^3), but slightly lower than those in buses (45 µg/m^3: range, 39-49 µg/m^3 [3]). Similar lower values for subway environments compared to other public transport modes have been demonstrated by studies in Hong Kong[4], Mexico City[5], Istanbul[6], and Santiago de Chile[7].

Such differences have been attributed to different wheel materials and braking mechanisms, as well as to variations in ventilation and air conditioning systems, but may also relate to differences in measurement campaign protocols and choice of sampling sites.

In some cases, PM2.5 concentrations on a given platform can exceed 100 µg/m^3, as a daily mean, demonstrating a clear need for improving air quality underground in some stations. On the other hand, subway stations can be remarkably clean. Levels of PM2.5 on the Collblanc[8] L9S platform (26 µg/m^3) in Barcelona, for example, are close to the European limits for outdoor air, proving that it is perfectly possible to breathe relatively clean air even in the confined space of an underground train network.

THE EFFECTS ON HEALTH

Air quality inside underground rail systems is not yet included in legislation designed to clean up city air. Current European Commission rules require authorities to maintain ambient PM2.5 levels in outdoor air below an annual average of 25 µg/m^3 (2008/50/EC). World Health Organization (WHO) recommendations are more ambitious, calling for a tiered approach to reducing PM levels that starts with 35 µg/m^3 and works progressively towards an ideal level of just 10 µg/m^3. Given the fact that subway particles are chemically so different from most outdoor PM, the obvious question arises: are they more toxic than other commonly inhaled particles in the city, for example, those characterizing traffic-polluted outdoor air? Some studies have concluded that subway PM are indeed relatively more toxic[9], whereas others have failed to detect any difference between the bioreactivity of outdoor and subway air[10], while others still have reported higher oxidative potential (OP) of traffic PM as opposed to subway PM[11]. When looking at all studies published, the evidence so far suggests that subway commuters are not being exposed to a more toxic atmospheric environment underground than when traveling through the traffic-polluted city above.

To date, there is no clear epidemiological indication of abnormal health effects on underground workers and commuters. New York[12] subway workers have been exposed to such air without significant observed impacts on their health, and no increased risk of lung cancer was found among subway train drivers in the Stockholm[13] subway system. But a note of caution is struck by the

3 Moreno et al., Urban air quality comparison for bus, tram, subway and pedestrian commutes in Barcelona. Environ. Res., 142, 495–510.

4 Chan, L., La u, W., Lee, S. & Chan, C. (2002). Commuter exposure to particulate matter in public transportation modes in HongKong. Atmos. Environ., 36(21), 3363–3373.

5 Gómez-Perales, et al., (2007)Bus,minibus, metro inter-comparison of commuters' exposure to air pollution in Mexico City. Atmos. Environ., 41, 890–901.

6 Onat, B. & Stakeeva, B. (2013). Personal exposure of commuters in public transport to PM2.5 and fine particle counts. Atmos.Pol. Res., 4, 329–335.

7 Suárez et al., (2014). Personal exposure to particulate matter in commuters using different transport modes (bus, bicycle, car and subway) in an assigned route in downtown Santiago, Chile. *Environmental science.* Processes & impacts. 16. 10.1039/c3em00648d.

8 Moreno et al. (2017). The effect of ventilation protocols on subway system air quality *Science of the Total Environment* 584–585, 1317–1323.

9 Karlsson et al., (2006)., Comparison of genotoxic and inflammatory effects of particles generated by wood combustion, a road simulator and collected from street and subway. Toxicol. Letters, 165, 203-211.

10 Spagnolo et al ., (2015) Chemical Characterisation of the Coarse and Fine Particulate Matter in the Environment of an Underground Railway System: Cytotoxic Effects and Oxidative Stress—A Preliminary Study. Int. J. Environ. Res. Public Health 12, 4031-4046.

11 Janssen et al., (2014) (2014). Oxidative potential of particulate matter collected at sites with different source characteristics. Sci. Tot. Environ., 472, 572–581.

12 Chillrud et al., (2004). Elevated airborne exposures of teenagers to manganese, chromium, and steel dust and New York City's subway system. Environ. Sci. Technol., 38, 732–7.

13 Gustavsson et al., (2008). Incidence of lung cancer among subway drivers in Stockholm. Am. J. Ind. Med., 51, 545–7.

Second Avenue Subway in the making, New York, 2013. MTA Capital Construction/Rehema Trimiew/Wikimedia, © BY-SA

observations of employees working on the platforms of Stockholm underground (where PM concentrations were greatest), who tended to have higher levels of risk markers for cardiovascular disease than ticket sellers or train drivers.

Subway particulate matter is sourced from moving train parts such as wheels and brake pads, as well as from the steel rails and power-supply materials, making the particles dominantly iron-containing

OF WHEELS AND BRAKES

Much subway particulate matter is sourced from moving train parts such as wheels and brake pads, as well as from the steel rails and power-supply materials, making the particles dominantly iron-containing. The dominantly ferrous particles are mixed with particles from a range of other sources, including rock ballast from the track, biological aerosols (such as bacteria and viruses), and air from the outdoors, and driven through the tunnel system on turbulent air currents generated by the trains themselves and ventilation systems.

Key factors influencing subway air pollution include types of brakes (electromagnetic or conventional brake pads) and wheels (rubber or steel) used on the trains but also station depth, date of construction, type of ventilation (natural/air conditioning), , train frequency and more recently the presence or absence of platform screen-door systems.

COMPARING PLATFORMS

The most extensive measurement program on subway platforms to date has been carried out in the Barcelona subway system, where 30 stations with differing designs were studied under the frame of IMPROVE LIFE project[14],with additional support from the AXA Research Fund.

During this project, we sampled widely from a range of subway lines and station types. Conclusions can be reached concerning which kind of subway stations are likely to have the best and worst air quality in any given system:

- The subway stations likely to have the worst air quality will be those with limited air volume (such as single tube lines with one narrow platform), weak or inappropriately designed ventilation systems (especially in deeper stations), a lack of platform screen doors protecting the commuter from the free ingress of contaminated tunnel air, a topography that involves elevation changes and therefore requires harder braking, and that are old enough to have generated years of particulate pollutants available for repeated resuspension throughout the system.
- In contrast, subway stations with the best air quality are likely to be larger and/or newer, with good air interchange with outdoor street air (although not sourcing from traffic hotspots in the city), with full length screen doors fitted to all platforms, and with a straight, horizontal trajectory that minimises brake and wheel wear.

14 The overall aim of IMPROVE (Implementing Methodologies and Practices to Reduce air pollution Of the subway enVironmEnt, LIFE13 ENV/ES/263)) is to test measures that can reduce PM concentrations in platforms and inside trains, taking into account variations in all the key factors such as station depth, date of construction, station design, type of ventilation, types of brakes used on the trains, train frequency and the presence or absence of platform screen door systems. It also comprises indoor carriage air quality. http://improve-life.eu/

Depending on the materials used in construction, you may breathe different kinds of particles on various platforms worldwide.
London Tube/Wikimedia, © BY-SA

The stations with just a single tunnel with one rail track separated from the platform by glass barrier systems showed on average half the concentration of such particles in comparison with conventional stations, which have no barrier between the platform and tracks. The use of air-conditioning has been shown to produce lower particle-matter concentrations inside carriages. Moreover, subway platform air quality is markedly influenced by the power setting of tunnel ventilation fans and whether or not the platform air is being introduced by impulsion or removed by extraction. Switching from platform impulsion to extraction with higher fan power in the tunnel results immediately in a marked increase in ambient inhalable PM, especially in the number of finest particles (submicron), which are presumably being drawn into the platform from the tunnel.

In trains where it is possible to open the windows, such as in Athens, concentrations can be shown to generally increase inside the train when passing through tunnels and more specifically when the train enters the tunnel at high speed.

Subway commuters are not being exposed to a more toxic atmospheric environment underground than when traveling through the traffic polluted city above

MONITORING STATIONS AND OTHER RECOMMENDATIONS

Although there are no existing legal controls on air quality in the subway environment, research should be moving towards realistic methods of mitigating particle pollution. Our experience in the Barcelona subway system, with its considerable range of different station designs and operating ventilation systems, is that each platform has its own specific atmospheric micro environment.

To design solutions, one will need to take into account the local conditions of each station. Only then researchers can assess the influences of pollution generated from moving train parts. Such research is still growing and will increase as subway operating companies are now more aware of how cleaner air leads directly to better health for city commuters.

These are some important points to consider in order to improve air quality in the subway environment:

- Trace metal components of moving train parts can be recognized in subway air and this prompts the question: are these materials as least toxic as possible? Some of the identified metals, such as manganese, copper, antimony and chromium, are known to produce toxic effects in humans, and so we would urge further research into the toxicity of inhalable friction- generated polymetallic particles, particularly brakes and copper-bearing catenary systems.
- At night, when neither train nor platform ventilation fans are operational, platform air quality improves when tunnel fans are working at lower power, whether or not they are operating on impulsion or extraction. The resulting reduction in air movement from tunnel to platform, due to subdued fan power and no train piston effect, presumably allows particles to settle out of suspension. Slowing down the speed of trains in places on lines where there are sharp curves and high gradients should reduce the emissions of iron-rich particles.
- Controlling the exchange between the outdoor and underground air masses using intelligent ventilation systems, avoiding sourcing from traffic hotspots in the city by careful selection and design of outdoor ventilation grill locations: impulsion of outdoor air at platforms during metro hours; Ventilation on platforms at frequencies higher than 25 Hz; Forced extraction of outdoor air at tunnel during operating hours; Air conditioning systems inside trains.
- The use of air purifiers: their effect is dependent on the distance to the passenger and the flow rate.
- Platform screen doors: modern subway lines are being fitted with platform screen doors, primarily for passenger safety reasons. The additional benefit to passenger health is their efficiency in reducing the ingress of contaminated tunnel air into the platform, especially of relatively coarse inhalable particles.
- Night maintenance: some good practices must be taken into account to ensure dust emission reduction such as conducting the cleaning as early in the night as possible and using dust suppressant (water and/or antiresupension polymer) when laying ballast.

WHAT DO WE BREATHE INSIDE OUR CARS?

Characterization of the infiltration of pollutants and recommendations

Amine Mehel
Professor and researcher, ESTACA'Lab

As many as 300 different types of pollutants can infiltrate car cabins

ESTACA'Lab is the research Laboratory of ESTACA, a French engineering school dedicated to transportation systems.

Amine Mehel is an Associate Professor in the Mechanical and Environmental research department, member of the Air Quality and Pollution Treatment group that he has helped develop since joining ESTACA in 2010. He received his Ph.D. in Multiphase Flow Dynamics from the University of Nantes and Ecole Centrale of Nantes in 2006. His main research interest includes the transportation and dispersion of pollutants in interactions with flow turbulence, pollutant characterization and measurements, modeling of UltraFine Particles dynamics, and multiphase flow CFD simulations.

A car cabin is a small, enclosed space that is subject to pollutant infiltration or self-emissions. Depending on traffic and ventilation conditions, pollutants can accumulate, exposing passengers and drivers to serious adverse health effects. These pollutants are of different types (gaseous or ultrafine particles) and can reach very high concentrations in comparison with outdoor air.

Our research is mainly focused on the infiltration process that concerns broad types of pollutants. Since the infiltration process depends on three main factors (concentration of outside pollutants, flow topology at emission points and internal vehicle parameters such as ventilation settings), we conduct on-board and wind tunnel measurements to characterize pollutant dynamics, in interaction with the flow topology. These measurements cover their dispersion from emission sources to their infiltration through air intakes, taking into account the local pollution level.

Results dealing with dispersion in wind tunnels have shown that the ultrafine particles emitted from tailpipe exhaust gas accumulate in the core of the vortices that appear in the vehicle near-wake. This behavior has an important role on their infiltration, since the cabin air intakes are located in the front of most cars. Another finding is that distances between cars, ventilation mode combined with traffic density and route topology could worsen cabin air pollution. Understanding the impact of these different parameters can help to improve vehicle in-cabin air quality.

INTRODUCTION

Concentrations of toxic gaseous and particulate pollutants are very high in urban areas, particularly near major roads and freeways. On-road vehicles are in fact the primary source of direct emissions[1,2,3]. These pollutants are transported from areas with very high concentrations to all over surrounding local environments, including vehicles. They can infiltrate the cabins of vehicles, cumulating and increasing the exposure of passengers. Several toxicological and epidemiological studies have associated exposure to high levels of such toxic pollutants (among others ultrafine particles (UFP) and Nitrogen oxides (NOx) to the worsening of respiratory inflammation, allergy and asthma[4], as well as numerous long-term health problems including lung cancer and cardiovascular diseases[5].

Two major pollutant characteristics are important in assessing exposure to such pollutants: concentration and particle size (for UFP). It has been shown that the ratio of inside-to-outside concentrations (I/O) during the infiltration process greatly depends on vehicle internal parameters, such as vehicle mileage, age, ventilation fan speed/settings and ventilation mode (recirculation on/off)[6]. Nevertheless, it is also subject to external parameters such as local flow topology[7,8,9]. In present ongoing research, we are investigating pollutant concentrations through two approaches. The first consists of on-board measurements where we measure both indoor and outdoor pollutant concentrations for various ventilation settings and vehicle interspacing distances.

The second focuses on an infiltration process study at a small-scale level in a wind tunnel. In this study, UFP dispersion from emission point (at the tailpipe) and interaction with flow at vehicle near-wake and air intakes is first investigated. Then, infiltration of UFP into a reduced car model is assessed. The combination of both approaches will help to improve the measurement methodology (e.g. position of the outdoor probe) but also understanding of the pollutant infiltration process. The objective is to develop solutions to improve car-cabin air quality.

POLLUTANTS FOUND IN CAR CABINS

The number of pollutants encountered in such small, enclosed spaces as car cabins can be greater than 300 types of carbon-based gases, ranging from mainly Volatile Organic Compounds (VOCs)[10] to combustive gaseous chemicals (NOx, CO, etc.) and particles[11,12] *(figure 1)*.

The VOCs[13] are emitted by a wide array of products in new car cabins due to off-gassing from materials, including natural or artificial leather, polystyrene, polyethylene, polypropylene, polyamide, adhesives, paints, polyurethane foam, etc. These materials are used in the dashboard, interior panels, seat coverings, flooring materials, and more. Unfortunately, within the confined space of an automobile's passenger compartment, concentrations of chemicals emitted from these components are consistently higher indoors (up to 10 times higher) than outdoors[14].

Additionally, external pollutants can also contribute to in-cabin contamination. The infiltration process is in fact the main mechanism contributing to the rise of UltraFine Particles (UFP) and PM (Particle Matter), NOx, CO, SO_2 and HC concentration levels inside car cabins. The infiltration process is related to the air inlet: air due to ventilation, opening windows or leakage. It has been shown that the ratio of inside-to-outside concentrations (I/O) during the infiltration process greatly depends on vehicle internal parameters such as vehicle mileage, age, ventilation fan speed/settings and ventilation mode (recirculation on/off)[5]. Nevertheless, it is also subject to the influence of external parameters such as traffic, route topology or weather[15,16]. Ultrafine nanoparticles have been the focus of numerous studies, as their high toxicity is great enough to be classified as carcinogenic by the International Agency for Research on Cancer (IARC) of the World Health Organization (WHO), or at least having strong adverse health effects besides VOCs[4,5]. Their particular dynamics contribute to the high variability of concentration levels, since such small-sized particles are subject to strong influence from turbulence and Brownian diffusion[*17]. It is therefore important to characterize local flow topology to enhance understanding of the pollutant infiltration process into car cabins.

[*] Brownian diffusion is the random movement of a small particle caused by the collision of the molecules of the air.

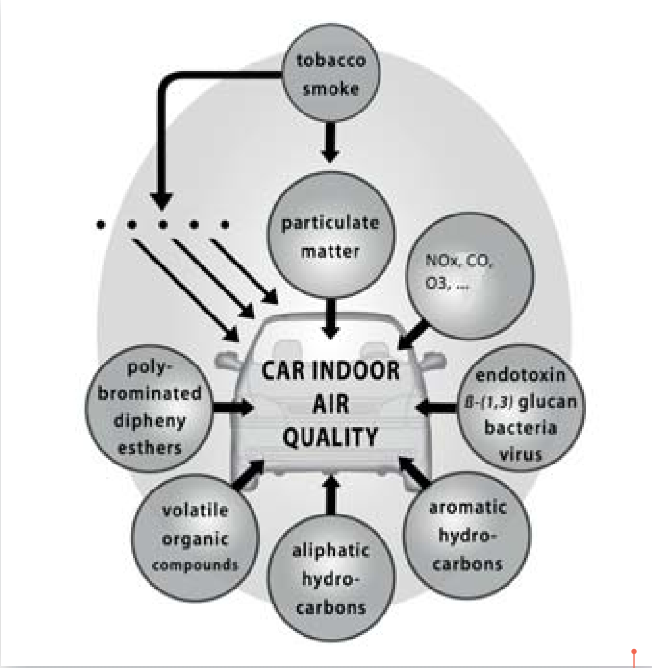

Figure 1- Common pollutant types found in car cabins (on the basis of Muller et al. (2011) [[18]])

DESCRIPTION OF TYPICAL EXPERIMENTAL APPROACHES FOR CAR CABIN POLLUTANT INFILTRATION CHARACTERIZATION

The originality of and need for combining both on-board and laboratory measurements to understand the transportation of pollutants from their emission point to their infiltration into the car cabin has been underlined. In this paragraph, we describe the typical experimental set-up for on-board measurements dedicated to the assessment of the I/O ratio of various pollutants. We also detail wind tunnel tests for UFP dispersion characterization in correlation with flow topology. Next is detailed the methodology used for both approaches, during a project that was entitled "CAPTIHV," which consisted in the characterization of pollutants issued from ground vehicles and infiltrating car cabins.

The first approach consisted of simultaneous on-board measurements of outdoor and indoor gaseous (NOx) and ultrafine particle concentrations in real driving conditions in the Paris area. The indoor to outdoor concentrations ratio (I/O) was measured in terms of mass concentrations for gaseous pollutants and particles, and number concentrations for UFP. The sampling was achieved through two probes mounted on the left side of the vehicle and at passenger mouth level for in-cabin air sampling (*figure 2*). Lastly, a synchronized video recording was used to obtain additional information. This means that further analyses can be performed on particular events occurring in front of the vehicle.

Figure 2 - Outdoor (a) and indoor (b) probes used for pollutant concentrations measurement © Amine Mehel

The vehicle used the most was the light-duty Renault Kangoo (2006 model, equipped with new OEM cabin filters). It is worthwhile noting that windows were closed for all runs, ventilation was on (mid-strength fans) and recirculation was off. Fan speed was kept constant to medium for all the tests. There were also measurements to characterize the influence of ventilation settings and windows on I/O ratios using two successive vehicles. The upstream car was the Kangoo while the downstream one was either a 2006 diesel-engine car fitted with old OEM cabin filters or a 2016 gasoline-engine car equipped with OEM filters of 20,000 km. The originality of these measurements using two successive cars is that we reduced the influence of the type of upstream car (engine type, model type, etc.) on the emissions in front of the test vehicle.

The on-board measurement campaigns were conducted from April 2016 (sunny weather, temperatures between 5 °C and 20 °C) to December 2017 (temperatures between 1 °C and 15 °C). Many routes were tested at different moments of the day (morning, mid-day and evening). Traffic was light to busy depending on road types (highways, urban, ring road). A total distance of 107 km was considered for a duration of three hours. The measurements were made at vehicle speeds ranging from 10 km/h^{-1} to 130 km/h^{-1}.

For wind tunnel measurements, we were interested in assessing the dispersion of UFP downstream of a reduced-scale squareback Ahmed body model[19] (*figure 3a*). The second car model (b) is a MIRA type model. This model is used as the downstream model that follows the Ahmed body model. It includes three air intakes with a hollow interior so as to allow UFP infiltration and measurements.

Figure 3 - Car models used for infiltration study: (a) Ahmed body, (b) Mira model © Amine Mehel

The flow air that was investigated was set at a velocity of $U\infty=12\ m\cdot s^{-1}$, which is typical of urban areas. We aimed at simulating the dispersion of UFP from vehicle exhausts in urban areas downstream of the car model and then their infiltration in the downstream Mira model. To achieve this, we injected UFP ranging from 20 to 100nm in size, and characterized their dispersion in correlation with their interactions with the flow field[20].

ACTUAL SITUATION CONCERNING I/O RATIOS AND INFLUENCING PARAMETERS

It is known that many internal parameters have an influence on I/O ratios, among them the ventilation mode, i.e. fresh air coming from outdoors, Outdoor Air (OA) or Recirculation Air (RC). This was confirmed by the CAPTIHV project results. Indeed:

- when RC mode is activated, only 22-40% of NO_2 infiltrates the car cabin. The level ranges between 25% and 90% for UFP
- when OA mode is on, all these pollutants infiltrate the car cabins.

Let me introduce here two definitions concerning the calculation of the average I/O ratio:

$$\overline{R_{I/O}} = \overline{\left(\frac{C_{int}}{C_{ext}}\right)} \qquad (1)$$

$$R_{\overline{I}/\overline{O}} = \frac{\overline{C_{int}}}{\overline{C_{ext}}} \qquad (2)$$

The first (Equ. 1) is the average of the instantaneous ratios (i.e. the overall average of in-cabin to outdoor concentration ratio, which is measured every 10s. The second mean ratio is the ratio of the mean in-cabin concentration to the mean outdoor concentration that is usually presented in different studies).

The difference between the two ratios is that the average instantaneous ratio $\overline{R_{I/O}}$ is indicated to characterize the infiltration process, for example when characterizing cabin filters. The $R_{\overline{I/O}}$ is the ratio of the mean in-cabin concentration to the mean outdoor concentration. Since it considers the mean concentrations measured during the entire trip, it makes it possible to assess the exposure of the passengers and hence is more indicated for this purpose.

The mean ratios of the whole single vehicle (Kangoo) measurement campaign are given in the table below:

Pollutant	Value	C_{in} (µg/m³) [(#/cm³) for PN]	C_{out} (µg/m³) [(#/cm³) for PN]	(I/O) Ratio ($\overline{R_{I/O}}$ for the average value)	Average (I/O) Ratio $R_{\overline{I/O}}$
NO_2	Average	80	117	0.82	0.68
	Maximum	1457	4757	50.00	-
PN	Average	42,000	44,000	1.11	0.95
	Maximum	391,000	421,000	24.18	-
PM_{10}	Average	27	28	1.07	0.96
	Maximum	582	1760	16.17	-
$PM_{2.5}$	Average	26	25	1.10	1.04
	Maximum	1760	1760	8.60	

Table 1: I/O concentration ratios obtained for different pollutants for the entire single vehicle on-board measurement campaign

We notice that, depending on pollutant type, average values can be greater than one, meaning that passengers can be more exposed than if they were outside the car cabin. We can observe that the $R_{\overline{I}/\overline{O}}$ ratio for NO_2, PN and PM10, unlike the average instantaneous ratio ($\overline{R_{I/O}}$), is smaller than 1. This is particularly the case for NO_2, which is 0.68, meaning that passengers are less exposed to NO_2 in the vehicle even if the ventilation mode is set to OA.

Besides the vehicle internal parameters, the external ones, such as road type, traffic density or meteorology, can also influence the I/O concentration ratio. Fruin et al.[21] conducted an extensive campaign of outdoor pollutant levels characterization where PM (particle mass concentration), UFP (particle number concentration), NOx, CO and CO_2 were measured. They showed that the roadway segment type (freeways, tunnels, arterial road) had the biggest influence on the PM, UFP and NO concentration variabilities. This conclusion also resulted from the CAPTIHV project. Indeed, tunnels increased outdoor and in-cabin concentrations by a factor of 1.6 and 1.9 respectively for NO_2 and by a factor of 2 for PN. Moreover, the time spent in the tunnel has an influence on this factor: the more time we spend in the tunnel, the higher the increase in concentrations (*figure 4*). Hence tunnels have a strong impact on I/O ratios and this finding was noticed in Kaminsky[22]. Besides tunnels, the CAPTIHV project showed that the Parisian ring road also has a strong influence. It increased in-cabin and outdoor concentrations for the above-cited pollutants by a factor of 1.6.

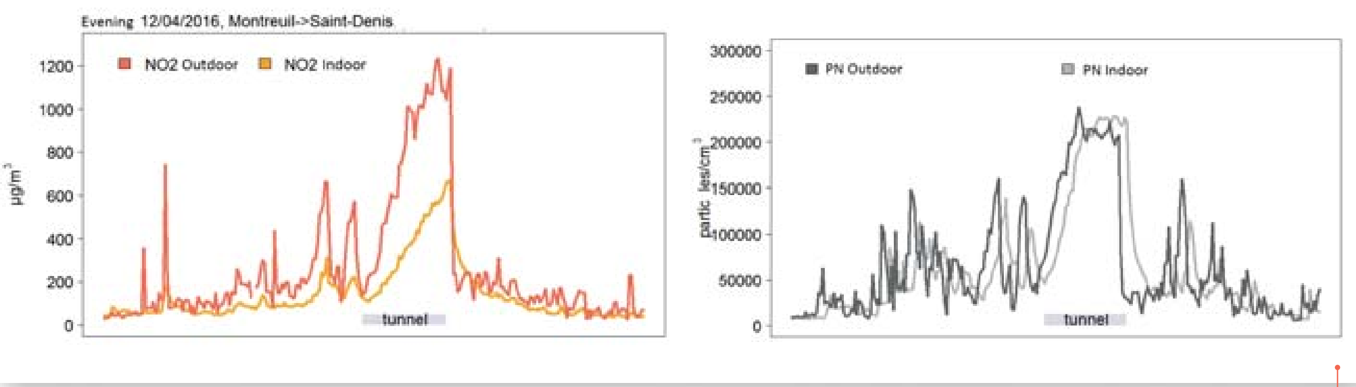

Figure 4 - Time evolution of in-cabin and outdoor concentrations for NO_2 and PN during a typical route including a tunnel

The on-board measurements using two successive vehicles also made it possible to assess the influence of inter-vehicular distance on I/O ratios. As the topology of the car wake flow is dependent on the distance from the upstream vehicle, this has an impact on particle dynamics and hence on their infiltration. This has also been investigated in a detailed manner using wind tunnel tests (next paragraph).

From on-board measurements, time evolution of the concentrations inside and outside the vehicle cabin as well as I/O concentration ratios were obtained. Typical results are presented in Figure 2 for NOx and in Figure 3 for UFP.

ACTUAL SITUATION CONCERNING THE IMPACT OF FLOW TOPOLOGY ON UFP INFILTRATION IN CAR CABINS

To understand the proximity of different moving vehicles and specifically vehicle inter-gap distances, measurements achieved in wind tunnels make it possible to characterize in a more detailed manner the link between flow topology and UFP dispersion/infiltration mechanisms.

First of all, Figure 5 shows the flow topology in the wake flow of the upstream Ahmed body model. Two counter rotating vortices, which constitute what is called the recirculation zone, can be seen.

The ultrafine particles emitted from the Ahmed body tailpipe interact with those vortices, which in turn influence the dynamics of the particles and hence their dispersion. The concentrations are presented in terms of non-dimensional concentration in Figure 6. In the recirculation zone, UFP vertical dispersion is enhanced due to the presence of these vortices (*figure 6*). As expected, the maximum concentration position corresponds to the tailpipe exhaust point.

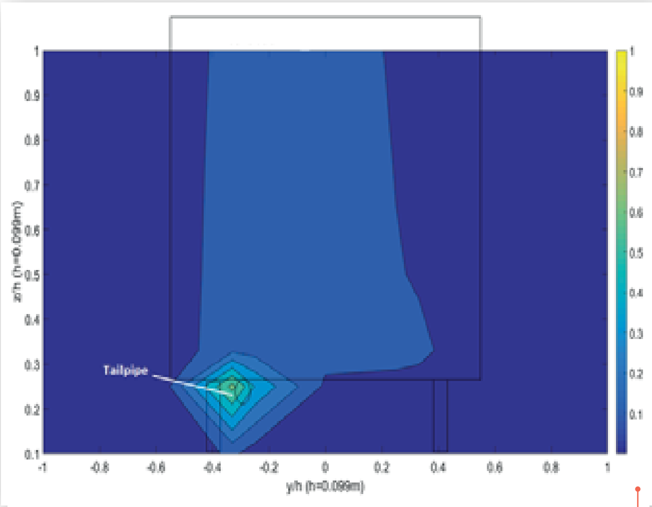

Figure 6 - Particles Number Concentrations field In the yz plane at a distance of x/H=0.5 from the rear of the Ahmed body model

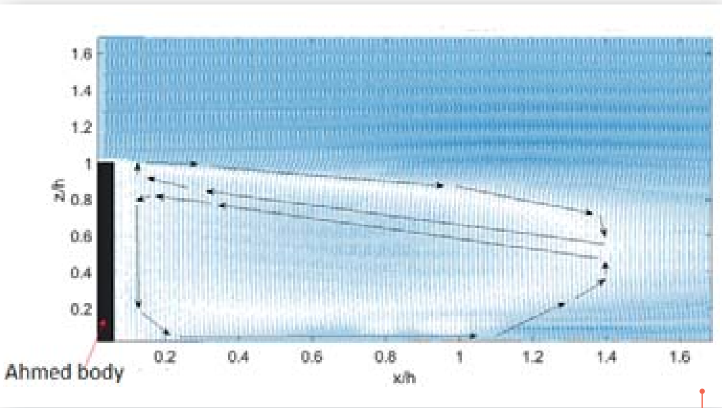

Figure 5 - Wake flow topology of the squareback Ahmed body

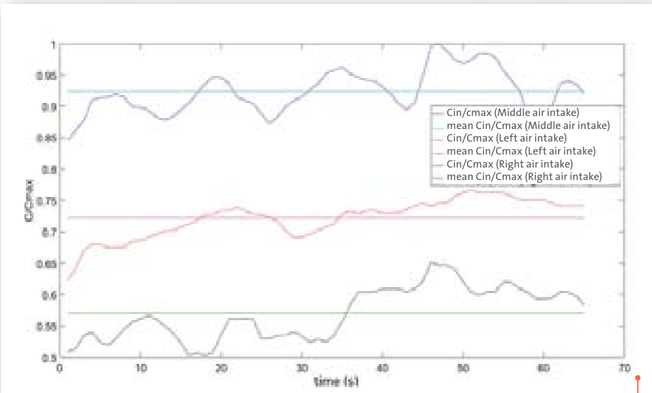

Figure 7 - Influence of the air intake position on non-dimensional indoor Particles Number Concentrations

The downstream Mira model is fitted with three air intakes. They were opened individually and the concentration measurements were achieved outside and inside the Mira model to obtain the outdoor/indoor concentrations. The results revealed that the air intake position has an influence on the infiltration process. Indeed, in Figure 7, the non-dimensional concentration is higher for the central (middle) air intake than for the left one and finally when the right one is opened. This can be explained by the PNC distribution, which showed that UFP are dispersed vertically then accumulate in the recirculation zone before diffusing in the longitudinal and transversal directions.

CONCLUSION

Car cabin pollution is due to internal pollutant emissions and external ones infiltrating vehicle car cabins, mostly NOx, CO, CO_2, UFP, PM and specific VOC (BTEX). In both cases, vehicle internal parameters such as window position and vehicle age and in particular ventilation mode and fan strength can influence in-cabin pollutant concentrations. On the other hand, the pollutant infiltration process is influenced both by the same internal parameters and by external ones such as traffic type and density, road types (tunnels, etc.), and the type and speed of vehicles ahead (upstream of the test car).

In our studies, particularly the CAPTIHV project, two approaches were used to investigate the dispersion and infiltration of gaseous and particulate pollutants inside vehicle cabins. From wind tunnel measurements, we were able to get access to the concentration distributions of pollutants issued from the tailpipes of a car model. These are strongly correlated with the near-wake turbulent flow, which depends on car-specific aerodynamics. The infiltration process was studied by conducting on-board measurements but also wind tunnel tests using a model with a hollow interior and three air intakes in different positions. It has been shown that pollutant infiltration, particularly for UFP, depends on vehicle inter-gap distances but also on the air intake position.

This shows that improving car cabin air quality could be complex and that it requires more experiments and simulations at different scales (local, upstream or cabin internal zones) to improve our knowledge and hence to implement efficient solutions for cleaner air in car cabins.

Meanwhile, some recommendations could be set out: when driving in dense traffic or on certain types of infrastructure (i.e. tunnels), it is recommended to switch on the recirculation mode for the air ventilation. However, it is better not to keep it activated for more than 15 minutes. Indeed, the CO_2 in-cabin concentration becomes high, which is not recommended when driving. Finally, it is recommended to keep a distance of at least 5 meters with the vehicle in front of us to minimize pollutant infiltration.

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2. ACTING FOR HEALTHY INDOOR AIR: FROM MEASUREMENT TO REMEDIATION

Numerous solutions are emerging to tackle the challenges of indoor air quality, whether industry-wide approaches such as those of the construction sector, innovative technological solutions using artificial intelligence or sensors, or mechanisms based on biological remediation.

BUILD BETTER TO BREATHE BETTER

A first approach to the challenges of indoor air quality is a technical one, that primarily concerns the construction industry. Construction is a sector with a large action potential on issues relating to indoor air quality. The industry is striving to reduce pollution at the source as well as developing labels to guarantee the ability of various materials and processes in providing good indoor air quality. Austrian architect Dietmar Feichtinger explains that preventing poor air quality starts at the design phase. The specific constraints and requirements of a building and characteristics of its future occupants have to be examined closely to suggest remediation solutions that are both appropriate and correctly scaled.

COMBINING ENERGY EFFICIENCY WITH HEALTHY BUILDINGS

Improving the energy performance of buildings requires increasing airtightness. However, this should not come at the expense of indoor air quality. The keys lie in conciliating energy efficiency targets with the chemical, biological and particulate parameters of indoor air quality, throughout the operational life of a building. The approach championed by OFIS Veolia, presented by Sabine Fauquez and Frédéric Bouvier, rests on three pillars: continuous assessment of air quality; management of ventilation and air treatment installations; and involvement of building occupants in improving indoor air quality. Projects run by OFIS in schools in France and the Czech Republic have proven highly instructive.

WHETHER DATA OR BIOLOGY, SCIENCE IS AT THE SERVICE OF AIR QUALITY

In terms of innovation, one of the central challenges consists in choosing techniques and technologies that align with a building's varied uses and deliver data that is both robust and reliable. Karine Léger, head of Airparif – an accredited non-profit whose members are economic actors, research bodies and representatives of public organizations from the Paris region – presents several initiatives designed to foster innovation impacting air quality, including the AIRLAB project for testing and assessing new approaches to measuring and treating pollution. Artificial intelligence is one area in which technology is developing, as demonstrated by AirVisual, a company founded in China by Yann Boquillod. Another complementary solution lies in using the pollution-abating properties of plants and their root microbiome. Bill Wolverton and Mark Nelson present the conclusions of studies undertaken most notably for NASA on phytoremediation, the process by which plants and their associated microorganisms absorb polluting agents to purify air and water.

Cédric Baecher, Fanny Sohui,
Leah Ball and Octave Masson,
Coordinators,
Nomadéis

MONITOR, INFORM, UNDERSTAND, INNOVATE: the role of Airparif, a non-profit organization accredited by France’s Ministry of the Environment to monitor air quality

Karine Léger,
Head of Airparif

Installation of microsensors as part of the AIRLAB Micro-Capteurs 2019 Challenge ©MTES (Ministry for the Ecological and Inclusive Transition)

Karine Léger is an environmental engineer who joined Airparif, a non-profit accredited by France’s Ministry of the Environment to monitor air quality in the Paris region, in 2001. She started as a project engineer before being appointed deputy head of communication and international policy. She was then appointed operational manager for communication, partnerships and digital, a role in which she helped to develop new specialist practices and extend Airparif’s activities into the international field. She was coordinator for the Citeair II project that enabled the emergence of a pan-European real-time index for assessing air quality.[1] Karine Léger was appointed head of Airparif in 2018.

In France, ambient air quality monitoring is conducted by independent non-profit bodies accredited by government authorities. Airparif’s main role is to track and analyze atmospheric phenomena (both over the long term and for episodic pollution events), help policymakers formulate action plans, foster innovation and inform various stakeholders.

The challenges of air quality are of particular importance in cities. Indoor air pollution is an often-forgotten issue in the field of air quality, since the general public is far more aware of atmospheric pollution than of pollution inside buildings. However, due to the accumulation of different pollutants and the fact that indoor air quality depends on outdoor air quality, indoor air quality actually tends to be worse than outside. This issue is especially important given that we spend around 80% of our time in closed spaces.

To meet these challenges, Airparif supports innovation via AIRLAB, a platform through which economic actors, research bodies and representatives from public organizations seek to test and assess innovative pollution measurement and treatment approaches. For example, one AIRLAB project relating to indoor air quality involves testing different categories of microsensors used indoors to give users unbiased information about the product’s suitability for its intended application. Airparif also provides ad hoc assistance to public bodies, at their request, to carry out measurements and provide consultancy services used to validate and interpret indoor air quality data obtained from sensitive locations, such as buildings used by particularly vulnerable members of the public. Lastly, its work also seeks to characterize the air pollution that people living in the Paris region are exposed to, incorporating existing work and data on indoor air quality.

1 The project website at www.airqualitynow.eu offers online air quality forecasts, is available in over 10 languages and accessible via social media and mobile apps.

Tell us a little about Airparif

Karine Léger: Airparif was founded in 1979. It is an independent non-profit organization whose mission is to monitor and provide information about ambient air quality in the Paris region. It is accredited by the Ministry of the Environment. Representatives from various sectors involved in the problem of air pollution sit on its executive board and are divided into four equal groups: state representatives (prefect of the Île-de-France region, Paris police prefect, Ministry of the Environment, etc.); representatives from various layers of local government (regional council, Paris city council, regional transport authority, etc.); economic actors (industries liable for the GTPA pollution tax[2] that are members of the AIRASIF collective: Air Liquide, Faurecia, EDF, Engie, Icade, Veolia, Enedis, etc.); and, lastly, accredited environmental protection non-profits (France Nature Environnement, Friends of the Earth, WWF France, Respire) and consumer protection non-profits along with well-known figures and non-profits with relevant expertise, such as representatives from the medical or research world.

The greater Paris region is home to over 10 million people, highly built up and with heavy road traffic, such that it is deeply affected by air pollution issues. Airparif acts in a variety of ways to ensure that "everybody has the right to breathe air that does not harm health," as enshrined in the Law on Air and Rational Energy Use (LAREU).[3] First of all, Airparif monitors pollution across the metropolitan area on a daily basis. With a full suite of technical tools (71 monitoring stations, modeling tools, measurement campaigns and an emissions inventory), 65 staff members and an annual budget of €8.5 million in 2016, Airparif records and maps 6 million locations across the region every hour. Our modeling work plays a determining role.

Modeling is used:

- as a decision-support tool for forecasters;
- to assess the impact of measures taken or planned by regional authorities;
- to provide content for daily updates;
- each year to calculate the size of the territory and the number of people exposed to levels above legal thresholds;
- for apps such as Itiner'air[4] used by walkers and cyclists to choose routes less exposed to pollution.

Indoor air quality is an often-forgotten issue in the field of air quality

How is Airparif involved with indoor air quality?

K. L.: In terms of indoor air quality, actions run by Airparif tend to be *ad hoc* and specific, complementary to actions run by other stakeholders such as consultancies and specialist observatories such as the Observatory for Indoor Air Quality. This might also take the form of working with a region, administrative department or public body that has collected air quality data within a certain context and is looking for the expertise needed to validate and interpret the data it has gathered. Airparif analyzes different contexts, takes additional air quality measurements and uses them to provide an objective framework for the data presented initially. In order to warrant accuracy of the measurements made and to respond to demands from residents and local authorities, Airparif is engaged in a quality management process that led to an ISO 9001 certification and an ISO/IEC 17025 Laboratory Accreditation. Its role as a trusted third party is part of its DNA.

Airparif also works with the Ministry of the Environment to help draft standardized national protocols for air quality inspections and data analysis, to be adopted by all France's accredited air quality monitoring non-profits.

Have you seen a change in people's attitudes towards air quality?

K. L.: Climate change has been on center stage for many years. More recently, air pollution has emerged as the biggest environmental concern among the general public due to its impacts on health, the economy and the environment. Atmospheric pollution and the climate crisis are two sides of the same problem, leading to especially severe consequences in cities such as Beijing, Buenos Aires, Hanoi and Teheran. Airparif has entered into cooperation agreements with these cities, whose attractivity is majorly impacted by poor air quality. The cardiovascular, respiratory and cerebral health impacts of this form of pollution have been well documented for years and can no longer be ignored. All these elements converge, leading many actors to adopt a position on this issue: improving air quality has become a major concern for international institutions such as the WHO, OECD and UNICEF. Major NGOs like Greenpeace are also raising public awareness of the issue. The same applies to national governments: the USA, for instance, has fitted sensors to monitor air quality in its embassies and consulates in a number of countries, the idea being that they can then inform their expatriates. Even space agencies are getting involved by measuring atmospheric pollution and supplying satellite data.

2 General tax on polluting activities.

3 This framework law enacted on December 30, 1996 aims to rationalize energy use and define a public policy incorporating air quality into urban development. Everybody has the right to breathe air that does not harm health. It is codified in the French Environmental Code.

4 https://www.airparif.asso.fr/actualite/detail/id/175 (in French)

Air quality training workshops for high school students

Despite this, much progress remains to be made. If we look at the French situation, the Report on Public Policies for the Prevention of Air Pollution[5] published in January 2016 by the Cour des Comptes [National Audit Court] noted the lack of a coherent national policy, with layers of uncoordinated actions accompanying the application of various EU directives. The report identifies inconsistencies between budgets, available actions, visibility, strategies, and so on. For instance, the government encourages the use of diesel fuel and wood-fired heating despite the known harm they cause. The situation is the same at the local level: air quality in the Paris region is getting better but too many people are still regularly exposed to levels of pollution that exceed WHO recommendations.

Indoor air pollution is an often-forgotten issue in the field of air quality: the public continues to believe that we are protected from pollution if we stay inside buildings, despite the fact that indoor air can be even more polluted than outside air. It's a matter of simple logic: on top of outdoor pollution, we add the pollution emitted by maintenance products, construction materials, different coverings and coatings, as well as that emitted by heating systems and lifestyles. This same sense of secondary importance is clear in public policies: budgets for monitoring indoor air quality are decreasing, both locally and nationally.

What are the impacts and issues raised by new technologies, particularly microsensors?

K. L.: Air is an emerging market with a worldwide scope, which is attracting a lot of investment from a number of economic actors. This trend is underpinned by the fact that the growth of environmental technologies, digital convergence, the rise of connected objects and the number of French actors highly engaged in these fields are generating new opportunities for monitoring and improving air. The biggest challenge with new technologies and microsensors is that data quality remains very uneven and that these solutions are not suitable for all types of uses.

Airparif has responded by creating a Lab[6] of which Veolia is one of the founding partners. AIRLAB is a platform that promotes open and collaborative innovation among an ecosystem of businesses, research institutes, and local and national authorities[7]. AIRLAB seeks to foster innovation and assess the impact of new solutions that may be rolled out in the near future on air quality. The platform adopts a highly original approach, centering on project assessments, which are required to demonstrate that they reduce pollution and protect the climate. To achieve this, Airparif provides its technical expertise and its monitoring tools. AIRLAB fosters the development, experimentation and evaluation of air quality solutions in the Paris region. Its mission also involves encouraging the diffusion of expertise nationally and internationally in the fields of city logistics, air quality in buildings, street furniture, heating, public information, mobility and citizen engagement with the issue of air quality. For indoor air quality, AIRLAB is host to a project developed by Veolia and Icade, exploring the use of microsensors to measure air quality and promote good practices and new solutions: ventilation, indoor air recycling, relative humidity management , measures of CO_2, particulates and volatile organic compounds.

Airparif has also recently launched its second microsensors Challenge, "*AIRLAB Micro-Capteurs 2019* [8]" an event run in partnership with a number of French and international partners including the French Development Agency (AFD), the French development aid agency, the Swiss Federal Materials Testing and Research Laboratory and the World Meteorological Organization. The Challenge serves a twofold purpose because it makes it possible to:

Air is an emerging market with a worldwide scope, which is attracting a lot of investment from a number of economic actors

1/ compare different air quality sensors in order to give potential users independent information about whether the product

5 https://www.ccomptes.fr/en/publications/public-policies-prevention-air-pollution

6 http://www.airlab.solutions/en/discover

7 Ile-de-France region, Paris city council, Grand Paris Metropole, the regional prefecture, Ile-de-France Mobilités, SNCF Logistics, Air Liquide, Icade, Citelum (EDF Group), Engie France networks and Veolia.

8 https://www.airparif.fr/actualite/detail/id/261 (in French)

Experiments with microsensors as part of the AIRLAB microsensors 2018 Challenge

is suitable for their intended use (outdoor air, indoor air, transportation, etc.);

2/ highlight the qualities of these devices and suggest areas for improvement in order to stimulate innovation as well as disruptive technologies in this field and help grow the market.

The Challenge also gives project developers and companies a chance to position themselves against the competition. Airparif tries to assess the efficiency of microsensors in a number of ways that relate to how the device operates and to its data acquisition modes: all in all, sensors are assessed according to 46 separate parameters.

Microsensors offer real advantages and opportunities – they are tools that can be used to raise public awareness and trigger behavioral change. In 2018, over 800 high school students from 23 schools in the Paris region worked on air quality as part of a program called "Taking Hold of Our Air",[9] during the course of which they were provided with sensors and an educational pack.

For outdoor air, especially when on the move, questions remain regarding the extent to which these microsensors can be used to supplement official measurement systems. This is due to the fluctuating reliability of measurements from device to device and over time, as well as the way in which they react to different pollutants depending on the components being measured and variations in temperature and humidity. Other important challenges include data processing, censor calibration and the development of data correction algorithms to allow for margins of error in measurement. Other unknowns and things to watch out for are sensor lifespan (12 to 18 months on average, sometimes less depending on the conditions they are used in) and the energy needed to process and store the data gathered (which has to be evaluated in light of the sensor's environmental performance). Reliability, accuracy, ease of use, cost, etc., are all parameters that Airparif aims to evaluate so we can provide information that is as accurate as possible and make recommendations tailored to the user's specific requirements, uses, resources and characteristics.

9 http://www.driee.ile-de-france.developpement-durable.gouv.fr/lyceens-collegiens-prenons-notre-air-en-main-r1538.html (in French)

ARCHITECTURE AND THE CHALLENGES OF INDOOR AIR QUALITY

Dietmar Feichtinger
Architect, Feichtinger Architectes

Pilot project to extend the French Lycée and renovate the Studio Molière in Vienna, Austria (2016) ©Dietmar Feichtinger Architectes

As an architect who designs buildings and engineering structures, Dietmar Feichtinger feels that architecture is an art that must serve wellbeing. After graduating in 1988 from the University of Graz in Austria, he started working in France in 1989. He began as a project leader with Philippe Chaix and Jean-Paul Morel, then founded Dietmar Feichtinger Architectes in 1994. The firm has led a number of award-winning projects in France and Austria, including the Simone-de-Beauvoir footbridge in 2006 (Equerre d'Argent, commended; Mies van der Rohe Award 2007, nomination; Footbridge Award), the Lucie Aubrac school complex in Nanterre in 2012 (Equerre d'Argent, commended) and the Mont-Saint-Michel jetty in 2015 (Equerre d'Argent for an engineering structure, Trophée Eiffel for steel architecture).

When designing a building, the indoor air quality solutions proposed must reflect specific contexts and uses. Choices and trade-offs in terms of ventilation systems and the volume and rate of air flow are heavily conditioned by the type of building in question. There is no ready-made response. Constraints and imperatives have to be examined in great detail so that appropriately scaled corrective solutions can be suggested.

The quality of indoor air depends on a great many factors. Beyond a building's technical characteristics, improving indoor air quality necessarily involves ambitious measures to cut outdoor pollution. But it also requires efforts to raise awareness and alter habits and behaviors in the ways a building is used every day.

We can identify two core challenges that relate to air quality in future construction projects: the difficulty in putting forward a solution that matches the requirements as well as the comfort-tolerance levels of all users combined with increasing litigiousness when it comes to air quality; and how we go about combining high-tech with low-tech to limit our dependence on all-electronic solutions. However, thinking about these issues must not lead us to arrangements that make no sense from an architectural standpoint, which can happen in other building-related areas, such as energy efficiency. One approach might be to focus on simplicity and coherency; every construction or renovation project must seek out the essentials, favoring raw materials and respecting their fundamental nature.

How does air quality interact with other challenges inherent to an architectural project?

Dietmar Feichtinger: The difficulty in an architectural project lies in striking a balance between various competing constraints. A building's primary function is to provide space for use as housing, offices, open space, public reception areas and so on, or a combination of these uses. It has to be integrated into a specific space as well as fit in with its immediate environment.

The trend in recent years has been to overemphasize energy performance and thermal insulation. There is nothing wrong with this as such, because mistakes were made in the past involving use of materials with a large environmental footprint or that did not sufficiently reflect the importance of energy efficiency. But we've ended up leaning too far the other way, with public sector clients now specifying energy-positive buildings that generate more energy than they consume. What's the point of constructing a building that behaves like a battery? Overemphasizing energy performance can negatively impact occupants' comfort and experience, for example, by heavily restricting the amount of natural light in a building. Another example is that, for reasons to do with HQE criteria,[1] you may consider positioning a building entrance on the southern façade to limit energy losses. But if the street address is on the north side, this is not an option.

This is the danger of becoming overly specialized and too focused on energy performance alone. Thinking in silos can lead to situations that don't add up. The value-added that architects bring lies precisely in incorporating all the elements and coming up with a coherent solution, something achieved through a holistic approach.

Architecture is regularly prey to fashion and trends that, taken to extremes, lead to exactly the opposite of the original intention. This means that we need to remain reasonable and look ahead to see where the limits may lie. In the 1980s through to the 2000s, office buildings were very energy-hungry, heavily glazed and mechanized, leaving occupants with very little room for maneuver. The opposite applies today: people want windows that open and materials that reassure, such as wood. But we need to understand that the next set of challenges in architecture will very likely center on very tall buildings, because of skyrocketing land values. Wood, although a reliable structural material perfectly suited to traditional homes, cannot bridge large spans and questions remain about its behavior when used in high-rise constructions, for example concerning its deflection behavior.

There is no one ready-made answer and air quality, like everything else, needs to be studied case by case if a suitable solution is to be identified.

Indoor air quality depends on so many factors: the materials used in the building's structure as well as its equipment, the ventilation system and how occupants behave

How do you think about air quality when designing a project? What are the aspects and decision-making criteria to consider?

D. F.: Solutions for indoor air quality must reflect specific contexts and uses. There are places where we live, and other places that we visit for shorter periods. You're not going to propose the same ventilation system for a performance space that hosts large crowds for a short time as for an office building that is occupied all day but with endlessly varying rates of occupancy. In the first case, you need a very powerful system able to filter and supply quality air to a large space. The second case demands a tailored approach. You have to analyze in great detail how each room in the building will be used so that you can propose suitably scaled corrective solutions, avoiding needless energy use while guaranteeing optimum air quality.

One interesting example we worked on dealt with indoor air quality in schools. This is an important issue when you consider that it has been shown that overly high concentrations of pollutants, particularly CO_2, caused by poor ventilation have an adverse impact on children's cognitive capacities. But most current solutions have their drawbacks, either in the form of excessive energy use when the ventilation system runs night and day, even when there are no classes, or as degraded air quality because of poor maintenance leading to clogged filters. The reality is that the most effective solutions look nothing like people's expectations: countless ventilation systems are hidden behind suspended ceilings, creating an illusion of cleanliness. But these systems are actually hotbeds of bacteria and dust, hard to reach and difficult to maintain. We advocate exposed ducting as it makes maintenance easier.

Returning to the issue of schools, we designed a hybrid solution for a pilot project, one that combines cutting-edge technology — an automated dual-flow ventilation system in each classroom — with giving teachers the ability to open windows to the outside if they want to. What we propose combines two key strategies: 1/ treating every room separately, each with its own appropriately sized ventilation system, 2/ automating part of the ventilation system while also leaving space for people to intervene.

1 An HQE (High Quality Environmental standard) building is one where environmental criteria are designed-in from the start of the construction or renovation process. HQE is not really a label based on regulatory standards, it is simply a quality process led by a set of guidelines. Established in France in 2002 by the HQE non-profit that oversees the trade name, the HQE™ approach gradually evolves as guidelines are revised and updated. Aligned with the principles of sustainable construction, or ecoconstruction, an HQE building must provide optimum comfort for its occupants while also respecting the environment, being cost-effective to operate and delivering high-level energy performance.

Pilot project to extend the French Lycée and renovate the Studio Molière in Vienna, Austria (2016) ©Dietmar Feichtinger Architectes

How can a building's air quality be improved?

D. F.: It's a vast question. Indoor air quality depends on so many factors: the materials used in the building's structure as well as its equipment, the ventilation system, how occupants behave and, above all, you have to bear in mind that the quality of indoor air is extremely dependent on the quality of outdoor air. This is absolutely central.

Is the best driver for better indoor air quality simply better outdoor air quality?

D. F.: There's no denying that better air quality can only be delivered through ambitious measures to reduce outdoor pollution. I feel this is something that has to be looked at when thinking about what the city should be like, favoring initiatives like the one in Bratislava, capital of Slovakia, a small city of approximately 420,000 that has banned cars from its center. But it requires political courage.

In terms of buildings themselves, it is important to understand that the keys do not lie in the design stage alone, you also have to take account of how buildings are used. You might have a building that has been extremely well thought out and built to optimize air quality, but if toxic cleaning products are used in it every day then your efforts will all be in vain. This underlines how important it is to raise awareness and alter habits and behaviors.

The keys do not lie in the design stage alone, you also have to take account of how buildings are used

What are the coming air quality challenges that construction projects will face?

D. F.: The first challenge I see centers on people's ever-increasing awareness of nuisances, making it harder to propose solutions that meet everybody's requirements without impinging on their wellbeing and tolerance thresholds. Some people feel cold very quickly if the ventilation is too powerful or a window is left open, others find it oppressive if windows are firmly shut all the time. This inevitably becomes complex as soon as both categories of people have to share the same space. At a hospital where we worked, the solution was to provide individual air nozzles for each bed. But it's not always possible to offer these types of solution in every situation, and they come at a price. This brings us to the question of equal rights to breathe good quality air, but also to the challenges of ever-greater litigiousness when it comes to air quality: at some private schools, parents are starting to raise the possibility of schools being responsible for a pupil failing an examination on the basis that the quality of the air was inadequate.

Pilot project to extend the French Lycée and renovate the Studio Molière in Vienna, Austria (2016) ©Dietmar Feichtinger Architectes

The second issue revolves around the current trend that tries to measure and control everything, with all the excesses this can entail. In air quality, this takes the form of the increasing trend to fit sensors to measure the concentration of pollutants in a building. I think these technologies are valuable for identifying the cause of pollution and finding solutions. However, they should not dictate how occupants behave, nor should they cause people to experience feelings of stress. Imagine the situation in a classroom if teachers regularly see red warning lights indicating that toxicity thresholds have been exceeded. It would be a major source of anxiety and very disruptive, as well as utterly counter-productive.

[There arises] the question of equal rights to breathe good quality air, but also [that of] the challenges of ever-greater litigiousness when it comes to indoor air quality

All of this points to the need to look for ways to combine high-tech with low-tech, limiting our reliance on all-electronic solutions. One approach might be to focus on simplicity and coherency. Every construction or renovation project must seek out the essentials, favoring raw materials and respecting their fundamental nature. This principle of simplicity delivers a number of positives: it limits toxic components, solvents and paints that damage air quality and restrict the technical performance of materials, and it facilitates the deconstruction and reuse necessary for sustainability. It's a virtuous model.

FROM IDENTIFYING TO ACTING: HOW TO GUARANTEE GOOD QUALITY AIR IN BUILDINGS

Sabine Fauquez
Head of Veolia's Air Expertise Cluster and CEO of OFIS

Frédéric Bouvier
Air Expertise Cluster Director, Veolia

Veolia's R&D teams are studying solutions targeting specific air quality problems, in partnership with leading research institutions

Sabine Fauquez is head of Veolia's Air Expertise Cluster and CEO of OFIS, Veolia's specialist health risks engineering consultancy. She was previously COO of Endetec, the subsidiary dedicated to environmental monitoring solutions, after 10 years spent in a range of management functions with Veolia Water. Sabine Fauquez holds a doctorate in analytical chemistry from Université Pierre et Marie Curie and a diploma in general management from the Centre de Perfectionnement des Affaires.

Frédéric Bouvier joined Veolia in 2018 as Director of the Air Expertise Cluster and has been appointed COO of OFIS. From 2015 to 2018 he was CEO of the Airparif1 nonprofit, where he launched Airlab, an incubator for innovative solutions for air quality. He previously headed the Atmo Rhône-Alpes regional observatory and the Central Air Quality Surveillance Laboratory. Frédéric Bouvier trained as a chemical engineer and holds a Master's degree in business management and administration.

1 Non-profit organization that monitors and studies atmospheric pollution in the Paris region.

The massive health impacts of air pollution have gradually put it firmly in the media spotlight, and almost everything we hear about air quality these days seems to be alarmist or resigned. Moving beyond doom-mongering to solve a major portion of the problem will demand solutions that are reliable, long-lasting and deliver guaranteed results – just like the approaches used to tackle other types of hard-to-deal-with pollution such as in water, hazardous waste and ground pollution. The same applies to indoor air pollution, which is another major public health challenge because we spend over 80% of our time in enclosed spaces. This attitude reflects the idea of the exposome[2], which guides public policies seeking to cut people's day-to-day exposure at every stage of their lives. It is also a response to strong pressure from society, which prefers to think of protection in terms of individuals.

For Veolia, guaranteeing air quality in a building means addressing the issue through three complementary approaches. First, it requires polluting phenomena to be diagnosed and described, identifying the nature of this constant and invisible form of pollution, and assessing its level. This is what we do through our AIR Control service. Then the pollution has to be treated by deploying techniques appropriate to the type of remediation required, as a function of the building type. This is our AIR Performance service. Lastly, and bearing in mind the impacts of air quality on individual behavior, associating the various stakeholders is essential to obtaining lasting results. This is our AIR Human service.

Schools, office buildings, hospitals and health care facilities, shopping malls, hotels, etc. – all are concerned and all need to provide good quality air to their users and occupants. New solutions are now available that rely on optimization of air treatment units developed for operating rooms and clean rooms, as well as on new continuous measurement technologies made possible by microsensors. Two levers are needed to support widespread rollout of these solutions: research and development to achieve commercial release of ever more innovative techniques that combine air quality with optimized energy use as a cost-effective package; and stronger regulation to introduce a performance obligation that will guarantee air of good quality, a process already seen in decisions recently enacted by some countries.

2 The "exposome" is a recent term that refers to the totality of harmful environmental, behavioral and professional exposure that people are exposed to throughout their lives. The exposome is used to identify and evaluate potential health risks so that individuals can better protect themselves and societies can reduce their health care spending.

INTRODUCTION

The entire world has to face the increasing prevalence of a new type of pollution: air pollution. It has emerged as the number one global environmental risk and a major challenge to public health. Outstanding efforts have been made to combat air pollution but the overarching trend points to a phenomenon that is getting worse, and the policy results appear inadequate. A few recent examples illustrate the anxiety of residents who increasingly refuse to live in polluted cities. In New Delhi, demonstrations in late 2016 protested slowness of government reaction to a toxic cloud that hung over the city for a week; China has seen over 500 daily protests against pollution since 2015; in Brussels, families have taken to the streets to demand action to fight air pollution, and so on.

Deliverable solutions exist for integrated comprehensive management of indoor air quality for public and private sector buildings

Authorities are starting to react at all levels. At the global level, the World Health Organization is currently drafting a new roadmap to strengthen the fight against air pollution and its causes[3]. At supranational level, legal action has been taken by the European Commission against countries that have failed to meet the requirements of the ambient air quality directives. At national level, states are tightening their legislation. China, for example, has made it a crime to manipulate air quality data. Municipalities and industrial companies are moving toward economic models that are cleaner, greener and less carbon intensive, with policies aiming to ensure that urban and industrial growth is compatible with protecting the environment.

Veolia has built up expertise to protect the health and wellbeing of residents. In terms of air quality, its know-how has existed for years, whether suppressing bad smells from sewage plants, scrubbing flue gas emissions and capturing volatile organic compounds from industrial activities, guaranteeing clean air in white rooms and hospital operating rooms, or running diagnoses and audits on air quality.

But much remains to be done and two macro levers must be considered. First is eradication of the sources of polluting emissions via upstream emission reduction and the development of business activities for modeling and measuring air quality, to evaluate the effects. The second concerns protection for people in enclosed spaces through the promotion of ventilation and filtration systems, indoor air pollution treatment and realignment of energy-efficiency regulations with health standards.

3 See the article by Maria Neira: Energy Transition for Better Air Quality: a Public Health Challenge

WHAT SOLUTIONS ARE THERE FOR IMPROVING INDOOR AIR QUALITY?

Expectations for indoor air quality are growing, in Europe in particular. In technical terms, increasing the impermeability to air of building envelopes – a corollary to the commitment to halve end-user energy consumption by 2050[4] – requires extremely precise and effective management of ventilation systems if good quality indoor air is to be maintained and Sick Building Syndrome avoided[5].

Rising demands are also being made by civil society. Issues of air quality are increasingly central to residents' and governments' preoccupations, as highlighted by Elabe's 2019 study of indoor air quality[6].

For a number of years, Veolia's research and innovation teams have been studying and creating solutions to three challenges:

- how to protect employees who are potentially exposed to inhalation of atmospheric pollutants;
- how to manage installations to maximize indoor air quality and energy efficiency;
- how to deliver solutions to specific problems raised by air quality.

Working in partnership with leading French research institutions such as Ineris, ANSES and Inserm, several tools have been developed to cut the exposure to chemicals of our employees and those of our clients in offices, hospitals and industrial sites. Internationally (Université Laval, Quebec, Canada ; Hong Kong University of Science and Technology, etc.), we have defined methods for reconciling energy efficiency with indoor air quality, including for chemical, biological and particulate contamination, during both the design and operational phases of ventilation and air treatment installations. There have also been innovations to help operational employees, particularly regarding predictive maintenance of air treatment units. Lastly, studies into the effectiveness of anti-bacterial coatings have made it possible to improve existing installations, and tools for monitoring and modeling emissions into the air, including bad smells, have been included in the water network and equipment supervision solutions offered by Veolia.

4 As required by France's Energy Transition for Green Growth Act, August 17, 2015

5 See the article by Fabien Squinazi: Managing indoor air quality to protect occupant health.

6 "La qualité de l'air intérieur," Elabe study for Veolia carried out in France, Belgium and Greater Shanghai, June 2019. See the relevant article elsewhere in this issue.

SOLUTIONS EXIST FOR FULLY INTEGRATED MANAGEMENT (DESIGN, INSTALLATION, PILOTING AND OPERATION) OF INDOOR AIR QUALITY, IN SYNERGY WITH ENERGY SERVICES

Our research translates operationally as follows: the first action is to fit buildings with sensors that continuously monitor air quality. Numerous environmental fields are seeing an explosion in the number of connected objects, and air quality is no exception. Sensors are being fitted to a growing number of cities, buildings, vehicles, and they equip people too. However, some sensors are not as effective as others, and not all are suited to every use. In the absence of standards, calling in an independent outside body to assess their reliability is vital, all the more as these sensors will be used for piloting air treatment units. We decided to ask Airlab[7] to run laboratory approval tests. We then ran on-site validation tests of the best sensors as part of our partnership with property developer Icade and at Veolia's head office, the V building in Aubervilliers. To receive approval, sensors have to meet criteria for cost, portability, ease of use, and accuracy for piloting indoor air ventilation or recycling, and be able to measure various parameters such as hygrometry, CO_2, fine particles and volatile organic compound levels.

Monitoring as a standard feature in buildings will provide large amounts of data on indoor air and new insights that will guide future rules for designing and operating buildings

The second focus is remediation via air treatment solutions. Open Innovation at Veolia has identified a number of responses, ranging from systems to integrate into existing air treatment units to self-contained units to place in a room to provide local air treatment. The most effective apparatus is chosen by running effectiveness tests on the systems to be deployed, looking at both technical and health benefits. Just the same as the reliability of measurement instruments is not a given, some reports[8] highlight the fact that the technologies are often little-understood and subject to efficiency claims that are hard to justify. Some poorly designed purifiers can even damage indoor air quality by creating new pollutants. Innovative ventilation solutions that deliver filtered air to occupied spaces in buildings and that are simple and cost-effective to deploy were also identified and tested. These are "reverse" solutions that blow filtered air into rooms, unlike traditional one-way extraction systems. This makes pre-treatment of outdoor air possible, which is not the case with one-way extraction. These offer efficient low-cost alternatives for mid-size buildings such as small schools that do not have a central air treatment unit. These solutions are also interesting for regions where radon gas is an issue.

Deploying these types of treatments involves meeting two challenges at once: delivering significant lasting improvement to air quality, and managing energy used for ventilation. Energy management and air quality issues are in fact intertwined. Most current energy efficiency projects involve increasing insulation and lowering the rate of air renewal in buildings, leading to the risk of trapping higher concentrations of pollutants in indoor spaces. This is why it is crucial to have this twin air-energy skill set to be able to roll out projects, whether new-build or refit, that meet the environmental and health challenges for buildings.

CANADA, MONTREAL – HEALTHY AIR FOR CHUM HOSPITAL

Centre Hospitalier de l'Université de Montréal (CHUM) in Canada was founded in 1996 as a result of the merger of three establishments. As part of an energy performance contract, Veolia was chosen to support the 2016 transfer of these three establishments to a unified new site. Questions relative to indoor air quality were central to this mission, including design, assistance, operation and risk management.

Considerable work went into the rotary heat exchanger systems (thermal wheels) used by the establishment's air treatment plants. Although very efficient energy-savers, these systems can suffer from problems with new air mixing with exhaust air, leading to questions about their suitability for sensitive sites like hospitals. The studies delivered recommendations for preventative and corrective maintenance to guard against this risk. The focus now is on work to identify how best to continuously assess microbiological risks in these systems.

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7 Airlab is the air quality innovation platform run by Airparif, an accredited air monitoring non-profit where Veolia is a founder member. See the article by Karine Léger: Monitor, Inform, Understand, Innovate: the role of Airparif, a non-profit organization accredited by France's Ministry of the Environment to monitor air quality.

8 2017 report from ANSES: Identification and analysis of different emerging indoor air purification techniques

FRANCE – BETTER WORKING ENVIRONMENT FOR SOCIÉTÉ GÉNÉRALE BANK

OFIS, the Veolia subsidiary that specializes in audits of indoor air quality, has been helping the Société Générale banking group to improve the working environment of its staff for over 10 years. Société Générale asked it to monitor indoor air quality at its former head office and 30 other branches in Paris. Thanks to the plan of action put in place, Société Générale has been able to meet the highest air quality standards, providing optimal comfort to staff and customers.

CAN GOOD QUALITY INDOOR AIR BE GUARANTEED?

Controlling exposure to pollutants in enclosed spaces goes hand in hand with an engagement on the indoor air quality to be respected. Our goal is to work with building managers to guarantee healthy air, tied in with optimized energy management, to deliver increased wellbeing and comfort for occupants.

For Veolia, guaranteeing air quality in a building relies on approaches built around three complementary services:

- "AIR Control", covering expert knowledge, monitoring and auditing. This service is used to map the current situation and propose a plan of actions for improving air quality;
- "AIR Performance", incorporating management of technical installations combined with guaranteed air quality thresholds to meet. This is also offered as "AIR Performance Plus" in cases where capital investment is required to meet the client's air quality targets;
- "AIR Human", encouraging occupants to help meet targets. They then become actors in the solutions and their views are taken account of as part of performance criteria.

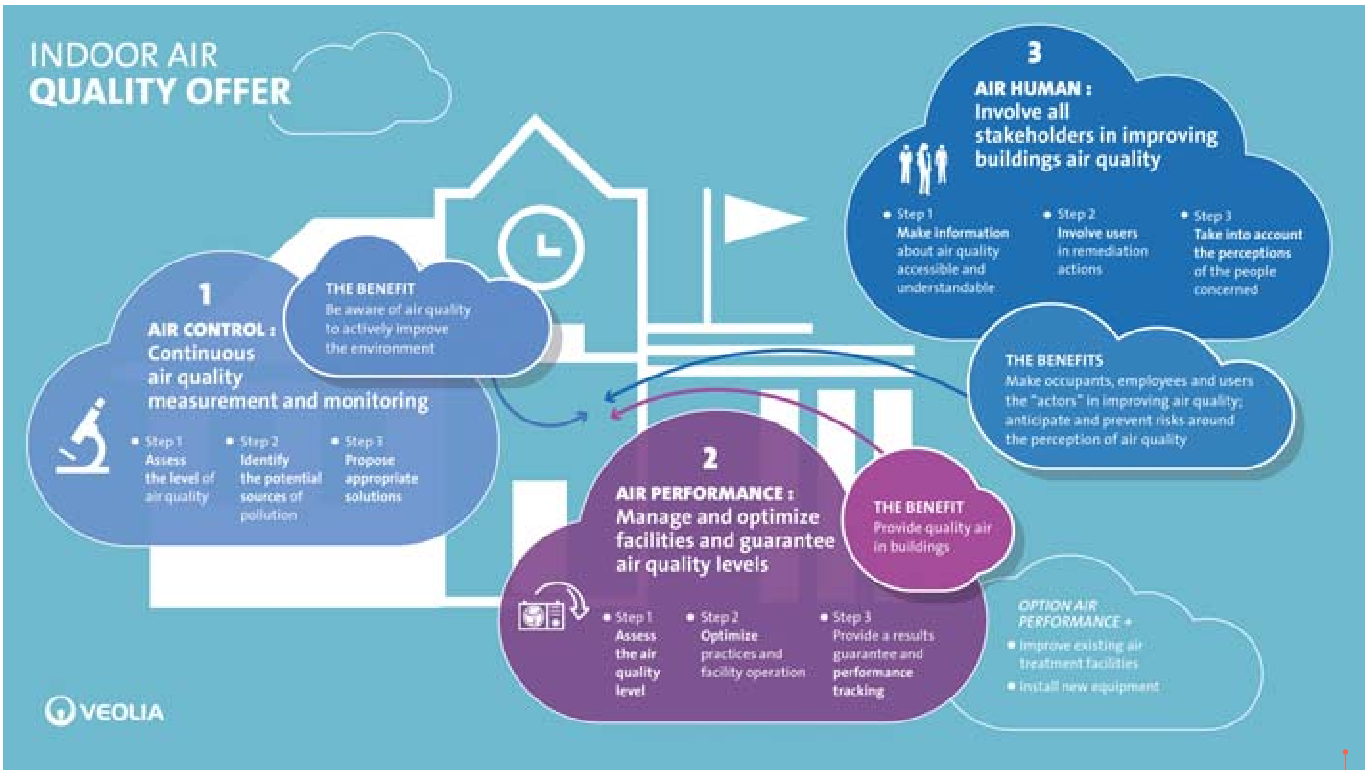


Figure 1: Veolia's three Air Quality Solutions

SINCE POOR AIR QUALITY HAS A GREATER IMPACT ON VULNERABLE PEOPLE AND CHILDREN IN PARTICULAR[9], SCHOOLS SHOULD BE PRIORITIZED

Preserving good quality classroom air is vital to learning and helping children to improve their concentration. Consequently, and for the first time in France, two schools in a municipality close to Paris *(see box)* were fitted with the new solution from Veolia (monitoring, treatment and awareness-raising). Since the start of the 2019 school year, every day almost 600 pupils and teachers breathe air that is guaranteed to meet WHO thresholds. Thresholds for fine particle concentrations[10], volatile organic compounds in the air, or the air confinement levels usually detected at most educational establishments are no longer exceeded in these two schools.

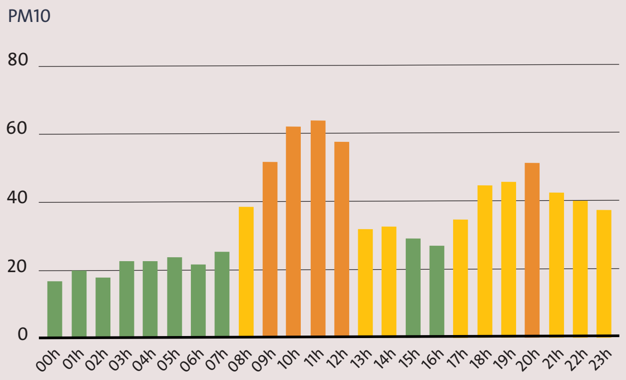
This is a major problem that can be found in many other countries, as illustrated by the example of Veolia Group teams in the Czech Republic.

9 Adults inhale 16 times a minute, compared to 40 times for children. This means that children are the most sensitive/exposed, especially as children form their respiratory system in the early stages of life.

10 In a representative study of 300 French schools, 93% of classrooms recorded concentrations of fine particles ($PM_{2.5}$) above the WHO guideline value - 2013-2017 study by Observatoire de la Qualité de l'Air Intérieur.

Particle measurements before and after use of *Air Performance*

Sep. 17, 2019 00:00 to Sep. 17, 2019 23:59



Nov. 04, 2019 00:00 to Nov. 04, 2019 23:59

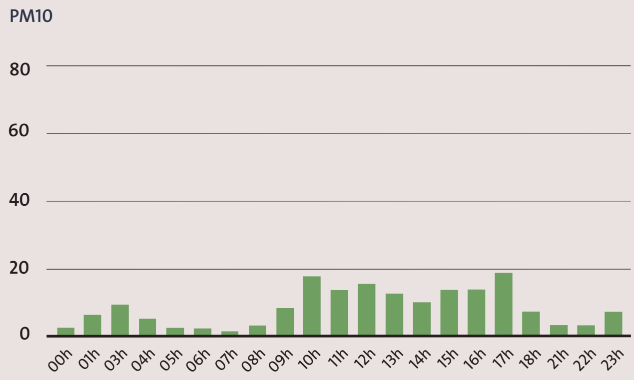
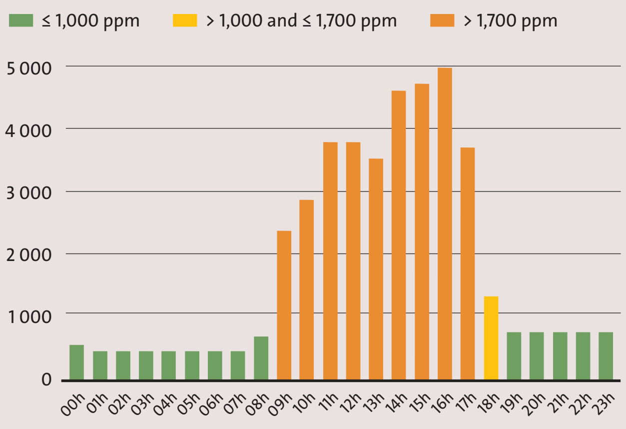


Figure 2

Measurement of CO_2 concentrations before and after use of *Air Performance*

Oct. 8, 2019 00:00 to Oct. 8, 2019 23:59



Nov. 19, 2019 00:00 to Nov. 19, 2019 23:59

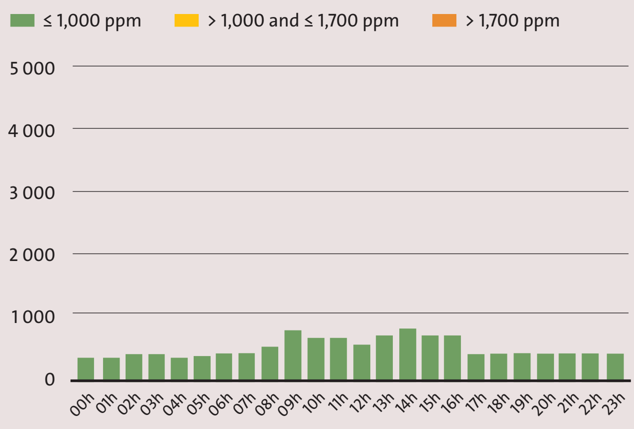


Figure 3

The same problem is to be found in many countries, as illustrated by the article on page 53 from Veolia in the Czech Republic.

Semi-centralised dual-flow air handling unit, La Fontaine elementary school (Le Raincy, France), class number 3 - © Jade Lachery

FRANCE, LE RAINCY: GUARANTEEING AIR QUALITY IN SCHOOLS

To mark France's national indoor air quality day on September 18, 2019, Le Raincy, a community of 14,000 people in the Paris region, announced an operation to deliver optimal air quality for its schools.

For Jean-Michel Genestier, mayor of Le Raincy, "a better understanding of air quality, via classroom sensors, was primordial in guaranteeing decent air to the 569 pupils at the schools involved."

Running at two elementary schools, this operation, from design to delivery, is an illustration of the three services – AIR Control, AIR Performance and AIR Human – offered by Veolia.

After auditing the buildings to identify sources of any pollutants that might be present in the classrooms, sensors chosen for their reliability were fitted to each classroom to provide continuous data about indoor air quality by measuring several parameters, including CO_2 and fine particles. The aim was to identify whether applicable regulatory thresholds were being exceeded.

Filtration and air renewal solutions were installed to guarantee pupils' air quality. These are piloted to ensure that the various air quality parameters are maintained below permissible thresholds while also optimizing energy use, as ventilation flow-rates are regulated according to real-time concentrations measured in each classroom.

And because there is more to guaranteeing air quality than just the technical aspects, experts provide advice and guidance on best practices through a set of teaching aids designed to make pupils active participants in the quality of the air they breathe at school and at home.

Lastly, in response to demands for information about air quality in schools from local politicians and residents, an indoor air quality dashboard has been created that summarizes air quality indicators in each classroom. The data is shared in total transparency with teachers and parents. Everybody is informed and aware of the positive impacts on air quality.

The solution fitted to schools in Le Raincy can be applied to other schools in France, 93% of which have high concentrations of particulate matter (exceeding WHO recommendations) and 41% have a CO_2 confinement index that is either very high or extreme.

BUILDINGS CAN BE SICK TOO: THE CASE OF THE CZECH REPUBLIC'S SCHOOLS

For many years, buildings have been undergoing insulation retrofits, where old wooden windows are replaced with plastic ones. This brings savings on heating, but the indoor air quality in sealed buildings deteriorates rapidly. This issue concerns over 60 % of schools all over the Czech Republic.

PROBLEMS WITH VENTILATION

The State Environmental Fund grants subsidies for insulating schools. "We provided support to a total of 1,200 schools and kindergartens to the tune of six billion crowns[14]." the Fund's spokesperson says, adding that more recent projects also include air conditioning.

However, school directors are now complaining that the savings made on energy are less than the new costs associated with the poor indoor air quality brought about by airtight buildings. They have to ventilate and air-condition regularly – and that costs money.

"The problem is acute, primarily in cold winter months when you cannot open windows that often to ventilate. Some children in classrooms sit near the windows and they feel cold very quickly. The other half of children do not even get a breath of fresh air because the windows are open for such a short time," says the director of a large school in Prague.

HOW HARMFUL IS A HIGHER CONCENTRATION OF CO_2?

Higher quantities of carbon dioxide affect both students and teachers – they get tired and their attention wanes.

Carbon dioxide is a natural component of ambient air, and it is a colorless and odorless gas. Living organisms produce it as a metabolite of cell breathing. In higher concentrations (>1,000 ppm) it affects human health, causing headaches, fatigue and loss of attention.

CO_2 concentration can reach about 1,500 ppm in a classroom during one lesson just due to the students and teachers breathing. After 90 minutes, it can be as high as 2,700 ppm. Increased fatigue and lack of attention become obstacles to teaching and learning.

"Our school underwent an overall insulation retrofit and window replacement a few years ago. Since then, air in classrooms gets stale much quicker and we have to ventilate more often. However, the children still get tired and sleepy. Some teachers also complain about greater fatigue," continues the school director.

Closed windows in classrooms full of children also cause a higher sickness rate. Infections are transmitted easier in environments with insufficient air replacement. Since there can be as many as thirty children in one classroom, the risk of infection is quite high. "Over time, we realised that fatigue was not the biggest problem. We did not see the connection initially; it was only after some time that we noticed the sickness rate among both students and teachers going up significantly."

HELP IS NOT EASY

Indoor air pollution is very difficult to detect just with human senses. This is why current buildings are fitted with sensors that measure the quality of the indoor environment. The sensors measure air temperature, humidity and CO_2 concentration. Based on these measurements, adequate ventilation actions are taken, preferably using an automatic system for controlled air replacement.

The current situation in many schools suggests that even regular manual ventilation is not sufficient for maintaining low CO_2 concentration levels in certain places. Automatic ventilation systems have become the only truly efficient solution for achieving user-independent low CO_2 concentrations over time.

"Having installed the detectors, we found that even opening windows frequently does not help. They say it is due to the windows being too tight," says one of the teachers. "We are currently addressing this issue intensively. Based on the available information, installing an active ventilation system is the most efficient solution to this problem. This is why we are collecting bids and we want to install the equipment in classrooms."

Thermal losses due to ventilation can be minimized using recuperation. Controlled ventilation ensures constant supply of fresh air and extraction of stale indoor air, regardless of the ambient conditions and without requiring the user's intervention. Healthy air in buildings is certainly worth the cost, though.

14 Close to 240 million euros.

SMART SYSTEMS FOR GOOD QUALITY INDOOR AIR: Interview with Martin Lang, Executive of LG Systems

Air quality in homes and schools is a hot topic these days. What are the consequences of poor indoor air quality? What's the solution? We asked Martin Lang from LG Systems Czech Republic, part of Veolia Group.

Lately, there's been much talk of worsening indoor air quality. Why is this happening?

Martin Lang: Buildings used to have natural ventilation thanks to their porous brickwork and windows and doors that weren't airtight. In the late nineties, large-scale insulation work began in the Czech Republic, supported by subsidies. Construction processes changed substantially, and there were great advances in how windows were made. Nowadays almost all buildings in the Czech Republic are insulated and fitted with new windows. The result is that there's no natural air exchange: in winter, condensation forms on the windows and mould starts growing. High humidity isn't the only problem. There's also a high carbon dioxide concentration indoors: the air gets stuffy and people don't have enough oxygen.

It's a major problem in buildings where there are lots of people: schools, hospitals, cinemas, theatres. In new construction projects, this is solved using heat recovery systems, but older buildings don't have them.

What are the consequences of higher indoor CO_2 levels?

M.L.: Lower immunity: in insulated school buildings, sickness levels are as much as twice as high as before. What's more, if there's not enough oxygen, the body will try to maintain its basic functions, at the expense of more depending brain activity. That results in fatigue, drowsiness and poorer academic performance, which is particularly problematic for schools.

Studies show that if a classroom is briefly ventilated, just ten minutes later CO_2 levels are too high again... You can't fix this by having the window open all the time – it results in substantial heat losses that weren't part of the plan, plus there's noise, which makes teaching difficult.

What proportion of schools does this apply to?

M.L.: It affects the majority of Czech schools. These are schools where the buildings were insulated without heat recovery systems.

What about other countries?

M.L.: The situation is similar. In the 1990s, all of Europe started talking about global warming, and environmental movements became more powerful. The result was a revolution in construction, favoring buildings with low thermal energy consumption. Today, other countries are facing the same problems we are. Lots of buildings that were insulated earlier haven't been fitted with heat recovery units.

What's the solution?

M.L.: Our company has developed a smart system to help optimize how homes function. The heart of the control system is a microcomputer that receives information from sensors. These sensors record various things, including indoor air quality, CO_2 levels and humidity – and if the limits are exceeded, the system alerts the user that the home needs ventilating. The system can also judge whether humidity is due to the fact that you're in the shower and it'll go down again, or whether it's longer term and you really need to ventilate. Smart heat recovery windows also substantially improve indoor air quality, although generally windows have to be opened and closed manually. Automatic opening and closing is possible, but for users it's not always desirable. A window might open in the room where the family is watching television, and they won't want any draughts or noise from outside.

What else can your smart system do?

M.L.: Our system means that the whole home is smart, and users can access all of the outputs from their computers or mobiles. The system can control central heating thermostats to optimize comfortable temperatures. Users can turn up the heating remotely if they're coming home from a weekend away. The system can turn lights and plug sockets on and off, using the existing fittings rather than dismantling or replacing the switches. If you're going away on holiday, our smart system can simulate movement in your home by turning the lights on and off and opening and closing the blinds, and it can switch off the majority of electrical circuits to avoid any accidents. We're planning to add a smart fridge or pantry that will do your food shopping automatically.

Our smart system also lets you check your water, energy and heat consumption remotely online. It shows your consumption in standard units and in koruna (Czech Republic local currency), with a forecast for your annual bills, and it will also highlight any anomalies. That means users can easily check at any time whether their monthly payments are sufficient rather than worrying about high heating, water and electricity bills at the end of the year.

You mentioned smart windows. What can they do?

M.L.: We are currently offering a smart window that includes a smart blind and an integrated heat recovery unit in the frame. It's particularly suitable for homes, and you don't need recovery units for all the windows in the room – the number of units depends on the size of the room that needs ventilating.

What else is in the pipeline?

M.L.: We're hard at work on the next revolutionary step in smart windows. We want to fit them with heat pumps to facilitate cooling and heating. To do this, we use a classic double-glazed window and install a third pane on it, with an integral smart blind and heat recovery unit. There are vents on the edges of the frame and "pockets" approximately fifteen centimeters long in the walls. Our unique smart window is then able to optimize the indoor air quality without having to open or close, just by adjusting those edges and pockets. It'll find application in flats, houses, schools, kindergartens, medical facilities, office buildings and other premises.

EVEN IN NEW-BUILDS INCORPORATING INDOOR AIR QUALITY CRITERIA, HEALTHY AIR REMAINS AN IMPORTANT ISSUE FOR OPERATORS

For our new head office, the "V" building, we set ourselves the target of achieving health and environmental excellence. This meant that ensuring good indoor air quality for all the building's users was one of the key challenges identified during the construction phase. The building was constructed to meet HQE® Excellent and BREEAM® Very Good certifications, meaning that it incorporated ambitious indoor air quality targets. The choice of materials to limit emissions of chemical compounds, the selection of efficient air treatment systems and the installation of over a hundred CO_2 measurement sensors all helped ensure that the building performs as intended. Today, in addition to annual air quality audits, the "V" is covered by our AIR Performance service, with air quality piloting that includes a performance guarantee. This new obligation has highlighted variations that previously went unnoticed and can potentially impact occupant comfort. For instance, alterations to how spaces are used, such as construction of a new partition or modification to an open space, can have knock-on effects on air quality that, in the absence of any adjustment to the ventilation system, are not properly compensated for. Similarly, continuous monitoring from the installation of almost 40 extra sensors to measure fine particles, CO_2 and volatile organic compounds provides enhanced insights into the variation of air quality's different parameters and allows adapting the control of air handling units accordingly.

This is an approach used in other parts of the world too, as illustrated by our Chinese colleagues.

VEOLIA IN CHINA

In China, companies that are able to offer complete monitoring solutions (for instance online monitoring of several air quality parameters with the required accuracy, smart monitoring, operation and data processing) are expected to have a competitive advantage in the future.

In that regard, Veolia has decided to reinforce its portfolio of services in China, since it expects Indoor Air Quality (IAQ) to become an important booster for Building Energy Services offers.

To demonstrate its legitimacy to operate in China, our company became the main shareholder of *DasLinkin*, a local company specialized in electricity services. This partnership will help to grow Veolia's network and geographic presence as well as its technical expertise in High Voltage & Low Voltage electricity services.

Linkin by Veolia developed an Indoor Air Quality pilot project in one of our contractual showcases; the Shanghai Pudong Water Concession:

- The team started by carrying out an indoor air quality audit in the office building and installed 11 sensors in various areas of the building[11] to track five indicators *via* a monitoring platform. According to the temperature, humidity level and concentration of CO_2, $PM_{2.5}$ and VOC, the platform could automatically provide operational guidelines to the end users.
- In the meantime, proactive actions have been launched to improve air quality. For example, the local team allowed a retrofit on the Air Handling Unit (AHU) device to improve $PM_{2.5}$ and VOC levels. Smart mobile air filters were also installed to automatically move across the office according to varying air quality needs.
- Finally, electricity consumption was integrated into the tracking platform to identify ways to reduce energy use.

Following on from the Indoor Air Quality monitoring pilot project, the ambition is now to allow the scanning and remediation of air pollution.

11 Ie. the lobby, meeting room, control room, open office area, pantry and outside of the building

This twofold action – continuously measuring indoor air quality at the same time as offering solutions to improve and conserve it — allows us to work with building managers, who were previously hesitant in the face of this complex and troubling problem and may have been tempted to downplay it. This is why our approach usually starts with the AIR Control service. Initial diagnoses combined with continuous monitoring give a detailed dynamic overview of the status of a building, showing the footprint of its indoor air quality. Once this is known, it becomes easier to suggest solutions to remedy any problems encountered.

This type of solution can be adapted to a very wide range of buildings: hotels, hospitals, sports centers, shopping malls, swimming pools, etc. We are continuing to work on solutions for treating specific complex types of pollution encountered in unusual atmospheres such as underground, including metro systems.

As the market grows, prices for measurement and treatment equipment will likely become even more cost effective, and growing volumes will accelerate wider use of indoor air quality treatment to deliver health uplifts to all. As shown in a paper published recently by Paris city council's Urban Lab[12] on a raft of air quality experiments, regulation will be an effective mechanism for supporting development of these solutions. The very recent example from Belgium,[13] which has switched from a process-based system to one that imposes an obligation to achieve results and guarantee indoor air quality, paves the way for tighter regulatory requirements that offer greater protection to human health.

CONCLUSION

Air is a common good and vital resource for us all – we each breathe 15,000 liters of it a day. From now on it is possible to guarantee good quality indoor air in buildings, and in so doing to reduce the major health risks air pollution poses. The primary challenges in the coming years center on having the capacity to deliver a widespread, rapid rollout of the solutions that are developed, and to optimize costs per cubic meter of treated air. In a broader sense, monitoring as a standard feature in buildings will provide large amounts of data on indoor air and new insights that will guide future rules for designing and operating buildings.

12 The laboratory for urban experimentation run by Paris&Co.

13 A royal decree of May 2, 2019 amends the Code on workplace wellbeing with regard to indoor air quality in workspaces.

USING PLANTS AND SOIL MICROBES TO PURIFY INDOOR AIR: lessons from NASA and Biosphere 2 experiments

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The Biohome, a sealed chamber facility created by NASA in the late 1980s to investigate interior plants' ability to purify the air.
© Bill Wolverton

Bill C. Wolverton is an American scientist who joined the NASA in 1971 as head of the Environmental Research Laboratory at the Mississippi Test Facility (now known as the John C. Stennis Space Center). There, he mainly studied phytoremediation for confined spaces, - the application of biotechnologies to treat wastewater, derived for land-based pollution treatment. As early as 1989, he studied at NASA the ability of plants to absorb several chemical compounds. After the publication of NASA's Clean Air Study report in 1990, he left NASA and launched his own research structure, Wolverton Environmental Services, which is still studying the topic of phytoremediation.

Mark Nelson is an American scientist, who served as Director of Space and Environmental Applications for Space Biospheres Ventures, which created and operated Biosphere 2, an Earth system science research facility located in Oracle, Arizona. He was a founder of the Institute of Ecotechnics, a U.K. and U.S. non-profit organization, which consults to several demonstration projects working in challenging biomes around the world. He is head of Wastewater Gardens International which has implemented ecological constructed wetlands, a technology used in Biosphere 2, in 14 countries.

Phytoremediation is the process by which plants and their root microbes remove contaminants from both air and water. Those purifying properties have been discovered within the frame of space habitation experiments: in the 1980s, scientists at the John C. Stennis Space Center shed light on interior plants' ability to remove volatile organic chemicals (VOCs) from tightly-sealed chambers. Further investigation, including the construction of a dedicated facility, Biohome, led to scientific breakthroughs and helped understand how to maximize interior plants' ability to purify the air. The experiment showed that indoor plants were able to remove VOCs that were continuously off-gassed in a closed system, thanks to the combined action of plant leaves and root microbes (by metabolization, translocation and/or transpiration).

Concurrently, the experiments led by Mark Nelson on Biosphere 2 demonstrated that high levels of crop productivity and maintenance of soil fertility can be maintained while biofiltration of the air is also achieved. The implications of the Biosphere 2 research on plant/soil biofiltration are that efficiency of trace gas removal depends on the populations of soil microbiota capable of metabolizing them.

Both experiments conclude that plant biofiltration is a promising technology that can help solve widespread global problems caused by air pollution. These solutions have a wide scope of application, and they require far lower capital investment and have lower operating costs than competing technologies. As such, they should be far more widely applied, especially within indoor areas.

INTRODUCTION

The earth is a dynamic, living planet with an evolving biosphere which has transformed the planet. The interaction of plants and microbes plays an important role in balancing the earth's ecosystems: in the simplest terms, plants and microbes act as the 'lungs' and 'kidneys,' continually filtering and disposing of impurities and waste products. We understand these functions in nature, yet many have a difficult time envisioning these same processes filtering the air and water within our built spaces.

Although humans yearn to stay connected to nature, many spend as much as 90 % of their time indoors where the air quality is often far from ideal, and indeed sometimes worse than outside. We have now introduced more than 85,000 synthetic chemicals into the environment and many off-gas toxins that become trapped within our buildings. Synthetic materials, equipment and digital devices also release trace gases. In order to conserve energy, modern buildings are tightly-sealed. As a result, a build-up of this variety of outgassing sources including airborne microbes and volatile organic chemicals (VOCs) often leads to poor indoor air quality (IAQ). Indoor air pollution is now rated among the top five threats to human health.

Aiming at improving IAQ, building engineers continually recommend increasing ventilation rates in an effort to purge the air. Most buildings bring in fresh air through an outside duct and mix it with re-circulated air. However, ventilation has four inherent problems: energy efficiency is compromised; outside air is often heavily polluted; outside air must be heated or cooled for human comfort; we can question how environmentally responsible it is to inject indoor air pollutants into the outside environment. Plant and soil-based systems, in part derived from systems designed for futuristic outer space exploration, can be part of the answer, bringing us back to fundamental processes that sustain life on earth. Two pioneer and decisive experiments investigated the capabilities and properties of such systems in the 1980's: the NASA's Biohome project and the Biosphere 2 project.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA) RESEARCH AND THE BIOHOME PROJECT

After the successful moon landing in 1969, NASA initiated programs to sustain life during long-term space habitation. Scientists at the John C. Stennis Space Center (SSC) took part in research to develop a 'Closed Ecological Life Support System'. NASA has within its charter that it should also seek applicability here on earth, such as treating environmental pollution. SSC scientists developed and installed constructed wetlands, now termed phytoremediation systems, to treat both domestic and industrial wastewaters at the facility. These plant-based systems have successfully treated wastewater for more than forty years, twice the average lifespan of conventional mechanical systems and saved NASA millions of dollars in operational costs[1].

In 1980, SSC scientists first discovered that interior plants could remove VOCs from sealed test chambers. NASA first published its findings in 1984[2,3]. To further investigate these findings, NASA constructed a 'Biohome' made entirely of synthetic materials and engineered to achieve maximum air and energy closure. The interior space was subdivided into a one-person habitat and a bioregenerative component whose basic functions were air purification and wastewater treatment [4].

Due to its synthetic building materials and furnishings, it was assumed that outgassing of VOCs would create IAQ issues. Upon entering the facility, most people experienced burning eyes and throat and respiratory problems.

Common interior foliage plants growing in commercial potting soil were placed throughout the living quarters to evaluate their ability to remove VOCs. Additionally, they placed one experimental fan-assisted planter containing a plant growing in a mixture of soil and activated carbon. Air quality tests before and after the placement of plants by mass spectrometer/gas chromatograph analyses revealed that nearly all of the VOCs were removed. Moreover, one no longer experienced burning eyes or other classic symptoms of 'sick building syndrome' (SBS) when entering the Biohome. This was the first 'real world' application of interior plants for alleviating SBS.

Technology termed 'phytoremediation' utilizes plants and their root microbes to remove contaminants from both air and water. During the early 1990s, studies sought to determine the mechanisms plant ecosystems utilize to remove VOCs from sealed chambers. The NASA studies employed only a one-time injection of VOCs into the test chambers. Questions arose whether plants could remove VOCs that were continually off-gassed from synthetic materials as commonly occurs in an indoor environment.

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2 Wolverton, B.C., R.C. McDonald and E.A. Watkins, Jr., Foliage plants for removing indoor air pollutants from energy-efficient homes, *Economic Botany* 38(2), 224-228, 1984.

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Interior view of the Biohome. © Bill Wolverton

Plexiglas test chamber used in the experiments conducted by Wolverton Environmental Services, Inc. © Bill Wolverton

To answer this issue, Wolverton Environmental Services, Inc. (WES) conducted extensive studies[56]. They had constructed two Plexiglas test chambers. Scientists placed two sections of interior paneling comprising urea-formaldehyde resins into each chamber. A lady palm *(Rhapis excelsa)* was added to one chamber while the other chamber, serving as a control chamber, did not contain a plant.

The lady palm and its soil removed formaldehyde that continuously off-gassed from the paneling sections. Temperature influenced the rate at which formaldehyde off-gassed from the paneling. The greater the temperature, the more rapidly formaldehyde was released. There was no removal of formaldehyde in the control chamber.

The lady palm showed no ill effects after extended exposure to formaldehyde. In fact, the lady palm increased its ability to remove formaldehyde as its exposure time increased. These studies indicated that plant root and soil microbes had rapidly adapted to the presence of formaldehyde and had contributed significantly to the chemical removal process. Further studies sought to determine the extent of plant root and soil microbe involvement in the removal of chemicals. Formaldehyde and xylene were introduced individually into sealed chambers containing plants having either exposed potting soil or soil covered with sterilized sand. The studies showed that 50 to 65 % of VOC removal could be attributed to root and soil microbes.

Due to the presence of microbes in the rhizosphere[7], interior plants are not damaged when exposed to high concentrations of VOCs but continue to improve their ability to remove chemicals over time. The root/soil microbes rapidly adapt and grow in number, producing new generations of microbes that are even more effective in using the chemicals as a source of food and energy. Scientists at the University of Sydney, Australia, later conducted similar studies and obtained comparable removal efficiency[8].

These findings added to studies show that both the plant leaves and root microbes contribute to the removal of VOCs from the indoor environment. It has been well-documented that plant leaves can absorb, metabolize and/or translocate certain VOCs to the root microbes where they are broken down. Studies show that 90 percent of these substances are converted into sugars, new plant material and oxygen. Scientists at the GSF-National Research Center for Environment and Health in Germany, produced the most definitive study yet on this phenomenon. They used radioactive carbon tracers to follow how the spider plant *(Chlorophytum comosum L.)* was able to break down and destroy formaldehyde[9].

Plant leaves and root microbes contribute to the removal of VOCs from the indoor environment

The other mechanism plants employ to move air down to their root system is transpiration. While moving water up from their roots to their leaves, a small convection current is created pulling air down to the root zone. Through this process, a plant not only moves atmospheric gases such as oxygen and nitrogen to its root zone, but also airborne chemicals. Because of this action, generally a plant with a high transpiration rate is more effective in its VOC removal capacity[10].

All of the initial NASA interior plant studies were with plants grown in commercial potting soil. To go further, WES has sought to build upon their pioneering research and has concentrated its studies upon the use of hydroculture rather than potting soil. Indeed, hydroculture offers several advantages for use in the indoor environment (uses no soil, reduces over-watering and spillage, reduces risk of growing molds, reduces the need to transplant, plants take only the moisture they need).

WES hydroculture studies show that plants emit substances from their leaves that reduce the number of molds and bacteria in the ambient air even though further studies will further elucidate these mechanisms. Indeed, these studies suggest that plants grown in hydroculture are 30 to 50% more effective in removing airborne chemicals than plants grown in potting soil.

The NASA project and further development by WES also led to the creation of a High Efficiency Planter Filter, whose commercial applications (portable plant-based air filters) indicate they are as much as 50 to 100 times more effective in removing VOCs from the indoor environment than regularly potted plants. These air filters employ a mechanical fan to pull air down through highly adsorptive substrate in which an interior plant is grown. The substrate traps any airborne contaminants, where microbes in the rhizosphere break them down into components that serve as a source of food and energy for themselves and their host plant. Because microbes rapidly adapt to become more efficient with exposure, a bioregenerative or self-cleaning filter is created. These products are highly effective in VOC removal in small, confined spaces such as office cubicles or specific rooms within a living space.

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7 The rhizosphere is the narrow region of soil that is directly influenced by root secretions, and associated soil microorganisms known as the root microbiome.

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BIOSPHERE 2 PROJECT

In the meantime, Space Biosphere Ventures investigated a similar phenomenon within the Biosphere 2 facility in Oracle, Arizona: originally designed as a new type of laboratory for studying basic processes of our global biosphere and the interplay of its internal mini-biomes, Biosphere 2 not only enabled detailed studies of self-organization and adaptation of its internal biomic areas and precise measurements of ecological dynamics including air, nutrient and water cycles; but was also a testbed for developing eco-technologies and ways of integrating required technologies with a living world to prevent damaging impacts[11].

When the Biosphere 2 project began in the mid-1980s, concerns about indoor air quality problems increased due to the impact of far tighter sealed buildings and homes to prevent energy loss. Amongst the many challenges of creating a virtually materially closed environment was achieving regeneration and maintenance of healthy air and water. Two serendipities led the Biosphere 2 design team to plant/soil biofiltration as an ecological, low-cost approach for preventing trace gas build up. The first was that B.C. Wolverton, then with NASA Stennis Space Center, was already working with the project to adapt constructed wetlands to treat and recycle all our human, animal and workshop/laboratory wastes[12]. Wolverton had also been one of the first to study the efficacy of plants to improve indoor air quality showing that common houseplants could effectively remove typical indoor air contaminants such as volatile organic compounds[13]. The second was meeting Hinrinch Bohn, a professor at the nearby University of Arizona, who came from Germany, a country where the technology had begun in the early part of the 20th century. He and his brother at the University of Connecticut continued research and development of this innovative approach, then called “soil bed reactors” Soil biofiltration is far more widely used in Europe, especially in Germany and the Netherlands, than in the United States. It is even considered best management practice for control of industrial malodor caused by pollutant gases[14].

The method takes advantage of the immense population numbers and metabolic diversity found in soil microbiota. Increased soil organic matter increases its effectiveness, leading to the use of compost and amended soils. The range of potential pollutant trace gases amenable to control by soil biofiltration is large – though much research remains to be done. But limitations include the rule of thumb that soil biofiltration can only work on gases that burn in air (are capable of oxidation). Neither is the technology capable of treating extremely concentrated pollution loads. Soil biofiltration engineering includes maintaining optimal moisture content and operating temperature, choice of substrate for desired porosity, surface area and soil organic matter content[15].

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Test modules of closed ecological systems from the Biosphere 2 experiments. Construction for the project started in 1987 and the first mission began in September 1991. © Mark Nelson

To research the applicability of soil biofiltration for the project, a three-year research program was initiated. The first question was whether growing plants could be combined with soil biofiltration. To test this, seventy-two beds growing food crops equipped with air pumps to push greenhouse air up through the soils were tested at the Environmental Research Laboratory (ERL) at the University of Arizona. These studies demonstrated that there were no negative impacts on crop growth and productivity. In fact, yields were somewhat enhanced, probably because soils were well-aerated[16].

Plant/soil biofiltration experiments in the Biosphere 2 Test Module studied rates of removal of injected trace gases such as ethylene, carbon monoxide, NOx, methane and technogenic gases like formaldehyde and toluene. This research coupled with similar tests using sealed aquaria at ERL examined the effectiveness of the technology and the impacts of factors such as flow rates, prior exposure of the soil microbiota to the specific trace gases and soil type and organic content of the soils[17,18].

16 Frye, R. J. and Hodges, C. N. 1989. Soil Bed Reactor Work of the Environmental Research Lab of the University of Arizona in Support of the Research and Development of Biosphere 2. In: Biological Life Support Technologies: Commercial Opportunities. NASA Conf. Publ. 3094. Pp 33-40.

17 Alling, A. & Nelson, M. (1993) Life Under Glass: The Inside Story of Biosphere 2. Tucson, AZ: Biosphere Press

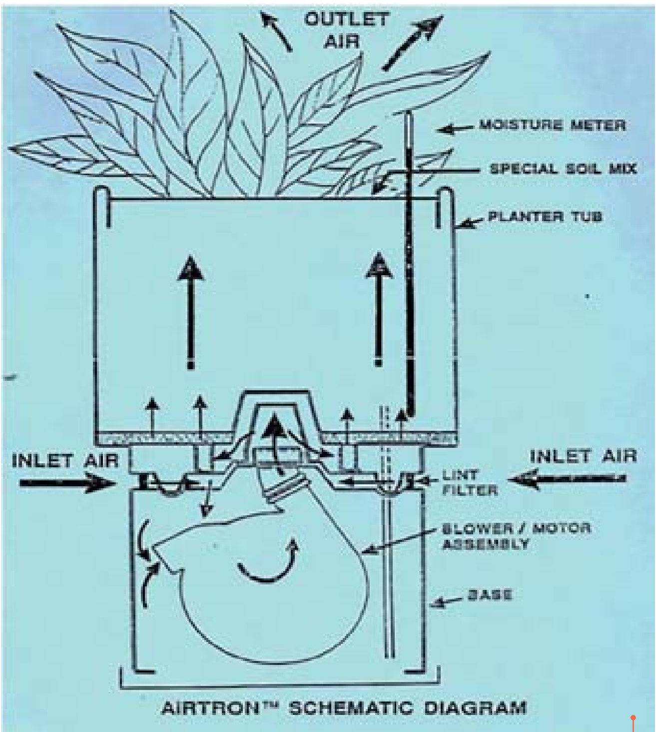
18 Frye, R. J. and Hodges, C. N. 1989. Soil Bed Reactor Work of the Environmental Research Lab of the University of Arizona in Support of the Research and Development of Biosphere 2. In: Biological Life Support Technologies: Commercial Opportunities. NASA Conf. Publ. 3094. Pp 33-40.

Biosphere 2's entire agricultural soil was engineered to function as a plant/soil biofilter as all the facility's air could be pumped through the soil in about 24 hours if trace gas concentrations required countermeasures[19].

The implications of the Biosphere 2 research on plant/soil biofiltration are that high levels of crop productivity and maintenance of soil fertility can be maintained while biofiltration of the air is also achieved, and that the efficiency of trace gas removal depends on the populations of soil microbiota capable of metabolizing them.

Since soil biofiltration was at the time limited to industrial pollutant gas applications, there was an opportunity to develop the technology for other applications, such as indoor air pollution. A commercial product called the "airtron" was developed by the Biosphere 2 project in the early 1990s. This device transformed what appeared to be an ordinary indoor house plant container into a plant/soil biofilter with the installation of an air pump below the planting soil which would force the air up through the soil, exposing its contaminants to soil/root microbes capable of detoxifying them.

19 Nelson, 2018, Pushing Our Limits: Insights from Biosphere 2



Schematic diagram of an "airtron" soil biofiltration unit developed by Biosphere 2 © Mark Nelson

Prototype unit used in the Mission Control building of the Biosphere 2 project. © Mark Nelson

OTHER RESEARCH

Extensive studies by WES as well as other scientists in Europe, Canada, India, Korea, Australia and Japan have provided scientific evidence that interior plants can help improve the air quality within energy-efficient buildings[20]. Interior plants are more effective in removing harmful airborne pollutants in tightly-sealed buildings than in heavily ventilated buildings. No filtering device can effectively clean the air within a building when mechanical ventilation is constantly bringing in outside air. Outside air, especially in metropolitan areas, is often laden with pollutants. Additionally, a building is not energy-efficient if outside air is continually heated or cooled to a temperature range for human comfort.

Interior plants can help improve the air quality within energy-efficient buildings

In addition, research has shown that when workers are in close proximity to living plants productivity increases, morale improves and stress is reduced. Evidence collected during the past twenty years overwhelmingly supports the beneficial health effects of interior plants. Living plants also remove carbon dioxide and produce oxygen. These can be important functions when a large number of plants are placed within greenhouse roof gardens, sunrooms or atriums[21].

CONCLUSION: LIVING IN HEALTHY INDOOR AREAS

These pioneering studies showed that plant and soil biofiltration can be an important bioremediation tool and a promising technology that can help solve widespread global problems caused by air pollution. Although the purifying power of plants has stirred controversy over the past years, the ability of plants to remove volatile chemical toxins under laboratory conditions and in airtight spaces is not doubted. Moreover, it requires far lower capital investment and has lower operating costs than competing technologies.

Like any technology, there are situations for which it will not be effective, such as highly concentrated air pollution, or for contaminants where slow reactions times would require unrealistic treatment time. However, there is enormous scope for the expanded use of this technology.

For space life support for extended human habitation, the technology is attractive because it produces many benefits since a food production unit can double as an air purifier, requires little maintenance and consumables and less energy than alternative approaches.

Plant/soil biofiltration also seems an ideal approach for dealing with indoor air pollution, because a rich soil has enough biodiversity to be able to naturally adapt to virtually whichever trace gases are being released within offices and homes. The transformation of indoor house plants, office green spaces such as atriums and even city vegetation, e.g. portions of parks, living walls or rooftop gardens, to also function as plant/soil biofilters can dramatically increase their ability to improve the air we breathe.

Large interior plantings are already commonplace in many public and commercial buildings. Trending within buildings at the moment are systems known by a variety of names, including green walls, living walls, bio-walls or vertical gardens. These systems are installed primarily for aesthetics. Very few take the concept a step further to employ the biological functions of plants and microbes to help improve IAQ. An exception is Takenaka Garden Afforestation, Inc., the largest interior plantscape company in Tokyo, which has developed an Ecology Garden®, and Paharpur Business Center, Nehru Place Greens in New Delhi, India [22].

The ultimate goal is to further plant-based air filtration technology whereby the air is treated for the whole building. The 'whole building concept' led to the development of modular planter systems that are much larger in scale, which allows a greater diversity of plants and can accommodate automatic watering systems. Most importantly, they may be connected to the building's heating, ventilating and air conditioning (HVAC) system[23] so that during the internal air-exchange process, the air circulates through various planter modules, stripping it of pollutants, before returning to the indoor environment. This process reduces the need for outside ventilation.

The need for further interest and investment into the 'whole building concept' is more and more essential. Plant/soil biofiltration is a quintessentially green technology, a wonderful example of ecological engineering that should be far more widely applied as we develop a more sustainable and regenerative relationship between our technosphere and our biosphere.

20 Professor Margaret Burchett, University of Technology, Sidney, Australia (extensive research on plants and their ability to improve indoor air quality).
Kozaburo Takenaka, Takenaka Garden Afforestation, Inc., Tokyo, Japan (Ecology Gardens for improving indoor air quality and patient/staff comfort in hospitals);
Professor Tov, Fjeld, Agricultural University of Norway, Oslo, Norway (Plants for human health and well-being in offices).
Kamal Meattle, The Paharpur Business Center, New Delhi, India (Interior plants for improving indoor air quality in office buildings);
Professor Priscilla Pegas, University of Aveiro, Portugal (Interior plants for improving indoor air quality in classrooms).

21 Wolverton, B.C. and Kozaburo, Takenaka, Plants: Why You Can't Live Without Them, Roli Books, New Delhi, India, 2010.

22 Kamal Meattle, The Paharpur Business Center, New Delhi, India, Interior plants for improving indoor air quality in office buildings.

23 Paharpur Business Centre and Software Technology Incubator Park. Heating, ventilating and air conditioning system.

ARTIFICIAL INTELLIGENCE AND INDOOR AIR QUALITY: BETTER HEALTH WITH NEW TECHNOLOGIES

Yann Boquillod
Founder of AirVisual

The AirVisual mobile app

Yann Boquillod is a graduate engineer who became interested in air quality issues as a result of living in China. Starting in 2010, his interest in the impact air pollution has on health led him to design a solution for measuring indoor air quality that until then had not existed. The creation of the company AirVisual, in 2015, led to the development of new sensors that are innovative and intuitive, making it possible to measure and interpret air quality (fine particles, CO_2, hygrometry, etc.). The 2017 acquisition of AirVisual by IAQair, a Swiss company specializing in air filters, now makes it possible to offer indoor air quality measurement and purification solutions that use big data and artificial intelligence.

Although many people imagine that enclosed spaces offer protection from outdoor pollution, the indoor air is very often contaminated by harmful substances created by everyday household cleaning and cooking activities as well as from outdoor pollution from sources such as vehicles and industry, particularly in the megacities of Asia.

Founded in 2015 by two French entrepreneurs, *AirVisual* is a company whose primary mission is to raise awareness of air quality. By offering connected sensors for measuring indoor air quality, the company makes it possible for everybody to optimize their indoor air quality, which in turn limits health risks from exposure to fine particles and excessive concentrations of CO_2. In addition, aggregating data from governments, satellite images and outdoor sensors that AirVisual has installed worldwide has enabled the startup to create an interactive world map of air quality on our planet, helping to increase awareness of the importance of air quality and encouraging solutions that are relevant to local contexts.

What drove you to create a startup focused on air quality?

Yann Boquillod: Air quality is a real public health challenge in Beijing because of the levels of exposure to pollution. My awakening to the true seriousness of this issue, dating from when I first moved there, explains the origins of AirVisual. I wanted to use my understanding of big data and artificial intelligence to address the problem of air quality. With my business partner, we decided to set up AirVisual in China because the local logistics and supply chains provide a real advantage compared to alternative locations. Also, the speed of project development in China allowed us to grow our company very quickly.

Another key advantage is that, in heavily polluted cities such as Beijing, enclosed spaces are seen as bulwarks against pollution, so people feel the need to measure their indoor air quality.

But when I first moved to Beijing, there were no possibilities for measuring indoor air pollution apart from the government sensors. Costing $30,000 to $50,000, these were very expensive machines for measuring outdoor air quality and they really didn't seem suitable for monitoring air quality in the home.

Easy access to unambiguous depictions of air quality is important for public health

This was what led to the development of our "Nodes", the sensors now known as *AirVisual Pro*, that measure:

- fine particles, which have long-term health impacts;
- the concentration of CO_2, to assess ventilation in enclosed spaces;
- simpler data such as temperature and humidity.

Air pollution is hard to see with the naked eye, which is why we wanted to make it visible. These sensors make possible an all-encompassing approach to perceived comfort.

What is the principle behind AirVisual?

Y. B.: From the start we were determined to change existing approaches to air quality by incorporating big data and artificial intelligence into our products, especially for data validation purposes, so that we could deliver a measurement system that was accurate.

AirVisual has a twofold objective.

The first is to protect indoor air quality, including with the help of artificial intelligence to provide users with solutions that are both suitable and actionable.

The AirVisual node *(AirVisual Pro)* is a portable personal device for measuring air quality. To calculate the concentration of $PM_{2.5}$, it uses a laser to count the number of particle-related interruptions in a stream of air directed by a tiny fan. The apparatus measures up to six pollutants present in the air, as defined by the AQI.[1] The data is sent to the cloud for analysis by an AI system. The system makes decisions on air quality remediation as a function of the results. Instructions are then sent directly to connected purification systems, providing management of indoor air quality in a way that is almost fully self-contained.

1 Air Quality Index: the six most common air pollutants are PM2.5 and PM10, ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide.

Using an *AirVisual Pro* sensor to measure indoor air quality

It is important to understand that this option is only suitable for countries where aeration and traditional filtration systems are not realistic options. In France, for example, opening windows in enclosed spaces at the right time will sometimes be enough, so there's no need to fit an air purifier. In China, the cost of fitting a complete household system can run to €3-4,000.

The use of outdoor sensors is an adaptation of our project to fit the market. Above all, it's an issue of real social importance. Our goal is to equip the planet with an extensive network of sensors to create a real-time global pollution map with as much granularity as possible. Today, we're able to view fine particle trajectories in real time anywhere in the world using *AirVisual Earth*, our interactive map. We do this using individual sensors to measure indoor and outdoor air quality. The data is then cross-referenced with official data from each country's air quality measurement services, resulting in a global image of fine particle pollution. Where data are hard to access, for example in vast uninhabited regions, we use satellite images and meteorological forecasts to model fine particle concentrations in parts of the world where sensors and public data do not exist.

The success of AirVisual Pro sensors is to a large extent due to their ease of use and the way that information is presented visually. In addition to quantifying certain metrics, we try to make sense of the data

Complementarity between indoor and outdoor sensors means we can adopt a systematic approach, offering solutions tailored to various pollution threats. Today, there are over 100,000 AirVisual sensors running worldwide. We have indoor sensors in 120 countries and 80 countries have our outdoor sensors. These sensors mean we can deliver real-time indications about air quality via a website and an app that currently numbers 10 million users.

What are the challenges to collecting and accessing this type of data?

Y. B.: Governments report their pollution data in a range of formats. Our role is to standardize the data so they can be compared to each other. This is a long-term process but it's a necessary part of forming an overall vision of pollution.

We decided to use the USA AQI index to present our data. This has a range of 1 to 500 and lets us differentiate between six different thresholds, each for a different level of precautionary steps to take.

A second challenge is that outdoor air quality data are sensitive, particularly in China, where publication of outdoor data is extremely reliable but restricted for legal reasons; sources of information are controlled and very few other sources of measurements are permitted. This is one of the reasons that led us to focus on indoor air quality, the other being that we want to improve access to data on indoor air quality to help prevent health risks for everybody.

The sensors are connected objects, but the data remains personal and are not published automatically. Users are able to consult their indoor air quality data without having to send this data to the cloud. The General Data Protection Regulation (GDPR)[2] is not a problem because we ask for users' permission before publishing their data.

Regarding data reliability, extremely strict rules have been drawn up governing the installation of outdoor sensors. We have to make certain of the quality of the installation because the data will be seen by around 10 million users. Similarly, if we issue a pollution alert, we have to be certain that the data are reliable, which is why we have such strict installation procedures. For instance, we ask users to send photographs showing where they have placed the sensor. We use an AI system to check that all the conditions for a perfect installation have been met. If the data seem to be wrong, the system sends notifications to the user and asks them to check the installation.

What do you think makes this type of technology so attractive to consumers?

Y. B.: The success of *AirVisual Pro* sensors is to a large extent due to their ease of use and the way that information is visually presented. In addition to quantifying certain metrics, we try to make sense of the data because not everybody understands the raw numbers for fine particles or CO_2 levels in the air. The data can be accessed via sensor screens or the app in a technique that has become very popular for monitoring outdoor air quality.

The sensors use icons and color codes that make it easy for everybody to have a clear understanding of the situation in real time. This visual system has been adopted by other organizations, including for example the government of Iran in its guidance note on air quality, as well as inspiring other applications in the same field.

What is the user profile for your indoor air quality sensors?

Y. B.: Today, more and more researchers are looking at relationships between a building's air quality and the productivity of its occupants. Although this research is still in its infancy, several studies highlight the impact of CO_2 concentrations on the performance of staff or pupils. More and more businesses are keen to provide their staff with

2 General Data Protection Regulation is the European framework regulation for the protection of personal data. For further information: https://ec.europa.eu/commission/priorities/justice-and-fundamental-rights/data-protection/2018-reform-eu-data-protection-rules/eu-data-protection-rules_en

a healthy working environment. Mercedes, for example, has invested considerably in equipment to improve air quality, especially in China. Sensors are also being increasingly installed at schools. We know that many children use the app to identify the times of day when better air quality encourages outdoor activities.

Sensors help to underline the need for a collective approach to the problem

AirVisual Pro sensors have also been installed in clinics, to provide data on a topic that is central to the challenges facing health care facilities worldwide.

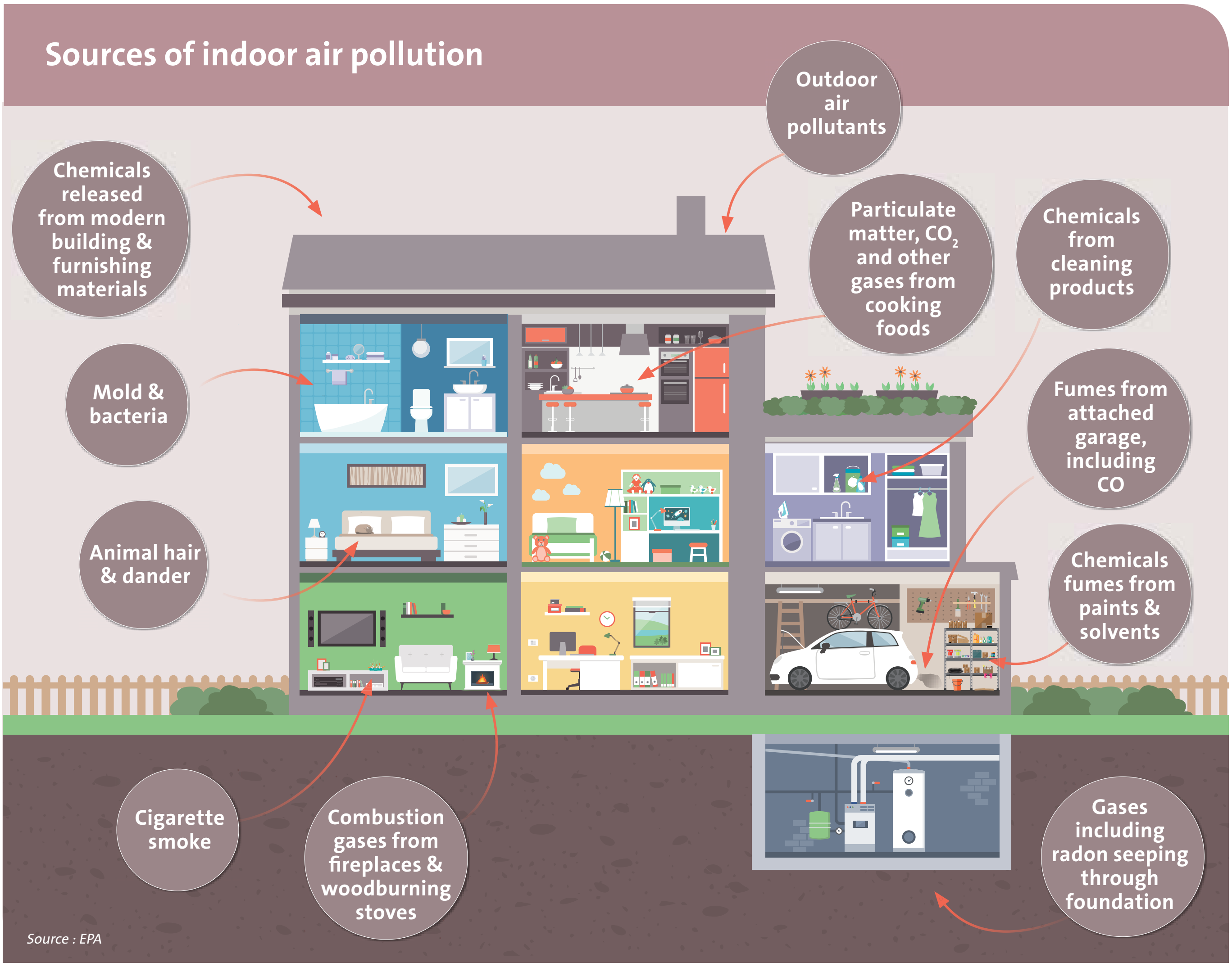
How can these new technologies influence policymaking?

Y. B.: Sensors help to underline the need for a collective approach to the problem. In Thailand,[3] for example, the deployment of over a thousand outdoor sensors has helped to raise nationwide awareness about air quality and has had a real impact on economic and political decision-making. Factoring in outdoor air quality needs to be thought of as a first step, and as something that can help to make governments aware of the urgent need for ambitious policies to promote healthier indoor air.

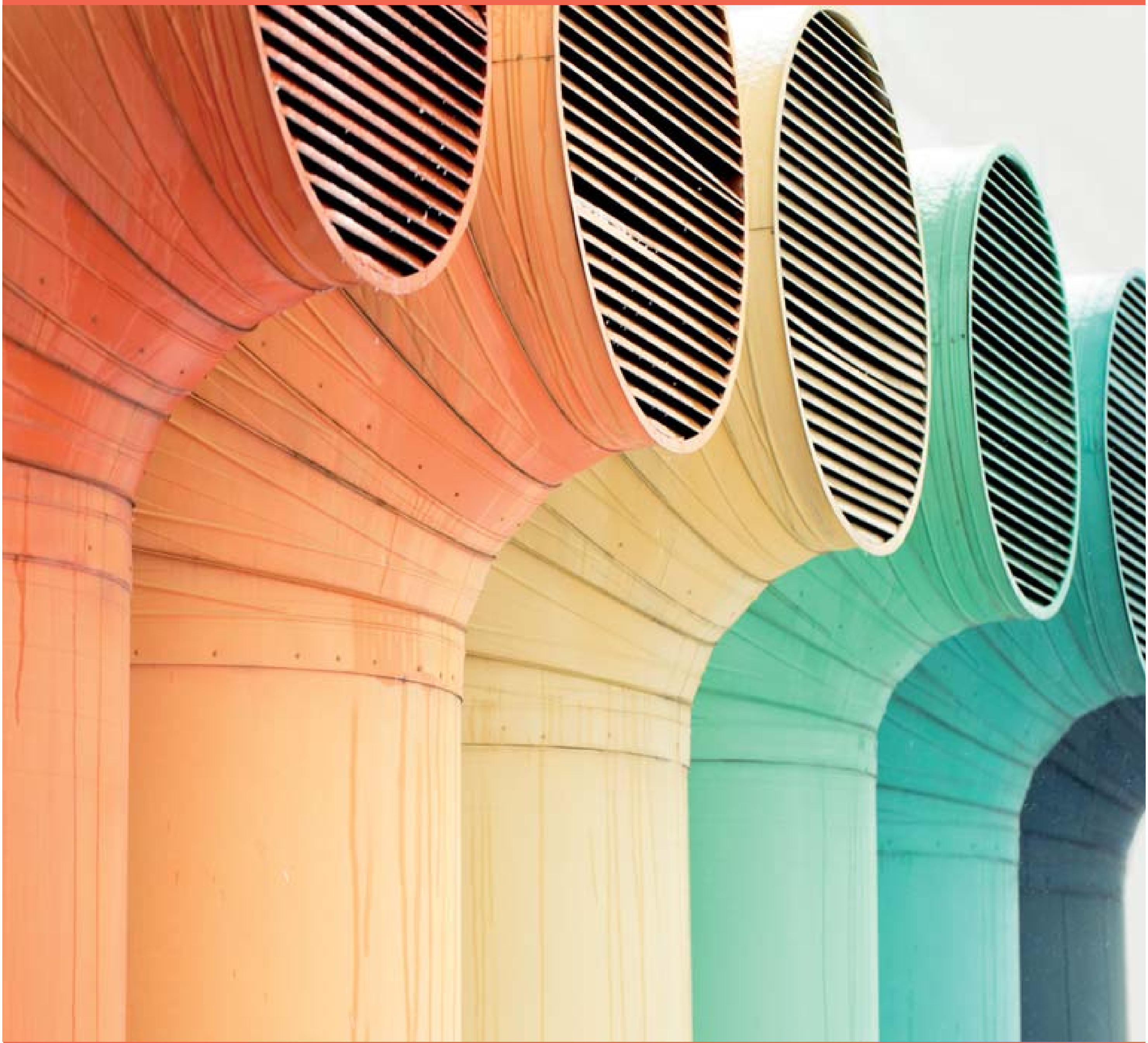
Similarly, studies using data from the sensors have shown that lower attainment levels at certain schools in comparison to others may be explained by levels of indoor air pollution and the impact this has on pupils' ability to concentrate.

Once governments truly start to take note of the increasing number of similar studies, this should help them to make decisions designed to improve indoor air quality, in public spaces at the very least.

3 https://www.airvisual.com/thailand



3. FROM PUBLIC PERCEPTIONS TO POLICYMAKING: SHINING LIGHT ON AN INVISIBLE POLLUTION



The keys to scaling up solutions for better air quality lie not only in implementing ambitious policies to provide clean air for all, but also in greater public awareness of the impacts of air pollution on health and the environment.

PROMOTING GOOD PRACTICES

An integrated vision of the problem including all stakeholders is essential to ensure better prevention and risk assessment. This is the approach adopted by the Climate and Clean Air Coalition (CCAC), whose secretariat, situated in the UN's Environment office, is led by Helena Molin Valdés. This initiative – whose members include governments, international organizations, research institutions, members of civil society and the private sector – rolls out, supports and promotes innovative solutions for tackling indoor air pollution around the world, with a special focus on poor rural areas. In terms of public policy, some countries are leading the way by enacting standards and procedures that encourage best practices and making systematic checks on indoor air quality. The South Korean example is presented by Dong Hwa Kang, associate professor at the University of Seoul.

INFORMING CITIZENS

Over and above tightening up standards and regulations, the question of the public's perception of air pollution is crucial. The study conducted by the Elabe consultancy in France, Belgium and Shanghai, reveals that indoor air pollution is now commonly identified as a health risk. It highlights parents' increasing concerns about the quality the of air their children are exposed to inside school buildings. However, persistent lack of information about air quality often results in highly subjective diagnoses, worsened by the difficulty of identifying exact pollution sources. This state of affairs suggests that efforts should be made to increase knowledge about this invisible form of pollution.

ART'S ROLE IN REVEALING INVISIBLE POLLUTION

The conundrum of raising awareness about indoor air quality springs from the difficulty of alerting people to the existence of a danger that is hard to perceive by essence. By reaching out to our emotions and symbolic representations, contemporary art helps materialize the threats that air pollution poses. Art makes it possible to surpass mere conceptual comprehension of an issue by offering a memorable sensory experience that deconstructs our certainties and spurs us into action. Committed artists such as Andrea Polli in the USA and Michael Pinsky in the UK, backed by scientists like Norway's Laura Sommer, occupy public spaces to present climate art which interrogates spectators regarding their own share of responsibility.

Cédric Baecher, Fanny Sohui,
Leah Ball and Octave Masson,
Coordinators,
Nomadéis

PUBLIC PERCEPTION OF INDOOR AIR QUALITY IN CHINA, BELGIUM AND FRANCE: the discovery of an invisible enemy

Laurence Bedeau
Partner in the consulting firm ELABE

Laurence Bedeau is a partner in the consulting firm Elabe. With a team of 20 consultants, she supports her clients in their communications strategy by combining three complementary business lines: consulting, opinion studies and strategic planning.

Specializing in public opinion issues, she worked at TNS Sofres, leading the Opinion-Corporate-Quality of Life at Work division of the CSA study institute[1].

Having remained relatively unrecognized by public opinion until the early 2000s, indoor air pollution is now seen by a majority of French, Belgian and also Chinese residents as the probable cause of symptoms such as headaches, fatigue, irritation of the eyes and respiratory tract, and health problems in general. However, the lack of information on indoor air quality in frequently visited enclosed spaces (private premises, workplaces and common areas, transportation) often leads to subjective diagnoses, exacerbated by the difficulty in identifying the sources of indoor air pollution. Nevertheless, it must be regarded as a public health issue, as reflected by growing anxiety among parents about the quality of the air their children breathe inside school buildings, for example. In this context, more robust legislation and standards are considered indispensable in ensuring better prevention and risk assessment.

INTRODUCTION

The focus of worldwide public attention on air quality is not new, but has completely changed in nature and intensity over the last 20 years. It is the product of a long journey toward awareness, the most recent stage of which is drawing the general public's attention to the air we breathe inside enclosed living spaces (homes, schools, offices, transportation, entertainment venues, eateries, etc.). These are the spaces in which we spend around 80% of our time, even when we live in mild climates. Having long been overlooked by the media and governments, indoor air quality is now a new specter looming in the long list of ecological dangers. The story of how public opinion discovered this new "public enemy" begins with a change of viewpoint at the moment the environment became everyone's problem, having previously been the credo of the worried few. This detour is necessary to understand why and how, in 2019, residents of Shanghai, Belgium and France all questioned the current weaknesses in assessing indoor air quality and called for collective action, whereas in the early 2000s, indoor air had been of interest only to academics.

1 Consumer Science and Analytics (CSA) is a leading institute for market research and opinion studies.

THE DAY THE ENVIRONMENT BECAME "EVERYONE'S PROBLEM"

In December 2017, two years after the Paris Agreement was signed, businesses, governments, public institutions and philanthropists at the *One Planet Summit* declared: "We are ONE planet."

This self-evident fact became a conviction with the emergence of a global awareness of our interlinked destinies. In Asia, America, the Middle East, Europe, Africa and Oceania[2], a large majority of people are saying *"whichever country we live in, our destinies are linked by the choices we make today in the fight against pollution."*

The certainty of this shared destiny is accompanied by a sense of urgency that transcends national borders[3]. It is taking on forms and adopting courses of action we have never seen before. In August 2018, Greta Thunberg initiated school strikes, an unprecedented form of mobilization. On every continent, climate marches took place, with massive participation of both middle- and working-class people. And all around the world, judicialization became part of the arsenal against climate change.

It would be naive or dishonest to ignore the dissenting voices, the tenacious resistance of climate skepticism, and private and public compromises to the environment's detriment. They are legion and ubiquitous, partly because fear alone is not enough to give up ways of life that have been forged over generations.

However, environmental concerns have gained in intensity and, above all, radically changed in nature. In doing so, they have transcended sociological, ideological and partisan divides.

So, what happened? A deeply selfish revolution: the environment has become an issue of personal well-being and thus everyone's problem.

At the end of the first decade of the 21st century, so-called "eco-anxiety" is no longer abstractly collective and distant (the "humanity" and "future generations" we were so fond of talking about in the 1990s), but individual and immediate.

People have been voicing concerns since the 1970s, but they were in a minority. In 1968, the Club of Rome met for the first time. In 1971, Greenpeace emerged. In France, Friends of the Earth took part in the 1974 presidential election. Political ecology was born, though public opinion was mostly unaware of it for almost the next two decades. The environment was the credo of the few.

2 "The challenge of our resources," an Elabe study for Veolia in December 2017, involving 14,000 people in 28 countries (national samples representative of the resident population aged 18 years and over in each of the 28 countries). https://challenge-of-resources.veolia.com/

3 A majority of residents in the countries surveyed believe it is necessary to act quickly to meet the ecological challenge (water, air and soil pollution, climate legislation). "The challenge of our resources," an Elabe study for Veolia in December 2017, involving 14,000 people in 28 countries (national samples representative of the resident population aged 18 years and over in each of the 28 countries). https://challenge-of-resources.veolia.com/

From the 1990s onward, public opinion began to react under the combined effects of government awareness-raising campaigns, the environment's appearance on the national and international political agenda and traumatic events, which although they were not necessarily the results of climate disruption, were attributed to it at the time (in France, for example, the floods of 1992, the hurricane in 1999, the "Black Tide" of January 2000 and the 2003 summer heat wave).

The years 2007 and 2008 were marked by the awarding of the Nobel Peace Prize to the Intergovernmental Panel on Climate Change (IPCC) and to Al Gore for his documentary *An Inconvenient Truth*. Ecological awareness was growing. The concerns reported in opinion polls increased noticeably and there was a proliferation of "responsible" actions.

But people got tired of being afraid. Concerns ebbed as fewer images appeared in the media, and emotions, which are naturally and necessarily temporary, subsided. Economic and social demands rapidly and legitimately diverted the public's attention to the "end of the month."

THE ENVIRONMENT IS THE CREDO OF A GROWING MINORITY AND THE OCCASIONAL CONCERN OF A SMALL MAJORITY

We now hear "the end of the world" reported more and more often. And more and more violently. It's coming – to the point where daily life regularly seems like a kind of dress rehearsal for what could become a permanent state of affairs: heat waves, droughts, pollution spikes and their economic and health consequences here and now are no longer hypotheticals that vary according to the mathematical model used. We have passed from theory (refutable) into experience (irrefutable): chronic respiratory illnesses, cardiovascular disorders, rain that no longer falls, heat that prevents us from working and curtails our mobility and leisure time, drought that weakens houses and reduces crops. Our immediate environment is deteriorating. Between 2011 and 2016, the proportion of French people who rated the environment in their neighborhood as good dropped from 58% to 34%[4]. Over the same period, the percentage of French people who said they personally experienced the consequences of climate disruption in their everyday life rose from 43% to 60%[5].

In 2019, 91% of French people are worried about the environment, with 61% of these "very worried[6]." Additionally, the environment has become the number one priority of French people who identify as working class, just ahead of buying power[7]. Pollution and climate events take no account of origin, social class, political views, religion or region. We have now reached a point where the gap between people who make environmental issues their priority and those who consider them secondary is considered the principal division in French society, ahead of even the social divide[8].

THE ENVIRONMENT IS NOW EVERYONE'S PROBLEM

Climate disruption and atmospheric pollution are the prime movers behind this paradigm shift. Science and medicine brought about the change of scale, by establishing and publicizing the causal links between health and environment, triggering a relentless, powerful increase in concerns about the contamination of the human body by pollutants in the air.

INDOOR AIR: THE EMERGENCE OF A NEW, INVISIBLE ENVIRONMENTAL THREAT

AIR POLLUTION IS NOW ONE OF OUR MOST FEARED ENEMIES[9]

In Europe, it is deemed the most worrying problem after climate change[10]. Indeed, on most continents, air pollution is cause for concern and one of the top three priorities for environmental action, alongside water and ocean pollution, and access to quality nutrition for health[11].

4 "Baromètre annuel sur les opinions et pratiques environnementales des Français," INSEE for the French Data and Statistical Studies Department (SDES), 2011 and 2016.

5 ibid.

6 Elabe study, July 2019.

7 "Fractures françaises," Ipsos for Le Monde, the Fondation Jean-Jaurès and the Institut Montaigne, September 2019.

8 ibid.

9 Third-greatest environmental concern, just behind water pollution and climate disruption, Elabe study, July 2019.

10 "Eurobaromètre spécial 468 : attitudes des citoyens européens vis-à-vis de l'environnement," covering the population aged 15 and over who are nationals of and reside in one of the 28 European Union member countries, October 2017. https://data.europa.eu/euodp/fr/data/dataset/S2156_88_1_468_ENG

11 "The challenge of our resources," an Elabe study for Veolia in December 2017, involving 14,000 people in 28 countries (national samples representative of the resident population aged 18 years and over in each of the 28 countries). https://challenge-of-resources.veolia.com/

KEY INSIGHTS ON AIR QUALITY IN CHINA

2012 can be considered a milestone year for air quality issues in China. Since then, "air quality" has become a hot topic for Chinese citizens, companies and the government. Many individual and systemic initiatives have been taken to achieve a positive shift in China, both in terms of data monitoring and air quality improvement. Here are some highlights.

Increasing awareness regarding air pollution issues:

- In 2013, GreenPeace and Beijing University published a report: *Dangerous Breath 2: Effect of PM2.5 on Chinese Urban Public Study*[12]. At that time, the conclusion showed that PM2.5 had caused 257,000 deaths in 31 major Chinese cities.
- The NGO campaign "Air Warriors", launched in 2014 by Zhao Liang, led to an investigation into some 1000 gas-emitting companies, as well as to 600 environmental upgrading projects and a 1.5 billion RMB investment plan[13].

Changing perceptions of the public:

- According to a 2013 public survey of Shanghai residents[14], social media is the preferred channel to obtain information about air pollution (46.0 %), followed by television (40.3 %), the internet (39.9 %) and mobile television (38.4 %). Few use the hotline call (0.6 %) or an App (2.9 %).
- As reported in the same survey, 58 % of Shanghainese respondents stated that they would reduce or stop outdoor activities during a bad air pollution period and 27 % said they would use protective equipment.
- Since 2011, the e-commerce sector has recorded a large increase in the sales of protective equipment (ex. masks, air purifiers) in China. Between November and December 2015, a period marked by numerous red alarms concerning air pollution, the sales of pollution masks on the Alibaba platform increased almost tenfold[15].
- In 2016, Beijing University and Yale University produced a report which concluded that Chinese city dwellers were willing to pay 539 RMB per year, around 3.8 % of annual family revenue, in order to reduce 1 mcg/m³ of PM2.5[16].

The Government's initiatives to enhance performance and information disclosure:

- Air monitoring is part of a whole national environmental monitoring system. The main focus is on ambient air and industrial emissions monitoring.
- Official information on air pollution is mainly disclosed by the Ecological and Environment Department as well as the China Environment Supervision Station. They take care of 3 main tasks: real time data disclosure in 338 cities, monthly top and worst air quality ranking and air quality forecasts several times per month. In 2019[17], a lot of progress was made in the 74 cities that had implemented the ambient air quality standards. Compared to 2013, the average PM2.5 and SO_2 concentrations decreased by 42 % and 68 % respectively.

12 https://www.greenpeace.org.cn/press-releasedangerous-breath-2/ 《危险的呼吸2: 大气PM2.5对中国城市公众健康效应研究》
13 http://epaper.cenews.com.cn/html/2019-09/30/content_88022.htm
14 https://max.book118.com/html/2018/0326/158823852.shtm
15 http://www.199it.com/archives/419969.html
16 https://mp.weixin.qq.com/s/4Po_qmFzYo9TkUgANazlow
17 <China Air Quality Improvement Report (2013-2018) http://www.gov.cn/xinwen/2019-06/06/content_5397950.htm 《中国空气质量改善报告（2013-2018年）》

WHY SO MUCH ATTENTION?

A 2019 study involving the general public in France, Belgium and Greater Shanghai[18] revealed that the link between health and air quality is an established one.

The effects of outdoor and indoor air on health are considered definite or at least probable by most residents, which represents a huge majority of people who think the state of their health is affected by the quality of the air they breathe, whether outdoors or in enclosed indoor spaces.

18 "La qualité de l'air intérieur," Elabe study for Veolia carried out in France, Belgium and Greater Shanghai, June 2019. https://www.veolia.com/fr/newsroom/dossiers-thematiques/ameliorer-qualite-air

Elabe 2019 study on French, Belgian and Chinese people's perceptions of air quality

In your opinion, does the quality of the air you breathe have an impact on your health?

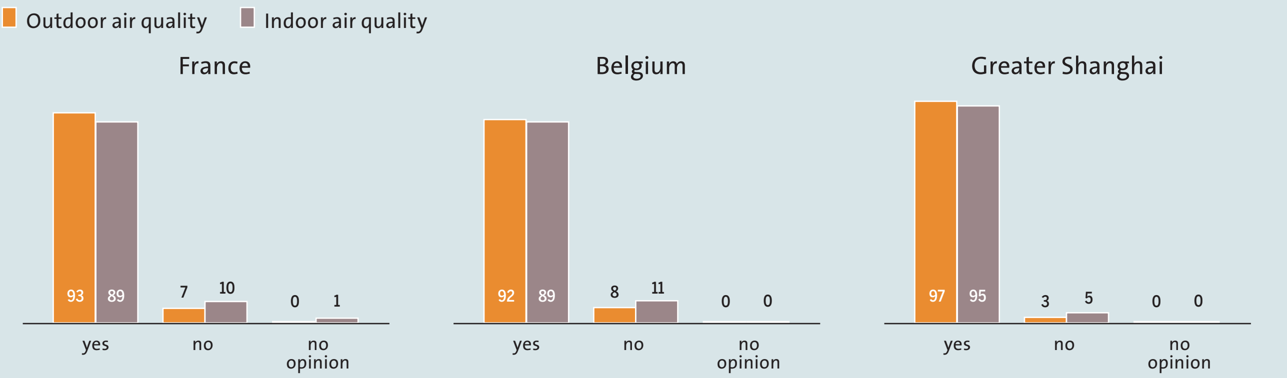


Figure 1

This alignment of opinion between ambient air and indoor air is recent. Indoor air pollution remained relatively unrecognized by public opinion until the early 2000s, unlike outdoor air pollution, which has been regulated for decades and, notably, more widely reported in the media. This reconciliation of opinion followed a chronology similar to that of the medical community's interest in indoor air. It was only in the 1990s that chemical and biological pollution of the air in homes became a plausible explanation for the increase in respiratory illnesses observed by allergists and respirologists[19]. After decades of social silence, the environmental approach to these illnesses began to spread and gradually construct the public existence of indoor air.

Today, indoor air has been identified as a possible source of headaches, fatigue, and irritation of the eyes and respiratory tracts. These symptoms remain occasional for the majority of Europeans. But they at least occasionally affect 29% of French people in their homes, almost two in five in public (entertainment, administration or health care) spaces, one in two in public transportation and 43% of the working population in their places of work. In Belgium, the figures are similar.

19 "Entre expertise et contestation : la problématisation de l'air intérieur comme nouvelle menace environnementale et sanitaire," Céline Guilleux, 2011.

Elabe 2019 study on French, Belgian and Chinese people's perceptions of air quality

Have you personally experienced any effects of indoor air quality on your health?

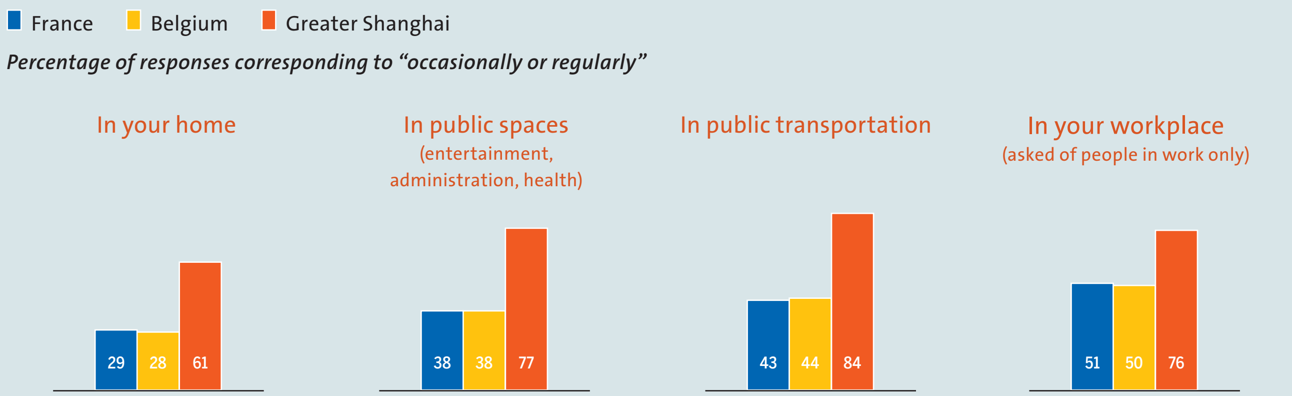


Figure 2

In Greater Shanghai, experience of this pollution is much more frequent: 61% of residents have already experienced these effects in their homes, three in four in their workplaces, 77% in public spaces and up to 84% in public transportation, of whom 37% experience them regularly.

BUT THE RISK IS STILL UNDERESTIMATED

A gap remains to be bridged between awareness of the issue and the correct information.

In France, Belgium and Shanghai, the health risk is being assessed incorrectly – indoor air pollution is still underestimated and the sources of pollution are relativized or ignored.

Make no mistake, French and Belgian people are aware they are guessing and getting it wrong: they all express the same sense of lacking information about prevention, measurement and applicable legislation in the area of indoor air quality.

Elabe 2019 study on French, Belgian and Chinese people's perceptions of air quality

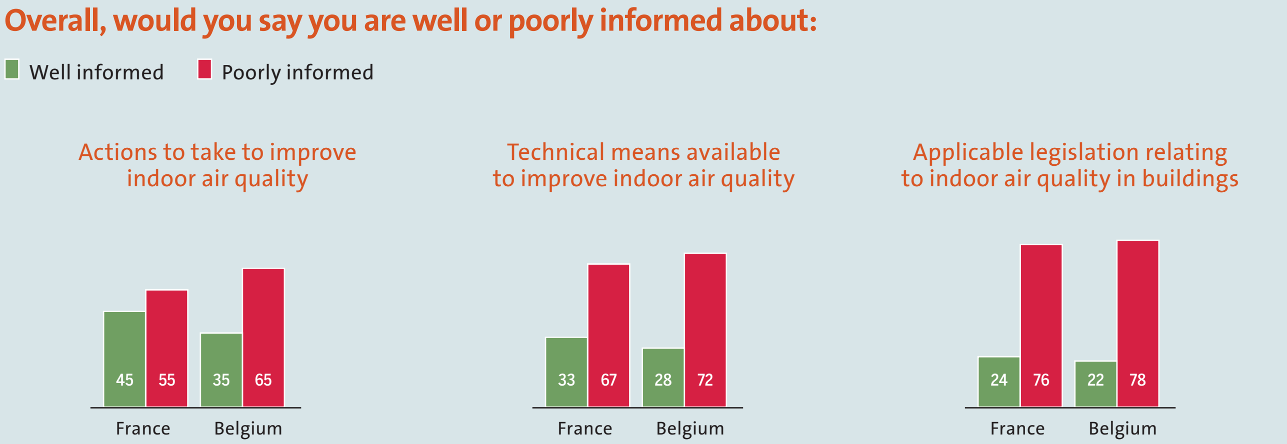


Figure 3

THE RISK OF OVEREXPOSURE TO POLLUTION INSIDE BUILDINGS IS NOT RECOGNIZED

Respectively 52% of French, 60% of Belgian and 62% of Greater Shanghai residents were surprised (with 14% to 16% of these very surprised) to learn that we are exposed to more air pollution inside our homes and the buildings we visit regularly than we are outdoors. Between 2% and 4% were actually convinced this information was false and refused to believe it.

Elabe 2019 study on French, Belgian and Chinese people's perceptions of air quality

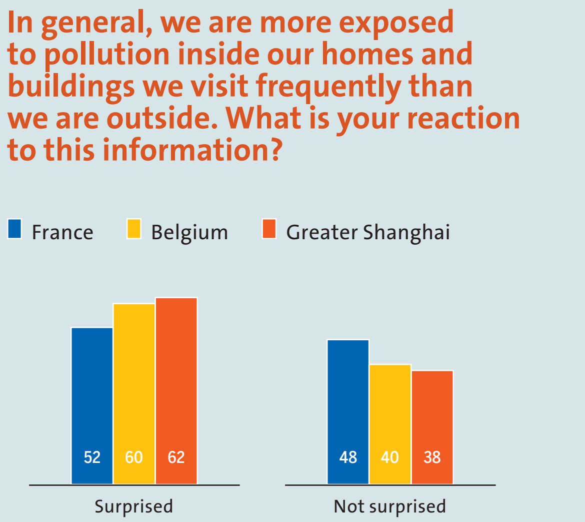


Figure 4

Given this lack of access to an objective assessment of air quality inside frequently visited enclosed spaces[20], diagnosis is made intuitively, by feeling, or viewed through the filter of the home's anthropological function, which is to shelter and protect. These are biased and unreliable indicators in this situation.

The general public basically established three major categories:

1/ Private spaces. These are deemed relatively free from pollution. The more "under control," personal and comforting the space is perceived to be, the more the air is assessed as being of good quality.

Our dwelling is the safest refuge (fewer than one in four people deem the air there to be polluted). In effect, it is difficult to admit that our house, our home is "poisoned" (92% of French people define their dwelling as "a place that feels safe")[21]. The universal image of the protective dwelling is without doubt a psychological obstacle to viewing this place as a potentially dangerous space.

The air in occasional accommodation (hotels, bed and breakfasts, holiday rentals) and in the workplace is also mostly positively assessed, albeit significantly less so. Doubt is much more frequent here.

2/ Open and common spaces. Administrative buildings, shopping malls, public entertainment and health care spaces, educational establishments and retirement facilities are all spaces where indoor air quality divides opinion or raises questions. Often, people even give up trying to make a diagnosis, as feelings are not sufficient. They simply admit they lack the means to assess air quality in these places.

3/ Transportation (individual or shared). In these spaces, a majority are certain they are breathing polluted air.

20 Around three in four respondents said they were poorly informed about air quality in the places they visit frequently.
"La qualité de l'air intérieur," Elabe study for Veolia in France, Belgium and Greater Shanghai, June 2019.

21 "Enquête Conditions de vie et aspirations des Français," CREDOC, June 2008.

The subjectivity of diagnosis is exacerbated by the difficulty in identifying the sources of indoor air pollution.

It was found that 55% of French people and 62% of Belgians considered themselves poorly informed about what actions to take to improve indoor air quality, including their choices of cleaning products. Also, 37% of French respondents, 31% of Belgians and 60% of Greater Shanghai residents deemed themselves only "reasonably well informed."

In this area, the estimation of information is the source of all errors. It leaves the field open to intuition and reliance on the senses (smell, sight).

How can we trust these when we know the risk is lurking even in this lovely candle we bought to "purify" the air, or fur from the cat we bought for our youngest child after lengthy negotiations, but which the whole family now adores? Heaping the blame onto household objects is not an easy change to make.

The proof is that in the game of identifying sources of pollution, there are more losers than winners.

Odorless or "family" sources of pollution are false friends, relativized or unrecognized: incorrect opinions ("not a source of pollution") or nonrecognition ("I have no idea whether it's a source of pollution") exceed 25%, and sometimes reach 41%, for insulating materials, particleboard or plywood furniture, and pets.

Conversely, things that produce unpleasant "odors" or show signs of "visible dirt" or "disrepair" are a clearly identified and feared source of pollution: tobacco smoke, badly maintained chimneys or stoves, molds, heating appliances, boilers, worn-out or badly maintained water heaters and glues are predominantly identified as significant sources of pollution.

In between these two categories, numerous sources are identified, but relativized because they are deemed unimportant: air fresheners, household products, paints, wall and floor coverings, dust, dust mites, candles, incense and room fragrances.

INDOOR AIR QUALITY IN SCHOOLS IN FRANCE: CONCERNED PARENTS WANT TO KNOW [22]

A PUBLIC HEALTH CHALLENGE FOR THE FRENCH, A CONCERN FOR PARENTS

Aware of indoor air quality's effect on their health, the French are naturally establishing this same link between children's health and the quality of the air they breathe in schools (86%, of whom 43% are certain and 43% consider it probable).

Albeit with a little more hesitation, seven in ten French people also associate air quality with an impact on their children's learning and memorization abilities (71%, of whom 27% are certain and 44% consider it probable).

Directly concerned by the quality of their children's learning environment, more and more parents are making these connections.

Elabe 2019 study on parents and indoor air quality in schools (September, 2019)

In your opinion, does the quality of the air children breathe in schools have an impact?

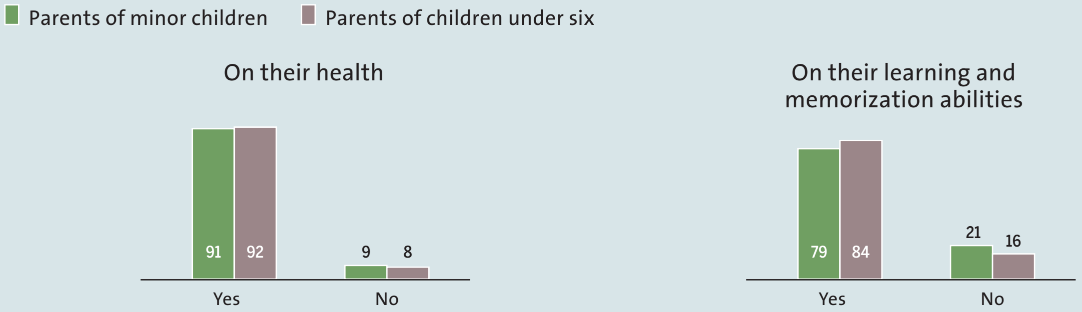


Figure 5

As a focus of attention for most parents, indoor air quality in their children's nursery, elementary, junior and senior high schools is a cause for concern for almost six in ten parents (59%). Concern is all the more acute when the schoolchild is young and therefore vulnerable (66% of parents of children younger than six say they are concerned about indoor air quality in their nursery or school, with 17% of these very concerned).

DEPRIVED OF INFORMATION, PARENTS WANT TO KNOW

Their concern is heightened by the lack of information: 81% of parents of children younger than 18 believe they are poorly informed about indoor air quality in the establishment where their child is enrolled, including 38% who feel very poorly informed.

This sense of shortcoming is confirmed by the inability of one in three parents to make even an approximate assessment of the quality of the air their children breathe in school: 33% state that they currently have no way of knowing what the situation is. And while 67% are prepared to hazard an assessment, this is most often hesitant and cautious: 39% of parents think the indoor air in their children's school is of reasonably good quality, but 23% think it is of quite poor quality. With information lacking, doubt sets in and concerns increase, which may be irrational or baseless in many cases. But it's there.

The first battle on the subject of indoor air quality is therefore in finding this "way of knowing" and putting an end to doubt: 83% said that as a parent, it is important for them to have access to an assessment of the quality of the air their children breathe (of these, 30% said very important).

22 "Les parents et la qualité de l'air intérieur dans les écoles", Elabe study for Veolia, September 2019. https://elabe.fr/les-francais-et-la-qualite-de-lair-interieur-dans-les-ecoles/

CONCLUSION

The gap between awareness of the threat to health and access to a minimum of information (Is the air I breathe of good quality? Should I take preventative or corrective measures or demand they be taken?) highlights the **seriousness of the information and prevention issue.**

The French, Belgians and Shanghai residents are not mistaken; they are convinced that information on sources of pollution and the actions to take is an essential lever for improving indoor air quality (90% consider it important, of whom 39% deem it very important).

But information and changes in individual practices are not enough.

The general public believes that **indoor air is not simply a domestic problem for which individuals alone are responsible.** More robust legislation and standards are considered indispensable, along with collective action and the involvement of all players concerned with indoor air quality, construction and legislation.

Elabe 2019 study on French, Belgian and Chinese people's perceptions of air quality

In your opinion, how important is each of these levers for improving the indoor air quality of buildings?

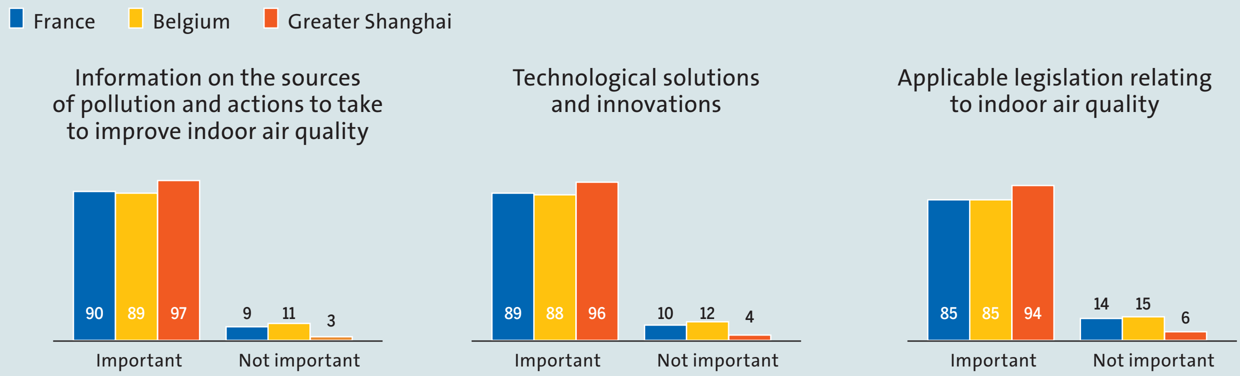


Figure 6

In your opinion, how important is each of the following actors in improving indoor air quality in buildings?

Percentage of the importance of the different actors' roles in improving indoor air quality in buildings	France	Belgium	Greater Shanghai
The companies that manage the buildings' ventilation and heating systems	89	90	95
Construction companies	88	86	93
Government	85	85	96
Health professionals	85	85	83
Manufacturers (furniture, decoration, construction, household products)	85	81	95
Retailers (furniture, decoration, construction, household products)	81	74	90
Installers and fitters	86	84	85
Local government authorities	81	77	88
Consumer associations	79	74	83
My employer *(asked of in-work respondents only)*	69	77	88

ELABE 2019 STUDY ON FRENCH, BELGIAN AND CHINESE PEOPLE'S PERCEPTIONS OF AIR QUALITY AND ELABE 2019 STUDY ON PARENTS AND INDOOR AIR QUALITY IN SCHOOLS (SEPTEMBER, 2019)

Surveys	Indoor air quality perception Survey 1: The French and indoor air quality	Indoor air quality perception Survey 2: The Belgian and indoor air quality	Indoor air quality perception Survey 3: Shanghai residents and indoor air quality	Indoor air quality in schools
Panel	A sample of 1,063 people, representative of Continental France residents aged 18 and over. Quota method applied to gender, age, socio-professional status, city-level and regional-level criteria.	A sample of 1,056 people, representative of the residents of Belgium aged 18 and over. Quota method applied to gender, age, socio-professional status, city-level and regional-level criteria.	A sample of 1,001 people, representative of the residents of Shanghai aged 18 and over. Quota method applied to gender and age criteria.	A sample of 1,010 people, representative of residents of metropolitan France aged 18 and over, and an oversample of 351 parents with children under 18, i.e. a total sample of 1,361 people, including 607 parents of minor children. Quota method applied to gender, age, socio-professional status, city-level and regional-level criteria.
Distribution	Online surveys			
Dates	Friday 12 to Monday 15 April 2019	Wednesday April 24 to Wednesday May 1, 2019	Thursday May 2, to Monday May 13, 2019	Tuesday September 3, to Wednesday September 4, 2019

A MULTIPARTY AND GLOBAL EFFORT TO ADDRESS AIR POLLUTION AROUND THE WORLD

Helena Molin Valdés,
Head of the Coalition Secretariat, Climate & Clean Air Coalition

Dirty cookstoves are one of the sources of household air pollution

Helena Molin Valdés is the head of the Climate and Clean Air Coalition (CCAC) Secretariat at the UN Environment office in Paris, a position that she has held since 2013. Helena is an experienced leader within the UN system. She was a senior executive with the UN Office for Disaster Risk Reduction (UNISDR), where she led work on resilience, disaster risk reduction, sustainable development and climate change related topics. She was UNISDR's regional director for Latin America and the Caribbean and worked with the Pan American Health Organization on hospital mitigation and disaster preparedness. Before joining the UN, Helena was a practicing architect, planner, and head of a Swedish NGO based in Central America that worked on community-based projects and appropriate technology development, including improved bricks production and cook stoves with the University of Lund.

The Climate & Clean Air Coalition (CCAC) is an initiative that unites governments, civil society, international organizations, research institutions and the private sector, committed to improve air quality and protecting the climate in the next few decades by reducing short-lived climate pollutants, such as black carbon, methane, HFCs and tropospheric ozone across sectors.

The CCAC acts as a catalyst to reduce these pollutants and implement and share immediate solutions addressing near-term climate change.

The CCAC works at identifying, promoting and supporting best initiatives and projects regarding air quality.

This article presents some exemplary projects improving air quality in rural and underprivileged areas:

- **In Mongolia, the CCAC has provided technical assistance to the Mongolian bank *XacBank*, in order to study affordable improved technologies for heating, such as electric and solar power;**
- **In Nigeria, the CCAC supports a women's association that has created a network of women entrepreneurs to provide affordable clean energy solutions across the country;**
- **In Sweden and Chile, an awareness campaign was launched on a global online platform sponsored by the CCAC. It asks woodstove users to follow a few simple steps when burning solid fuels to get better heat output, while reducing fuel use and harmful emissions by as much as half;**
- **The CCAC supported the Gold Standard Foundation in the creation of a monitoing methodology and ISO standard specific to cookstoves. The aim is to improve access to carbon financing markets and make stoves more affordable.**

Given that indoor air pollution is primarily a result of poverty and, as such, impacts the most vulnerable populations (women and children), initiatives that improve indoor air quality must be considered as a global priority.

What is the Climate and Clean Air Coalition and what is its role regarding air quality issues?

Helena Molin Valdés: The Climate and Clean Air Coalition (CCAC) is a voluntary partnership of governments, intergovernmental organizations, businesses, scientific institutions and civil society organizations committed to improve air quality and protect the climate through actions to reduce short-lived climate pollutants[1] (SLCP).

This global network, created in 2012, currently includes over 140 state and non-state partners, and hundreds of local actors from the private sector, supporting fast action and delivering benefits on several fronts at once: climate, public health, energy efficiency and food security.

The Coalition helps partners and stakeholders create policies and practices to deliver substantial reductions in short-lived climate pollutant emissions. It supports actions on the ground through 11 initiatives designed to provide transformative action in specific sectors or as cross-cutting efforts to reduce air pollution:

- Seven initiatives focus on specific sectors (heavy duty vehicles, oil and gas, waste, bricks, hydrofluorocarbons and efficient cooling, household energy, agriculture) to identify the most cost-efficient and practical pathways to reduce their emissions. These actions include training and institutional strengthening, support for developing laws, regulations, policies and plans, technology demonstrations, political outreach, awareness raising campaigns, co-funding and catalyzed funding, and development of knowledge resources and tools. The coalition works closely with relevant communities, industry representatives, NGOs and policy makers to support targeted improvements in technology, best practice and policies;
- Four other initiatives carry out work across sectors to accelerate emissions reductions for all short-lived climate pollutants (SNAP[2], finance, assessments, health).

1 Short-lived climate pollutants are powerful climate forcers that remain in the atmosphere for a much shorter period of time than carbon dioxide (CO2), yet their potential to warm the atmosphere can be many times greater. The main SLCP are black carbon, methane, tropospheric ozone, and hydrofluorocarbons.

2 SNAP: Supporting National Action and Planning on Short-Lived Climate Pollutants. The Coalition's SNAP Initiative is a collaborative programme aimed at supporting the efforts of Coalition partner countries to scale up action in a coordinated and prioritized way.

Solar energy in Madagascar

In addition, the Coalition's activities follow sixteen measures addressing black carbon[3] and methane, identified in a 2011 UN Environment and World Meteorological Organization (WMO) assessment[4], and also alternatives to hydrofluorocarbons (HFCs) in the cooling sector. These measures target the primary sectors responsible for short-lived climate pollution emissions: replacing wood stoves and burners with pellet stoves; banning open-field burning of agricultural waste; recovering and using gas and fugitive emissions during oil and natural gas production; upgrading wastewater treatment with gas recovery and overflow control, etc. are all examples of measures promoted by the Coalition. Almost half of these measures could provide co-benefits for air quality, human health, ecosystems and food security. If implemented globally by 2030, these measures could reduce global methane emissions by as much as 40% and global black carbon emissions by as much as 80% relative to a reference scenario, preventing up to 0.5 °C of warming[5].

The Coalition has also set up a Solution Centre[6] to provide resources, training materials, and expert advice on a range of measures and policies to reduce short-lived climate pollutant emissions (guidelines and tools, webinar and training, expert assistance, resource library).

What are the risks related to indoor air quality, especially for the poorest, but also for the environment?

H. M. V.: Indoor air pollution has a direct impact on health. According to the World Health Organization, air pollution in general is responsible for 7 million premature deaths per year. More than half of those (3.8 million) can be attributed to household exposure to smoke from dirty cookstoves, heatstoves and fuels, as the main reason for indoor air pollution is the use of kerosene, coal, wood and other biomass burning for cooking, heating and lighting. Today, 3 billion people – more than 40% of the world's population – still do not have access to clean lighting, cooking fuels and technologies in their homes.

The WHO has been monitoring household air pollution for over a decade, and while the rate of access to clean fuels and technologies is increasing everywhere, improvements are not keeping pace with population growth in many parts of the world, particularly in sub-Saharan Africa. In addition, some people suffer from more exposure and impacts than others. These include women, children and elderly persons, since they spend more time at home. The more we look at the impacts of indoor air pollution on health, the more we realize that it is a much more serious problem than previously thought. We know now that one of the most important health interventions we can make is to ensure that people can access clean household energy. Indoor air pollution must also be considered with regards to justice and gender issues. Very often, indoor air pollution is primarily a result of poverty, including energy poverty. What we do know is that it impacts women and girls disproportionately:

- Fuel collection and risks associated with the use of some traditional technologies are affecting livelihoods. For instance, hazards from kerosene use include poisoning, fires, and explosions. Use of these polluting cooking, heating and lighting technologies also contributes to outdoor air pollution. Sustainable Development Goal number 7[7] sets the specific goal to "ensure access to affordable, reliable and modern energy for all by 2030". It has also been shown that new wood stoves deployed in high income countries can make important contributions to both indoor and outdoor air pollution with associated health impacts;
- Cooking exposes women and children, who are often close to their mothers while they are cooking, to noxious emissions: indeed, household cooking and heating account for 58% of global black carbon emissions;
- Children using highly polluting kerosene lamps to do their homework are exposed to long-term health risks while trying to make a better life for themselves;
- Collecting firewood is an exposed activity for women, considering the dangers they face while doing that, including violence, sexual violence and abuse;
- Particulate emissions from dirty cookstoves or heatstoves are directly disrupting meteorological processes affecting precipitation that millions of people depend on for their available drinking water and crop irrigation. Collection of fuelwood for cooking and heating as well as charcoal production contribute to forest degradation and land use changes.

Around 3 billion people – more than 40% of the world's population – still do not have access to clean cooking fuels and technologies in their homes, the main source of household air pollution

The other important global aspect of indoor air pollution is its impact on the climate. We know that cooking and heating stoves are major emission sources of black carbon, which is a powerful climate forcer and impacts local weather patterns. Black carbon

3 Black carbon is a potent climate-warming component of particulate matter formed by the incomplete combustion of fossil fuels, wood and other fuels. Complete combustion would turn all carbon in the fuel into carbon dioxide (CO_2), but combustion is never complete and CO_2, carbon monoxide, volatile organic compounds, and organic carbon and black carbon particles are all formed in the process.

4 https://library.wmo.int/index.php?lvl=notice_display&id=12414#.XWk29CgzaUk

5 Integrated Assessment of Black Carbon and Tropospheric Ozone, United Nations Environment Programme, World Meteorological Organization (WMO), 2011

6 https://www.ccacoalition.org/en/solution-centre

7 Ensuring universal access to affordable electricity by 2030 means investing in clean energy sources such as solar, wind and thermal. Expanding infrastructure and upgrading technology to provide clean energy sources in all developing countries is a crucial goal that can both encourage growth and help the environment.

is an important contributor to warming, because it is very effective at absorbing light and heating its surroundings. Per unit of mass, black carbon has a warming impact on climate that is 460-1,500 times stronger than carbon dioxide (CO_2). When deposited on ice and snow, black carbon reduces their ability to reflect sunlight, and heats the surface. The Arctic and glaciated regions such as the Himalayas are particularly vulnerable to melting as a result. This threatens the water supply of billions of people. In Arctic countries, this is leading to awareness campaigns, to reduce the impact of household emission sources on local air pollution.

While many national and international actors are already working on the challenge of transforming the way billions of people around the world cook their food and heat and light their homes, SLCP[8] considerations remain mostly absent from ongoing efforts, and integration of health and climate change mitigation approaches is still lacking. As such, dirty cookstoves and heatstoves represent an important, yet largely untapped opportunity for SLCPs emissions mitigation and realization of air quality, climate, environmental, social and economic benefits.

Indoor air pollution must also be considered with regards to justice and gender issues. Very often, indoor air pollution is primarily a result of poverty [and] it impacts women and girls disproportionately

The CCAC is trying to help address the issue in many ways, including by helping countries around the world seize the opportunity for black carbon and air pollution mitigation. This year, with other partners, it launched a research study to deepen the understanding of the relationship between emissions and exposure.

According to you, which levers can be implemented to improve indoor air quality?

H. M. V.: A crucial lever is improving access to clean energy for 3 billion people. Getting renewable energy on small local distribution grids will help people phase out fossil and polluting fuels. The CCAC has worked with development banks and micro-finance institutions to develop programs to support impoverished communities and enable them to get access to renewable energy.

One example is *XacBank*, in Mongolia. In this country, the smoke from coal and wood burning is a major contributor to black carbon and PM2.5 air pollution, and has made the capital, Ulaanbaatar, one of the most polluted cities in the world. The Coalition is thus providing technical assistance to the Mongolian bank *XacBank* to study affordable improved technologies, like electric and solar, for heating. In partnership with the Frankfurt School of Finance & Management, the Coalition is also supporting a feasibility study that will advise *XacBank* on the design of a financial product to help poor families afford cleaner heating options.

There is a need to create conditions for efficient combustion. Very concrete levers exist: in places with poor access to alternative fuels or renewable energy, installing more efficient cookstoves partly answers indoor air pollution issues and can also help mitigate the climate change impacts. These cookstoves ensure that solid fuels are burned more efficiently, and that proper combustion takes place, reducing both the amount of pollution generated during cooking and the amount of fuel used.

Another important lever lies in the household lighting sector. According to the World Bank, about 101 million (out of 212 million) people in Nigeria do not have access to the electrical grid. In rural areas, only 34% of Nigerians have access to the grid. Most people rely on kerosene lamps, candles and torches for lighting. Yet, this type of lighting can be easily replaced by inexpensive solar lighting. In Nigeria, a group of rural women are working to protect themselves and their families from dangerous air pollution: the Rural Women for Energy Security (*RUWES*), a sisterhood of over 2 million Nigerian women, is taking control of household energy decisions by creating clean energy enterprises, training women in the manufacturing and maintenance of clean cookstoves and solar systems, and creating a network of women to provide affordable clean energy solutions across the country. *RUWES* is creating a viable market and sustainable supply chain for clean energy technologies, provides a source of income for women by helping them become clean energy entrepreneurs, and supplies clean energy to homes and small businesses. It helps women access finance for business incubation and entrepreneurship. By 2020, *RUWES* hopes to provide 20 million clean cookstoves across Nigeria's six-geopolitical zones.

However, those projects must be considered in a harsh economic context (impoverished households with very low revenues and almost no access to job markets, meaning that people might not be able to purchase new equipment despite being on the energy grid), while the cultural dimension can also be an obstacle (reluctance to change cooking or heating habits). Changing the way billions of people around the world cook their food, and heat and light their homes remains a very challenging task, and current levels of financial support going to the sector remains largely insufficient.

Finally, helping leaders realize the opportunity that the sector represents to reduce black carbon emissions and hence mitigate climate change can be an important lever that the CCAC is trying to help materialize.

8 Short-lived climate pollutant

In your opinion, what are the best public policies and environmental practices related to indoor air pollution and energy efficiency (developed countries excepted)?

H. M. V.: Some countries have implemented effective and ambitious public policies: The *Santiago Respira* campaign in Chile[9] is a good example of how to build public opinion support and to collect ideas for a "decontamination" plan. Another example of effective public policy can be found in Peru with the ambitious stove distribution program named *Clean Cook stove Program Peru*[10].

In Asia and Africa, progress towards improved and cleaner stoves has been slower. However, some initiatives must be underlined: Kenya has the leading market for improved cookstoves thanks to a bunch of innovative and successful companies. For instance, *Koko networks* is a venture-backed technology company operating in East Africa and India. It builds and deploys dense Networks of cloud connected "*KOKOpoints*" inside local corner stores, which serve as consumer access points for goods and services delivered in partnership with major suppliers. The network is distributing ethanol gel for cooking which delivers significant cost savings and quality of life improvements. In parallel, a number of companies like *Envirofit*[11] do "pay-as-you-cook"[12] methods meaning that the user and the distributor can track and monitor the consumption of the gas, to make it affordable for low-income earners and the middle class.

Governments can also support the energy transition by transferring subsidies away from polluting fuels like kerosene and coal to solar, biofuels, biogas[13], Liquefied petroleum gas (LPG), and other cleaner solutions.

India's LPG reform is a rare success story. It has achieved much in the difficult area of energy subsidy reform. *PaHaL*[14], India's cooking gas subsidy, is the largest

9 Santiago Respira aims to improve air quality through solutions that target multiple sectors such as energy, transportation, and waste management.

10 Clean Cook stove Program Peru. To date, more than 107,000 Peruvian families have received a new cookstove.

11 Envirofit International is a social enterprise that innovates smart energy products and services that improve lives on a global scale

12 By paying through Mobile Money, the quantity of gas to use during a certain period of time, also called "Pay As You Cook".

13 Which can be locally produced from dung and organic waste through bio digesters

14 Pratyaksh (Direct) Hastantarit (Transfer) Labh (Benefit) in Hindi.

Nigerian women from the Rural Women for Energy Security (RUWES) with clean cookstoves direct benefit transfer program in the world. *PaHaL* has increased efficiency and reduced leakage compared to the previous in-kind subsidy regime, resulting in significant fiscal savings for the government with minor costs. By providing additional fiscal space, it has also facilitated a rapid expansion of clean cooking fuel, especially to poor rural households who were previously left out of the LPG network. In the process, it is reducing exposure to household air pollution with positive long-term health benefits, in particular for rural women and girls.

What have been the most significant and innovative initiatives of the private/ associative sectors regarding indoor air quality over the last few years?

H. M. V.: In the last few years, many renewable technology initiatives to reduce the price of solar lighting systems have been developed and deployed, especially in rural energy poor areas. Working to improve solar and other renewables while also reducing the price of these systems is important to reduce household air pollution in many places.

Other initiatives are emerging around carbon/climate finance mechanisms and innovative financing schemes developed with manufacturers, banks and other financial institutions, to finance clean household energy technology. The CCAC supported the creation of a black carbon monitoring methodology by the Gold Standard Foundation, to give more efficient cookstoves access to carbon financing markets and make stoves more affordable. Stove manufacturers need the subsidies from carbon finance to lower the price of technology.

Some firms are answering the air pollution issue through innovation: *IKEA* created in 2019 a curtain that absorbs air pollution[15]. The curtain uses a unique technology, developed in partnership with universities in Europe and Asia, as well as IKEA suppliers and innovators. The way it works is similar to a photosynthesis process, activated by both outdoor and indoor light. However, this is clearly a high-end market solution, which does not address the problems of the most impoverished households.

Nexleaf Analytic is an important social enterprise using innovation to fight air pollution. This nonprofit technology company has a unique bottom-up approach for bringing data-driven solutions to public health and climate change interventions in low- and middle-income countries. The firm builds and uses cloud-based sensors, dashboards with visualizations and customizable analytics tools designed to help its partners monitor the uptake of improved cooking technologies and access climate finance credits. For instance, they built and installed *StoveTrace* in more than 700 households in India, a cloud-based remote monitoring system for improved cookstoves in rural households, which measures how often the stoves are used. The data allows stove manufacturers to track the way their products are used. It also enables payments to households via carbon markets and carbon funds to subsidize and encourage the use of cleaner stoves.

There is a growing market for products that protect people from both outdoor and indoor air pollution. However, mere protection is not enough. We need the private sector to innovate and to move us away from polluting technologies but also polluting commercial models and production chains as fast as possible. De-carbonising and moving to low-to-zero emissions forms of energy (whether for transport or energy production) throughout the life cycle of the associated technologies is the condition to ensure good public health.

De-carbonising and moving to low-to-zero emissions forms of energy through the life circle of the associated technologies is the condition to ensure good public health

15 https://www.ikea.com/us/en/about_ikea/newsitem/021919-IKEA-GUNRID-curtain

ADDRESSING INDOOR AIR POLLUTION CHALLENGES THROUGH CONCRETE PUBLIC POLICIES IN SOUTH KOREA

Dr. Dong Hwa Kang
Associate Professor of Architectural Engineering Department,
University of Seoul

Ventilation units on a building façade

Dr. Dong Hwa Kang is an Associate Professor of the Architectural Engineering Department at the University of Seoul (UOS). Before joining UOS in 2014, Professor Kang worked as a Postdoctoral Research Fellow at the Institute for Research In Construction of the National Research Council Canada and as a Postdoctoral Scholar at the Pennsylvania State University. He received his B.S., M.S and Ph. D degrees in Architectural Engineering from Seoul National University.

Professor Kang's current research interests focus on ventilation and air cleaning system design to minimize the adverse effects of indoor air pollution on occupants. His publications deal with numerical modeling of indoor pollutant emissions from building materials, contaminant transport and dispersion analysis in buildings, and the development of particle filtration systems integrated into a double skin façade in buildings. Professor Kang is a member of international and Korean professional associations including ASHRAE (American Society of Heating, Refrigerating, and Air Conditioning Engineers), ISIAQ (International Society of Indoor Air Quality and Climate), KOSIE (Korean Society for Indoor Environment), AIK (Architectural Institute of Korea).

In this interview, Dr. Kang illustrates some of the ways in which a country can address indoor air quality issues through legislation. Taking South Korea as a case study, the article explores the measures available to governments to ensure efficient control of indoor air quality, and to elaborate a plan for improvement going forward. Through a discussion on public-private interactions, the author shows that indoor air quality is a complex issue that requires an alignment of all policies, market forces and citizens in order to be managed appropriately. By and large, it is the dialogue and transparency between these different actors that ensures that good practices are promoted, and appropriate measures taken. While South Korea seems particularly advanced in orchestrating a response to air quality issues on a national scale, it is hoped that other countries will be inspired by the results achieved and follow suit by drafting innovative legislation on the topic.

What are the main issues regarding indoor air quality in South Korea (types of pollutants, rate of fine particles, etc.)?

Dong Hwa Kang: For some years, the main concern in Korea regarding indoor air quality has been the existence of fine particles such as $PM_{2.5}$ and PM_{10}. The high concentration of fine particles in the atmosphere during spring and winter as well as issues relating to the management of indoor fine particles in residential buildings are attracting much attention from building companies and residents. According to a recent study[1] which investigated the impact of outdoor particulate matter on indoor air quality in Korean residential buildings, an indoor fine particle infiltration factor of 0.65 was measured for apartments in Korea[2], indicating that fine particles in the atmosphere significantly impact indoor air quality. Accordingly, the sales of air cleaners have been increasing, as people attempt to reduce indoor fine particle concentration levels.

Another central issue is the presence of radon[3] in apartments. The Ministry of Environment recently conducted a survey on apartments that revealed radon presence and raised the need for remedial action, leading to the creation of new management criteria for indoor air quality. In 2018, the recommended radon criterion for new apartments was newly set at 200 Bq/m^3, and this restriction was reinforced to 148 Bq/m^3 in July 2019. Generally, radon gas is known to enter buildings through cracks in underground structures, but the radon in Korean apartments is thought to come from building materials. However, there is no standard method for evaluating the radon exhalation rates of building materials, although efforts are being made to create such a standard.

According to you, what are the most effective measures that the Korean government has taken to tackle the indoor air quality issue? What are the latest evolutions in public policies?

D. H. K.: There is a strong interest in apartment residents' health and in apartments' asset value in Korea, which has stimulated the government to legalize strict management criteria for indoor air quality. Korea is one of the few countries in which indoor air quality is legislatively managed. For instance, the problem of Sick Building Syndrome caused by volatile organic compounds (VOCs) and formaldehyde in new apartments was addressed thanks to regulations such as the 2009 Housing Act[4] adopted by the Ministry of Land, Infrastructure and Transportation (MOLIT) and the Indoor Air Quality (IAQ) Act for Public Use Facilities[5] adopted by the Ministry of Environment (MOE).

There is a strong interest in apartment residents' health and in apartments' asset value in Korea, which has stimulated the government to legalize strict management criteria for indoor air quality

In 2014, the government established the "Five-Year Basic Plan for Indoor Air Quality Management" to systemize management of indoor air quality. The plan is a National Basic Plan which proposes coordination methods between ministries that prepare detailed measures for indoor pollutant and management facilities, and that supervise and manage these pollutants. The plan requires an analysis of the state of indoor air quality management and related issues to be conducted every five years, in order to guide future policy directions. Currently, the 4th Basic Plan for Indoor Air Quality Management (2020 to 2025) is being drafted. It aims to set up effective management measures for the presence of VOCs and formaldehyde in various multi-use facilities (including newly built apartments), as well as to reinforce management measures for current issues such as fine particles and radon, for instance by developing educational programs or material labeling programs.

In addition, in order to provide more practical and holistic control measures, the Construction Standard for Healthy Housing (CSHH) was introduced in 2014 by decree to extend the Housing Act. The CSHH covers:

1) Source controls such as the application of low-pollutant-emitting building materials;
2) Ventilation controls such as the compulsory installation of ventilation systems;
3) Removal controls such as the application of VOC-absorptive building materials.

The CSHH works as follows: the construction project entity (generally a construction company) which plans to build or remodel a new apartment building of more than 500 units must prepare a CSHH self-evaluation report including detailed plans to meet the requirements suggested by the CSHH. The submission of the self-estimation report as well as the report for the confirmation of self-estimation is a crucial process to control the implementation of the CSHH. The construction company should file both reports with a public office at both the design stage and the construction-complete stage. The report for the confirmation of the self-estimation should be made by a construction inspection company and submitted to the public office. All in all, the policy supports effective control of the implementation of the CSHH.

1 Choi, D.H. and Kang, D.H. (2017) Infiltration of Ambient PM2.5 through Building Envelope in Apartment Housing Units in Korea. Aerosol and Air Quality Research 17(2), 598-607.

2 The infiltration factor represents the equilibrium fraction of ambient PM that penetrates indoors and remains suspended in the indoor air.

3 Radon is a radioactive, colorless, odorless, tasteless noble gas.

4 Housing Act, Ministry of Land, Transportation and Maritime Affairs, 2009.

5 Indoor Air Quality Control In Public Use Facilities Act, Ministry of Environment, 2008.

View of the city of Seoul, South Korea

In case respecting the CSHH increases construction expenses (for example by using sorptive[6] building material), the construction company is allowed to pass on these additional costs to the sale price of the apartment (even though that price is regulated by government law).

What is the process to check that the measures are well implemented?

D. H. K.: Based on the CSHH self-evaluation report submitted to a public office at the design stage by the construction company, residential housing units should be inspected at the construction-complete stage prior to occupancy by a construction inspection company, in order to confirm that the detailed plans, suggested by the project entity, have been properly implemented. Both the construction company and the construction inspection company should then write a report to the public office, confirming that the CSHH has been respected.

Building companies have cooperated with ventilation companies and made innovative attempts to address fine particle issues

In addition, a check-up of the ventilation system must be performed by a TAB (testing, adjusting, and balancing) engineering firm chartered by the Society of Air-conditioning, Refrigerating Engineers in Korea (SAREK). All housing units must be tested to check ventilation systems. The detailed check-up procedure is specified for TAB of ventilation systems in a residential building by SAREK.

Have you observed any significant improvement since the implementation of the Construction Standard for Healthy Housing? Has this norm been revised since its implementation in 2014?

D. H. K.: According to the Construction Standard for Healthy Housing (CSHH), building companies and building owners must use building materials that meet the regulatory pollutant emission criteria. However, subsequent surveys on the indoor air quality of newly built apartments have revealed a high rate of nonconformity. The exact reason for this nonconformity is unclear, but a possible cause is airtight construction, which is done in order to reduce a building's energy consumption. As a solution, each local government establishes its own criteria to enforce the use of sorptive building materials. For instance, the city of Seongnam has passed regulation that requires the use of sorptive building materials for over 60% of the indoor wall area. In comparison, the CSHH recommends that only a minimum of 5-10% of the indoor wall be made of sorptive building materials.

6 Sorptive building materials can decrease the concentration of an indoor air pollutant by capturing pollutant particles.

Korea has established an Eco label for the building sector. Does this label take into account indoor air quality issues? If so, how does this label work?

D. H. K.: The Eco Mark and HB (Healthy Building) Mark of Korea have induced the use of low-emission building materials by informing consumers of VOC and formaldehyde emissions from building materials. These eco label systems, however, are not suitable for the management of all building materials distributed in the market. This is because eco labels are only provided in relation to building materials for which their manufacturers have requested certification (on a voluntary basis). The Indoor Air Quality Control Act prohibits the use of building materials that exceed the specified emission criteria for pollutants (formaldehyde and VOCs) in apartments. Current building material restrictions have limitations in managing complex and diverse building materials affected by indoor pollutants as they depend on surveys of samples collected from the market, which are not necessarily representative. Therefore, further reinforcements have been implemented in relation to the management of building materials since 2016 by obliging manufacturers and importers to receive certified emission data from authorized testing agencies before supplying materials to apartment construction companies.

There must be efforts to find a solution which allows appropriate indoor air quality to be maintained while reducing energy consumption. Examples of research topics include the development of energy-saving heat recovery ventilators and air cleaning systems

What have been the most significant and innovative initiatives of the private sector regarding indoor air quality over the last few years?

D. H. K.: Building companies in Korea have developed and applied various housing technologies to meet the demands of residents in relation to indoor air quality. Building companies have cooperated with ventilation companies and made innovative attempts to address the issue of fine particles, such as with the installation of FAC (Fresh-air Air Cleaner) systems with enhanced filtration systems, air shower systems which can remove the dusts from occupants' clothes at the entrance and so on. These methods have never been previously attempted in residential apartments.

In order to respect the pollutant thresholds and legal criteria prescribed by government acts, as well as the demands of residents, building companies engage in active research and development of construction technology. This process is currently being repeated as recent issues relating to indoor air quality – fine particles and radon – have emerged. Building companies are also making various efforts to address issues head on, for example by installing HEPA filters[7] on mechanical ventilation systems (the Housing Act prescribes that a new building with over 100 living units should adopt mechanical ventilation systems or natural ventilation devices capable of maintaining a 0.5 air exchange rate).

Which research topics do you think should be further investigated within the frame of indoor air quality?

D. H. K.: The airtightness in buildings is continuously increasing in order to reduce energy consumption. In such airtight buildings, however, the concentration of pollutants may increase because it is not easy to discharge indoor air pollutants. Therefore, there must be efforts to find a solution which allows appropriate indoor air quality to be maintained while reducing energy consumption. Fresh outdoor intake has been one effective solution put forwards in ventilation textbooks. However, in Korea, where outdoor air is polluted due to fine particles, such solutions might be more difficult to find. Therefore, I believe that we need to conduct more studies on the development of indoor air quality management measures for airtight buildings. Examples of research topics include the development of energy-saving heat recovery ventilators and air cleaning systems. Considering the impact of outdoor-originated pollutants on indoor environments, studies seeking to identify the correlation between building airtightness measures and indoor air quality will be important. In addition, the continuous construction of databases on various indoor pollutants will serve as useful information to effectively manage indoor air quality at all design, construction, and operation stages for buildings.

7 HEPA filters (High Efficiency Particulate Arresting), which means High Efficiency Particulate Catchers, absorb the particles suspended in the air.

WHO OWNS THE AIR? EMISSIONS TRADING AND CONTEMPORARY MEDIA ART

Andrea Polli,
Artist and Professor, University of New Mexico

Andrea Polli - Particle Fall projected on the Stevens Center building in downtown Winston-Salem, NC © Jared Rendon-Trompak

Andrea Polli, professor with appointments in the College of Fine Arts and School of Engineering at the University of New Mexico (UNM), is also an environmental artist working at the intersection of art, science and technology. Her interdisciplinary research has been presented as public artworks, media installations, community projects, performances, broadcasts, mobile and geolocative media and publications. She creates artworks designed to raise awareness of environmental issues. These works often showcase scientific data (obtained thanks to collaborations with scientists and engineers) through sonification, light installation or experimental architecture. She has received numerous grants, residencies (at Eyebeam for instance), and awards including the Fulbright Specialist Program (2011) and the UNESCO Digital Arts Award (2003).

The accelerating climate change crisis and the realization that humans are the primary cause of it has raised questions about ownership and responsibility. Who "owns" the climate change crisis and who is responsible for mitigating and reversing it if possible? One overwhelming response by governments on an international level has been to propose a market solution by selling the atmosphere. Is the commercial marketplace the only answer? How can art, technology and media offer alternative cultural practices and open new forms of understanding the air?

Andrea Polli's projects *Airlight series* and *Particle falls* are animated light projections that reveals the invisible dangers in the air we are breathing. It is a dramatic public artwork that raises awareness of the real time presence and impact of particle pollution.

BUYING THE AIR TO RAISE AWARENESS ON AIR POLLUTION?

The accelerating climate change crisis and the realization that humans are the primary cause of it has raised questions about ownership and responsibility. Who "owns" the climate change crisis, and who is responsible for mitigating and reversing it if possible? The overwhelming response to these questions by governments internationally has been to propose a market solution, by selling the atmosphere. This article explores the idea of air for sale from economic, political, and cultural arts perspectives, and asks, "Can art help extricate the science and policy of climate change from its current quagmire?".

The idea of environmental and natural resource economics came from the understanding that environmental resources are finite, and since these resources can be destroyed, there should be incentives for protecting them. Ecological economics provides both a mechanism for the valuation of environmental resources and an incentive for keeping within an established environmental "budget". In 1997, the US Congress described it in this way:

"From an economic perspective, pollution problems are caused by a lack of clearly defined and enforced property rights. Smokestack emissions, for example, are deposited into the air because the air is often treated as a common good, available for all to use as they please, even as a disposal site. Not surprisingly, this apparently free good is overused. A primary and appropriate role for government in supporting the market economy is the definition and enforcement of property rights. Defining rights for use of the atmosphere, lakes, and rivers is critical to prevent their overuse. Once legal entitlement has been established, markets can be employed to exchange these rights as a means of improving economic efficiency."

Perhaps the arts, specifically contemporary conceptual artworks, have played a role in making buying air culturally acceptable

One might think that the idea of "air for sale" is only an abstraction[1]. There are, however, many ways that air has been commercialized—for example, in the use of bottled oxygen in medicine and sports, or the nearly ubiquitous presence of air conditioning. Recreational uses include the rising popularity of something called the "oxygen bar" and canned air, where oxygen is touted as a cleansing and medical "therapy": customers pay for a five-minute session or so, in which they are able to relax and breathe clean, sometimes scented, air. The oxygen bar started as a trend in the 1990s in Japan, Mexico, and South America and quickly spread to nightclubs, spas, casinos, and malls in Europe and the United States. In 2003, the oxygen bar at Olio!, a restaurant at the MGM Grand Hotel in Las Vegas, boasted 200 to 400 customers per day. Portable canned air is becoming just as popular and widespread. In Japan, a recent large-scale commercial venture is O2supli, a portable can of oxygen. The oxygen comes in two flavors, "strong mint" (called the brain can) and "grapefruit" (called the body can) at a price of 600 yen ($7.50) a can: "The idea behind the product is to allow buyers to replenish their oxygen levels any time they feel a lack of it due to stress, fatigue, or other factors.

WHEN ART BECOMES IDEA, IDEA BECOMES COMMODITY[2]

Perhaps the arts, specifically contemporary conceptual artworks, have played a role in making buying air culturally acceptable. As creative works, art and architecture have value in society—not just cultural value (although they have that too), but monetary value.

Artists have adopted several strategies to address the politics of air. In the 1950s and 60s, Yves Klein's idea of *Air Architecture* challenged the definitions of art and architecture, but on a wider scale may have contributed to the commodification of the public resource that is air. Klein was interested in the ways that humans can use science and technology to conquer the ephemeral, to the point of turning even air and fire into building materials. Klein saw science and technology as the saviors of architecture, promoting new forms and structures made from sculpting the air and other "immaterial-materials." He believed that *Air Architecture* would actually improve the environment, saying that "Air Architecture must be adapted to the natural conditions and situations, to the mountains, valleys, monsoons, etc., if possible, without requiring the use of great artificial modifications."[3]

Another example is Tue Greenfort's Bonaqua Condensation Cube of 2005, which pays homage to Hans Haacke's Condensation Cube of 1963. The contemporary work uses Bonaqua, a popular brand of bottled water, as the water of condensation. Greenfort is directly addressing the issue of ownership. What was considered a public resource in 1963 had become a commercial product by 2005. Like the earlier work, the piece is positioned in a gallery with the expectation of being at least attributed a monetary value, and at most purchased. Also like the earlier work, this piece pokes fun at the absurdity of the commercial-gallery system, but paradoxically remains a part of that system.

Laurie Palmer's 2005 Hays Woods/Oxygen Bar project at Carnegie Mellon University highlights the natural processes that create air and draws attention to the fact that air is a public resource: the oxygen bar is a mobile breathing machine, offering free oxygen produced by the photosynthetic work of green plants (from Hays Woods.)

1 See George England, *The Air Trust* (1915), discussed in Fleming, *Fixing the Sky*, 36–38.

2 Alberro and Buchmann, eds., *Art after Conceptual Art*.

3 Klein, Noever, and Perrin, *Air Architecture*.

Pushed around the streets of Pittsburgh, the bar attempted to reproduce in miniature the beneficial cleansing and refreshing effects of green city spaces on the air we breathe. The oxygen bar anticipates the imminent loss of public resources that filter Pittsburgh's dirty air and replenish it with oxygen—in particular, Hays Woods. At the same time, the oxygen bar anticipates the active participation of citizens of Allegheny County in land use decisions affecting public health.

In much recent art, air has become the marker, not of the difference between art and life, but of the aspiration of art to trespass beyond its assigned precincts, to approach and merge into the condition of "life"

The questions raised by the works discussed here do not represent a criticism of the artworks; the artists should be praised for bringing up these complex questions. The paradoxical problems that arise are a function of the systems in which the works exist, either the gallery art world, with an economy based on the buying and selling of works, or the public art world, in which works are owned by government or private interests, including those works which operate in semi-public forums like the common market or the internet. In the context of climate change, the works bring up larger questions about the potential of art in a time of global environmental crisis, and more specifically the potential of art to collaborate with science.

AIRLIGHT

Airlight is the name given to a visible white smog caused by the illumination of fine dust particles in the air. The term is often used in Los Angeles, where fumes from car exhaust create airlight, described by author Lawrence Weschler as "a billion tiny suns." The *Airlight series* first began as *Airlight Taipei* in summer 2006. Summer in Taipei is unbearably hot and humid, forcing residents to stay in air-conditioned buildings most of the day. The city is crowded, with over six million people in the greater Taipei area. Although public transportation is excellent, several elevated highways cut through the city, like contrails cutting through the dense air. Taipei's geography works against its air quality. Taipei is located at the base of a bowl, surrounded by small mountains with only one small outlet for the stagnant air that often stays trapped for days. In addition, Taipei is downwind of southern China, where the energy demands of recent modernization have meant the development of more coal-burning power plants. Wind flow from west to east brings a large amount of the pollution from China's coal industry to the Taipei air.

During a residency at the Taipei Artist Village, I had the great fortune to meet and collaborate with Dr. Chung-Ming Liu, director of the Global Change Research Center and professor in the Department of Atmospheric Sciences at National Taiwan University. For our project, Dr. Liu gathered and formatted real-time Taipei air quality data for almost twenty sites around the city onto a website. This allowed me to automatically download hourly amounts of particle pollution, ozone, and other pollutants in the atmosphere and translate this information in real-time into a changing rhythmic visual and soundscape, rendering the "noise" of the pollutants into a kind of rhythmic "noise" that expressed what Dr. Liu called the "daily variation" of air quality in the city.

The traffic engineering office of Taipei city possesses many public traffic cameras, so I was able to synchronize the sound of the air quality with live traffic webcam images. I used the pollutant levels to make the images break apart, appearing and disappearing with rising and falling pollutant levels. This repetitive structure created a rhythmic, ambient sound that functioned very much like background noise.

The imagery was also structured around the idea of noise. The original image was an unaltered traffic cam image that would pixelate based on the levels of pollutants in the air. This has the effect of a blurring and focusing of the image, in a rhythmic way in time with the sound. The rhythmic blurring and focusing of the image produced the impression of quivering or breathing, giving the image a kind of life. In discussing ephemeral and process-based art, Steven Connor says that "in much recent art, air has become the marker, not of the difference between art and life, but of the aspiration of art to trespass beyond its assigned precincts,

Particle Falls © Jared Rendon-Trompak

Particle Falls © Jared Rendon-Trompak

to approach and merge into the condition of life." In the *Airlight* series, I have attempted to give a kind of "life" to the air quality data being collected, creating an alarming scream and image blur that increases in intensity as the levels of pollutants increase.

PARTICLE FALLS

The creation of *Particle Falls* fulfills three basic objectives: to use art and technology to make the invisible visible and tangible to the public; to imagine and present new public space possibilities designed to inspire; and to demonstrate that individuals and communities armed with information can help create positive change.

Particle Falls is a night-time projection that allows viewers to see current levels of fine particulates first presented cascading down the facade of the AT&T building in San Jose (California), using the latest projection technology. The project includes a nephelometer, which measures the smallest air particles (PM2.5). The global monitoring of these particles is one of the most recent developments in aeronomy. Fewer bright particles over the waterfall mean fewer particles in the air. In essence, *Particle Falls* is a large-scale public art installation that acts as a monitor, an alarm and a thing of beauty all at the same time. The work is made possible thanks to Tim Dye's *AirNow* project, which consolidates all the US based air quality information and shares live air pollution data throughout the US, to raise awareness of air pollution among the public and thereby encourage behavioral change. Raising awareness about environmental pollution in San Jose was a key aim of *Particle Falls*. Santa Clara County received a failing grade for air quality in the American Lung Association's 2009 State of the Air Report and currently surpasses unhealthy short-term particle pollution thresholds at a yearly average of 11 days, the 24th highest level in the US. The number of people that airborne particulate pollution kills each year has tripled in California.

Consistent with the city's sustainability aims, the work shows how humans impact the environment. The work was positioned in a transport corridor and was sensitive enough to respond to the pollution of a passing truck or even a pedestrian smoking a cigarette. If installed over a longer period of time, the work would be capable of demonstrating how a public works project like a light rail project might improve the quality of life for the people of San Jose. Since San Jose, *Particle Falls* has been shown in ten cities internationally, including in Paris in conjunction with the COP21 Climate Conference.

CONCLUSION

By focusing on particles in the air — rather than carbon dioxide, which is invisible — the artist is broadening her interest to environmental pollution generally.

These projects have a multifaceted approach: from a social perspective, they have encouraged public interaction, providing audiences with web and cell phone access to the data, and allowing citizens to collaborate with scientists, designers and engineers. In addition, from a technological and economic perspective, they have enabled the combination of public art with new and emerging technologies and online media, using updated environmental monitoring data to drive real-time animation, and highlighting new, greener technologies by using alternative energy and lower power consumption systems when possible.

POLLUTION PODS: CAN ART CHANGE PEOPLE'S PERCEPTION OF CLIMATE CHANGE AND AIR POLLUTION?

Michael Pinsky,
Artist

Laura Sommer,
Researcher at the Norwegian University of Science and Technology

Pollution Pods in Trondheim, Norway during the 2017 Starmus Festival © Michael A Pinsky

Michael Pinsky is a British artist whose international projects have often taken the form of residencies that explore issues of the public realm. Taking on the combined roles of artist, urban planner, activist, researcher and resident, he engages closely with local people and resources, allowing the physical, social and political environment to define his methodology. His work has been shown notably at TATE Britain; Museum of Contemporary Art, Chengdu; Saatchi Gallery; The Victoria and Albert Museum; La Villette, Paris; Modern Art Oxford, Armory Center of the Arts, Los Angeles... Dr Michael Pinsky graduated from the Royal College of Art. He has received awards from the RSA, Arts Council England and the Wellcome Trust amongst others, and his exhibition Pontis was shortlisted for the prestigious Gulbenkian Museums Award.

Laura Sommer is one of two PhD candidates working on the Climart project. She has a bachelor's degree in Psychology and deepened her understanding of climate and natural matters during her master's in Global Change Ecology. Laura Sommer worked at the Department of Psychology of the Norwegian University of Science and Technology, focusing on creative environmental communication, behavioral change and cognitive psychology.

The artwork *Pollution Pods* is part of the *Climart* project, a wider research program that looks to explore the ways in which art can change people's perception of climate change. Before presenting the *Pollution Pods* project itself, Michael Pinsky describes his process of artistic creation and explains how his work engages with the challenge of "representing the invisible". The conception of *Pollution Pods* is part of a scientific work studying the type of reaction that climate art can bring about in audiences, thinking specifically about the extent to which artworks lead people not only to reflect on the reality of their daily lives, but also to alter their behaviour.

With *Pollution Pods*, the artist hopes to disrupt our embodied experience of pollution, which is generally that of a background phenomenon to which we grow accustomed. To do this, five geodesic domes, five closed physical spaces containing toxic air from different cities around the world, are connected, forcing visitors to experience abrupt change in air quality. *Pollution Pods* is an eminently sensorial experience, whose objective is not so much to offer a privileged audience the thrill of danger safely contained, but rather to push visitors to reflect on their own contradictions and trigger behavioural change, as the embodied knowledge of pollution renders willful ignorance almost intolerable.

GETTING PEOPLE TO ENGAGE WITH THE CLIMATE CRISIS: WHAT DOES ENVIRONMENTAL PSYCHOLOGY TELL US?

"Aesthetic practices that take up political disruption are not simply raising awareness or communicating messages. This is not politics as propaganda. Instead, aesthetic practices operate through a 'radical uncanniness' that realigns, disrupts and reinvents political engagement as material and sensible events (Rancière, 2004 [2000]). Such disruption can become a way to materialize and articulate what would otherwise be un-sayable and un-thinkable."
(Gabryss & Yusoff, 2012)

Since the beginning of my career, my artistic practice has engaged with pressing environmental issues. For COP21, held in Paris in 2014, I emptied out the St Martin Canal and recovered the many objects discarded by Parisian residents during the previous year. Of course, we found many of the ubiquitous city bikes and shopping trolleys, but surprisingly we also found single bed frames and small fridges, most likely an indicator of transient and migrating populations. I took audio samples from these jettisoned artifacts to create a composition to accompany the objects which I mounted on the surface of the canal. I was attempting to draw attention to our insatiable appetite to consume and how this needs to be facilitated by an effective waste disposal system. This artwork called *'L'Eau Qui Dort'* caught the attention of a group of environmental scientists based at the Norwegian Institute of Science and Technology who were working on a project called *Climart*. They chose to include *L'Eau Qui Dort* in a study of thirty-seven artworks shown at COP 21 to see if art can change people's perception of climate change.

In the first publication that emerged from this data collection (Sommer & Klöckner, 2019[1]), the researchers divided the artworks into four "clusters" based on the emotional reactions viewers showed to the artworks. Then they looked at what thoughts, or "cognitions", in psychological terminology, the spectators of the artworks had when they saw the artworks. The cognitions under investigation were chosen from what environmental psychological research indicated would be relevant to engage people with the climate crisis: Did the artworks, for example, make people reflect and contemplate? Did the topic of the artwork have relevance to their daily life? Did it highlight the personal impact their behavior was having on the environment? Such were the questions that the spectators were asked to assess when sharing their thoughts on the artworks.

In a last step, the researchers tried to define common characteristics of the artworks in the clusters and link them to the emotional and cognitive reactions. Cluster 1, which contained artworks that were participatory, playful and colourful, seemed to make people feel good, but the cognitive reactions showed that these artworks also had the lowest level of reflection, contemplation and relevance for daily life. The researchers therefore decided to call this group of artworks "*The Comforting Utopia*".

L'Eau Qui Dort was part of the second cluster, called "*The Challenging Dystopia*". The thoughts people had about this dystopian art were that it was confrontational, had something unusual that made them stop, was relevant for their daily life and made them aware of the impact of their own behavior.

1 Sommer, L. K., & Klöckner, C. A. (2019). Does activist art have the capacity to raise awareness in audiences? A study on climate change art at the ArtCOP21 event in Paris. Psychology of Aesthetics, Creativity, and the Arts.

Pollution Pods in Portland, UK © Michael A Pinsky

Exploring the Pollution Pods at the TED 2019 conference in Vancouver - Photographer - MA - Marla Aufmuth

The group of artworks which the researchers found to release the strongest positive and negative emotional response, as well as cognitive reaction, showed solutions and made the cause and effect of behavior visible. This group was called "*The Awesome Solution*".

In a second publication (which is still under review), the researchers then found that:

- the influence of negative emotions on the reflections and thoughts about the artworks was stronger than that of the positive emotions, but that both indirectly influenced policy support;
- the thoughts and reflections caused by the emotions were what made the viewers support climate policies.

Klöckner and Sommer concluded from this that the subjectivity of the reaction triggered by climate change art is what makes the art experience powerful, and that some characteristics of an artwork are more helpful than others to achieve a subjective, emotional and reflective reaction in the viewers.

People do not change their behaviour unless an issue affects their everyday life

DRAFTING OF *POLLUTION PODS* PROJECT

Following COP21, the *Climart* scientists wanted to study an artwork in more depth and use their findings from COP21 to influence the creation of a new artwork. I was selected by the group to create a new commission in Trondheim. My projects have been created to raise environmental concerns and attempt to change behaviours, perceptions and opinions, but I have never really known in an empirical way whether my projects have been at all successful in this endeavour. At last, here was an opportunity to understand how my approach affects participants.

During the first phase of the project, I discussed with the team their findings and their approaches to the study. We discussed the causes and consequences of climate change and we discussed unpalatable solutions. We discussed the feeling of hopelessness people have when they see the typical visual icons of climate change; the sad polar bear on a melting iceberg or a starving child standing on a sun cracked desert. We discussed how the frame of art is uniquely time-privileged since the viewer is expected and expects to take time to reflect. We discussed how art can bring people together physically and psychologically

Pollution Pods by Michael Pinsky at Somerset House for Earth Day 2018
© Peter Macdiarmid for Somerset House

A visitor experiencing the contaminated air of Pollution Pods
in Trondheim, Norway © Thor Nielsen / NTNU

to create a sense of togetherness and promote common action. We discussed how art can question and create new social norms.

From all these conversations and the findings from the ArtCOP21 studies, one thing became clear; people do not change their behaviour unless an issue affects their everyday life. Certainly, the direct effects of climate change are impacting parts of the world as the sea level rises and temperatures increase, along with the frequency of extreme weather phenomena. But in the major western cities, the impacts of climate change still seems remote. So, I started to think about my life in London and about some of the causes of climate change. People feel the impact of fossil fuels in the city as airborne pollution. Whilst the pollution itself does not greatly contribute to climate change, the causes of air pollution and climate change overlap hugely.

One of the reasons why people are not motivated to change their behavior, in regards to either Climate Change or pollution, is that we habituate to the gradually changing environment. Global changes are relatively invisible, which makes the violence that comes with them slow. This certainly applies well to pollution. We are capable of adjusting our senses to accommodate to and mentally block out background noise, visual clutter and toxic air. It is only when we pass through the threshold from one environment to another at speed that we really encounter and acknowledge the difference. This often happens when we exit a train or plane: our senses have not yet had time to acclimatise to the new environment.

The global changes are relatively invisible, which makes the violence that comes with it slow

It was with this statement in mind that I started to develop the idea of a number of connected rooms, each containing the polluted air from a major global city. As visitors would be 'transported' from city to city moving directly from one room to another, their senses would not have time to acclimatise, leading them to experience the visceral shock of entering each distinctly polluted environment.

At first, I thought that creating these environments would be quite straightforward. I would just go the cities I had selected to sample, suck air into a compressor and then transport this back to Norway to release the toxic air into the rooms. I decided to reach out to scientists for advice. My first port of call was the Norwegian Institute for Air Research. Their feedback to my approach was both interesting and clear. The process of compressing the air could lead to a volatile solution. The process of releasing the air in a confined space was dangerous. The other aspect they drew my attention to was that one's impression of pollution is radically altered by humidity and temperature. With this feedback I started to consider the best approach to this concept. The first challenge was figuring out how to materialise something that is essentially invisible.

In my projects, I consider both the narrative of the work, which I see as its horizontal axis, and the visual moment, which becomes the vertical axis. Often, socially-engaged practice and issue-based artwork can have strong and effective stories but lack visual clarity. An artwork that is visually memorable, seductive, surprising and shocking can etch itself in people's minds in a way the written word cannot. The visual manifestation of the work can function as a shortcut to the themes it is trying to embrace. However, artworks that are only a literal illustration of a problem lose any sense of the nuances contained within the narrative. These are what I call "*Oh, I Get It*" artworks. The visual essence of the work should be in dialogue with the issues it is trying to unravel and facilitate the audience's reflections on the themes without being didactic.

For the *Climart* project, I was drawn to the geodesic dome as a container for these polluted environments. These structures are both used in crisis scenarios and in the famous biosphere experiments. The structure designed by Buckminster Fuller[2] also alludes to his seminal manifesto, *Operating Manual for Spaceship Earth* which remains surprisingly topical today, decades after its initial publication. I proposed to create a circle of these domes, each connected by a tunnel, suggesting the interconnectedness of our biosystems and to remind us that air passes freely across national borders. By directly quoting Fuller's iconic structure as its primary visual statement and spatial metaphor, *Pollution Pods* would conjoin art and technology, while questioning division and containment as a prime technique of Modernity.

An artwork that is visually memorable, seductive, surprising and shocking can etch itself in people's minds in a way the written word can struggle to do

SCIENTIFIC EVALUATION

From the scientific side, the researchers had to answer for themselves which aspects of the Pods they expected to impact viewers the most: Would it be the experience of the single domes? Should the visitors be asked about their feelings and thoughts after every dome, or after the whole experience? What feelings and thoughts could be reasonably assumed to be triggered by the artwork? What would be the best outcome measure to assess reactions to the artwork?

They decided to do qualitative interviews with a random selection of the audience and a quantitative questionnaire measuring the feelings and thoughts people had after experiencing the whole artwork. The qualitative study found that what the *Pollution Pods* offer to visitors is a form of experiential learning, which reduces the psychological distance of climate change to the visitors. The art installations enable them to sense how air-pollution and climate change impact them and will impact them in their daily lives.

On the other hand, the questionnaire study by Sommer, Swim, Keller and Klöckner (in press) found that intentions to act were strong in visitors and increased to some extent after visiting the Pollution Pods. The changes in intentions individuals reported were positively associated with emotions such as sadness, helplessness, and anger. Furthermore, changes in intentions were associated with thoughts connected to the "awareness of the environmental consequences of people's actions, their willingness to take responsibility for these consequences, and belief in the relevance of environmental problems to their daily life" (Sommer, Swim, Keller & Klöckner, in press[3]). Even though the intentions were favorable, few visitors took advantage of the possibility to estimate their CO_2 emissions – therefore, changes in actual behavior after visiting the artwork could not be measured, which is a common problem in environmental psychological research. Nevertheless, Sommer and colleagues emphasised the value of art, which is especially effective in drawing attention to the personal relevance of climate change and the individual's responsibility to act. In this respect, the *Pollution Pods* were successful in highlighting exactly those reflections.

Note: the scientific results have only been partially published. As such, detailed results can only be presented for some of the studies described in this article.

2 Richard Buckminster Fuller (July 12, 1895 – July 1, 1983) was an American architect, systems theorist, author, designer, inventor and futurist. He developed numerous inventions, mainly architectural designs, and popularized the widely known geodesic dome. In 1968, a year before the first moon landing, Buckminster Fuller's book, "Operating Manual for Spaceship Earth" reconceptualized the Earth as a vessel, to propose that humanity must take responsibility for maintaining the atmosphere in a state to support life.

3 Sommer, L. K., & Klöckner, C. A. (2019). Does activist art have the capacity to raise awareness in audiences? A study on climate change art at the ArtCOP21 event in Paris. Psychology of Aesthetics, Creativity, and the Arts.

DESCRIPTION OF THE POLLUTION PODS

Pollution Pods is an artistic installation where five geodesic domes are connected by polygonal passageways to form a ring.
Within each dome, the air quality of five global cities (London, Beijing, New Delhi, Sao Paulo, and Tautra) is recreated. A carefully mixed recipe emulates the relative presence of ozone, particulate matter, nitrogen dioxide, sulphur dioxide and carbon monoxide which pollute these cities. The visitor will pass through increasingly polluted cells, from dry and cold locations to hot and humid.

The experience of walking through the *Pollution Pods* demonstrates that these worlds are interconnected and interdependent. In this installation, it is possible to feel, taste and smell the environments that are the norm for a huge swathe of the world's population.

Crucially, the "pollution" in the *Pollution Pods* is a laboratory simulation, an olfactory representation of toxins, made by a corporation that produces artificial flavourings and perfumes to make commodities taste or smell more appealing. Here, art appears to imitate life, offering a privileged audience the thrill of danger safely contained. But the simulated pollution not only "references the real to which it is subordinate", it is also implicated in the phenomena it represents: the environmental control equipment used, in every stage of its lifecycle from resource extraction, through to manufacture, use, and disposal, generates pollution. Similarly, extending the boundary of the physical installation to include its bioplastics manufacture, its electricity consumption, and its transportation by land, sea and air reveals networks of ecological impacts from the microscopic scale of particulate emissions to the macroscopic scale of climatic disruption. Though presented as hypothetical and elsewhere, the danger is real and present.

Pollution Pods presents an emblem of utopian faith in technology as a secular fantasy of control that engenders a haunting anxiety around the return of what has been repressed and excluded. Being immersed in the work is to experience the separation of artistic experience from the everyday as illusory, and to recognize the artworld as a subset of the world.

By putting the vital act of breathing under the heightened attention of art, the *Pollution Pods* makes the contradiction between embodied knowledge and willful ignorance almost intolerable. Perhaps the visceral memory of these toxic places will make us think again before we buy something else we don't really need...

CREDITS

Pollution Pods was originally commissioned by the Norwegian University of Science and Technology for Climart and has been built with the support of BuildwithHubs. *Pollution Pods* has received funding from Arts Council England. The tour of Pollution Pods is managed by Cape Farewell. The pollution cocktails were created by IFF's global network of scent experts and dispersed using Aroma technology.

IN FACTS

Pollution Pods has been shown to the public at STARMUS, Trondheim, Norway; Somerset House, London, UK; World Health Organisation's First Global Conference on Air Pollution, Place des Nations, Geneva, Switzerland; Klimahaus, Bremerhaven, Germany; TED Annual Conference, Vancouver, Canada; Clean Air Week, Media City UK, Greater Manchester UK; B-Side, Portand, UK; Melbourne Science Gallery, Australia; UN Climate Change Summit, UN Headquarters, New York City, USA; Nuit Blanche, Brownsea Island, Activate, UK.

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Philippe Kourilsky
Honorary Director-General of the Pasteur Institute
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