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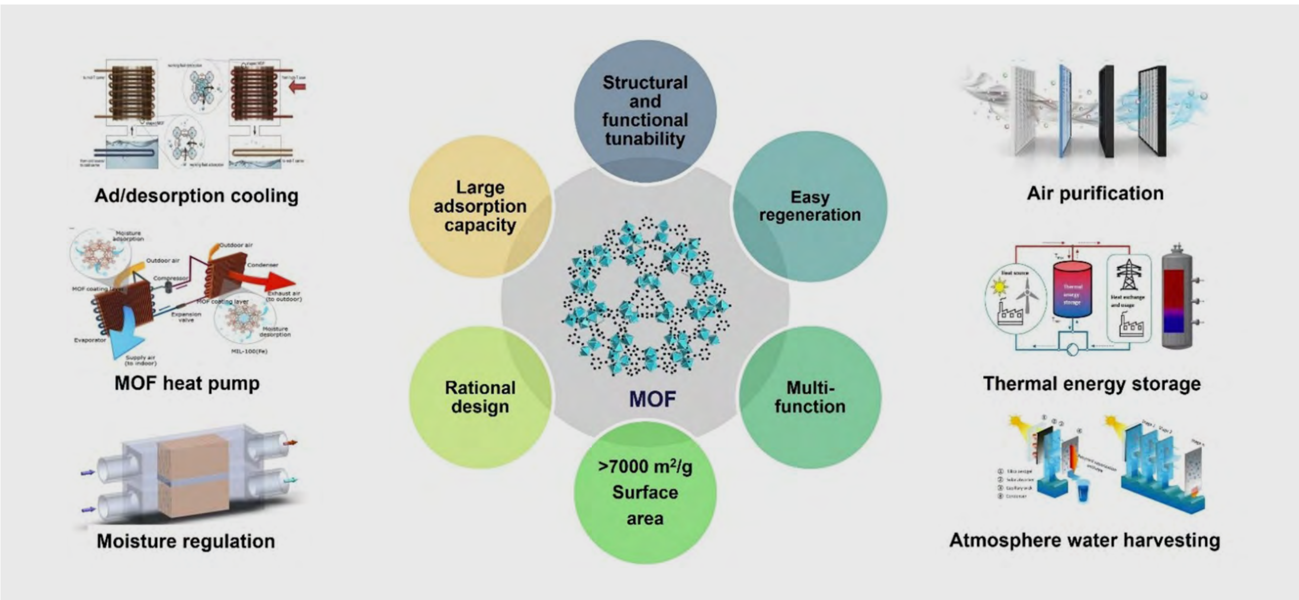
Smart Materials for Sustainable Buildings

Menghao Qin, Christian Serre, Guillaume Maurin, Xin Zhang, Jianshun Zhang (EBC Annex 92)

The rapid growth of heating, ventilation, and air-conditioning (HVAC) systems in buildings worldwide has become a major driver of global energy use. Heating alone accounts for about 45% of building-related emissions and still relies heavily on fossil fuels, which supply more than half of its energy demand. Cooling typically relies on mechanical compression processes that use volatile fluorinated gases with high Global Warming Potential (GWP). Remarkably, the core technology behind modern air conditioning has changed only marginally over the past century. Despite their widespread adoption, these systems continue to be energy-intensive and impose a significant environmental burden. Reinventing the way we heat and cool buildings, through the development and deployment of advanced smart materials and innovative physical and chemical processes, offers a promising pathway to significantly reduce energy demand, improve indoor air quality, and mitigate the environmental and climate footprint associated with modern living.

In recent decades, chemists and materials scientists have created a wide range of innovative smart materials with remarkable abilities for regulating heat and moisture. Among them, Metal–Organic Frameworks (MOFs), a field recognized with the 2025 Nobel Prize in Chemistry, along with phase change materials (PCMs) and polymer hydrogels, stand out for their exceptional performance. These materials can be engineered directly into walls, ceilings, or ventilation systems, where they help control temperature and humidity either automatically or with minimal energy input. They can also be integrated into mechanical systems, such as adsorption heat pumps or chillers, humidity pumps, thermal batteries, air cleaners, etc. By stabilizing indoor conditions and improving air quality, they offer a promising way to reduce the energy needed for air conditioning, ventilation, and air purification, making buildings more comfortable and sustainable at the same time.

IEA EBC Annex 92 aims to develop energy-efficient strategies for heating, cooling and air purification by leveraging novel smart materials, particularly advanced sorbents such as MOFs (or Covalent Organic Frameworks [COFs]) and their composites, through cross-disciplinary international collaboration. This ambitious initiative gathers existing scientific knowledge and data on emerging sorbent materials for



MOFs applications for built environment control
Source: Menghao Qin

heating, cooling, and dehumidification, pollutant removal, and thermal energy storage, while exploring both current and innovative applications of these materials in heating, air-conditioning, air purification, and thermal storage systems. It will also identify and address key knowledge gaps by fostering links across different disciplines. Experts in building science, materials chemistry, mechanical engineering, materials science, and environmental health will work together with a broad range of stakeholders to accelerate the development of more efficient and sustainable heating, cooling, and indoor air quality (IAQ) control systems based on smart materials.

Recent advances in smart materials

In the field of advanced materials, considerable progress has been achieved in the past few decades with the emergence of a series of new classes of organic, inorganic and hybrid crystalline or amorphous materials (polymers, coordination polymers, hybrid perovskites, inorganic and organic two-dimensional [2D] materials …). This includes not only the development of new porous solids (mesoporous silica, MOFs, COFs, porous cages, hydrogels…) but also materials with sometimes unique physical and chemical properties such as stimuli-responsive frameworks (e. g. phase change materials, flexible porous solids …). MOFs and COFs are regarded as among the most versatile classes of smart materials; these ordered porous solids possess unprecedented chemical and structural diversity. To date, this has led to the discovery of more than 130,000 experimentally reported MOF structures while theoretical calculations suggest an almost infinite number of possible metal-ligand combinations. MOFs and COFs exhibit tunable hydrophilic/hydrophobic balance as well as variable pore size (0.3 to > 5 nm) and shapes (channels, cages, 1D to 3D porosity). These porous materials have so far been proposed for a wide range of potential applications, including gas storage, separation, catalysis, energy, remediation, sensing or biomedicine. When MOFs are constructed from non-critical metals and simple organic building blocks, their production at an industrial scale can be achieved through batch or continuous flow routes, at moderate costs comparable to those of other synthetic porous solids like zeolites. The first commercial applications of MOFs have emerged only very recently, primarily in CO_2 capture and cooling and dehumidification, paving the way for broader industrial deployment. Although COFs and porous organic cages often exhibit greater chemical stability than most MOFs in liquid-phase environments, further efforts are still needed in order to address scalability challenges due to the use of toxic/expensive building blocks/solvents during synthesis. MOFs/COFs are also usually much easier to regenerate within a narrow range of temperature or pressure than the traditional activated carbons, zeolites or hydrogels, paving the way for the design of new, less energy-demanding processes (remediation, separation, catalysis …).

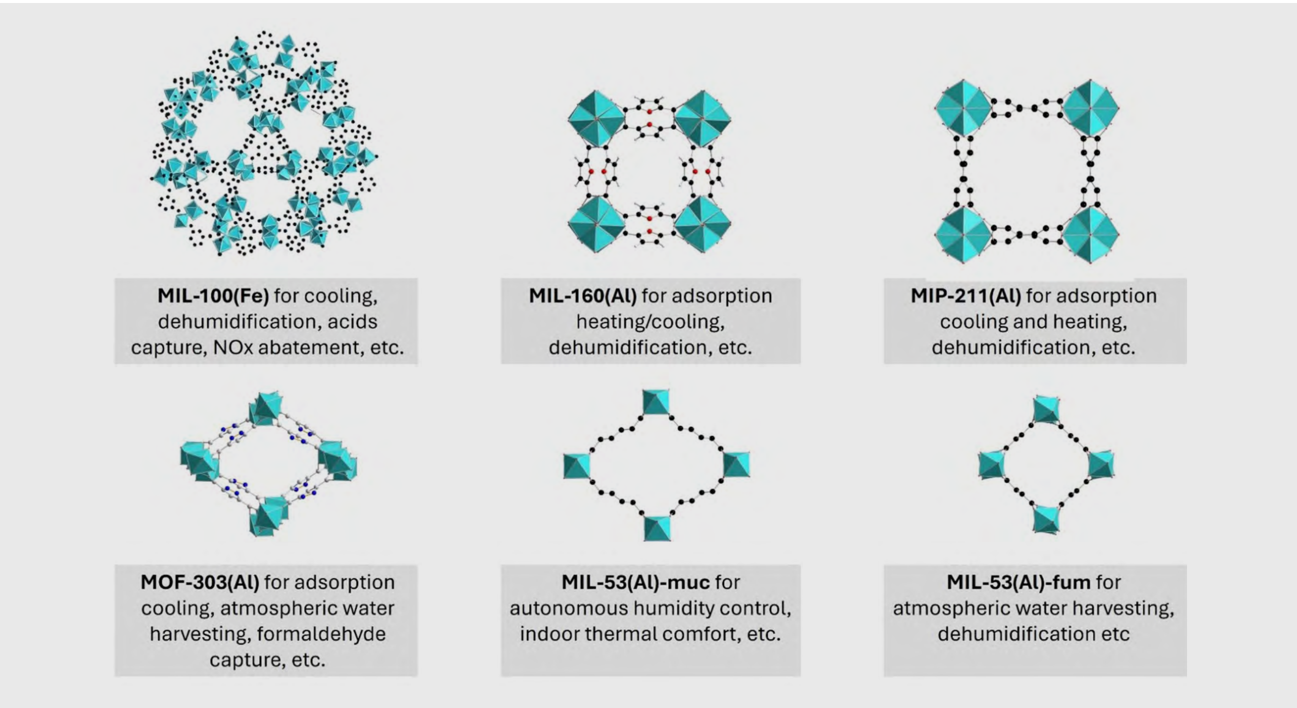


Illustration of MOF structures and their applications.
Source: Christian Serre

The vast majority of these discovered MOFs have resulted from advances in synthetic methods (e. g., high-throughput synthesis) or in advanced characterization techniques (X-ray diffraction, electron diffraction and Nuclear Magnetic Resonance [NMR]…), driven largely by chemical intuition and in many cases, serendipity. The recent emergence of artificial intelligence methodologies, combined with new combinatorial synthesis and characterization tools is expected to accelerate the design of functional porous solids for targeted applications including indoor air quality management and adsorption-based heat transfer systems.

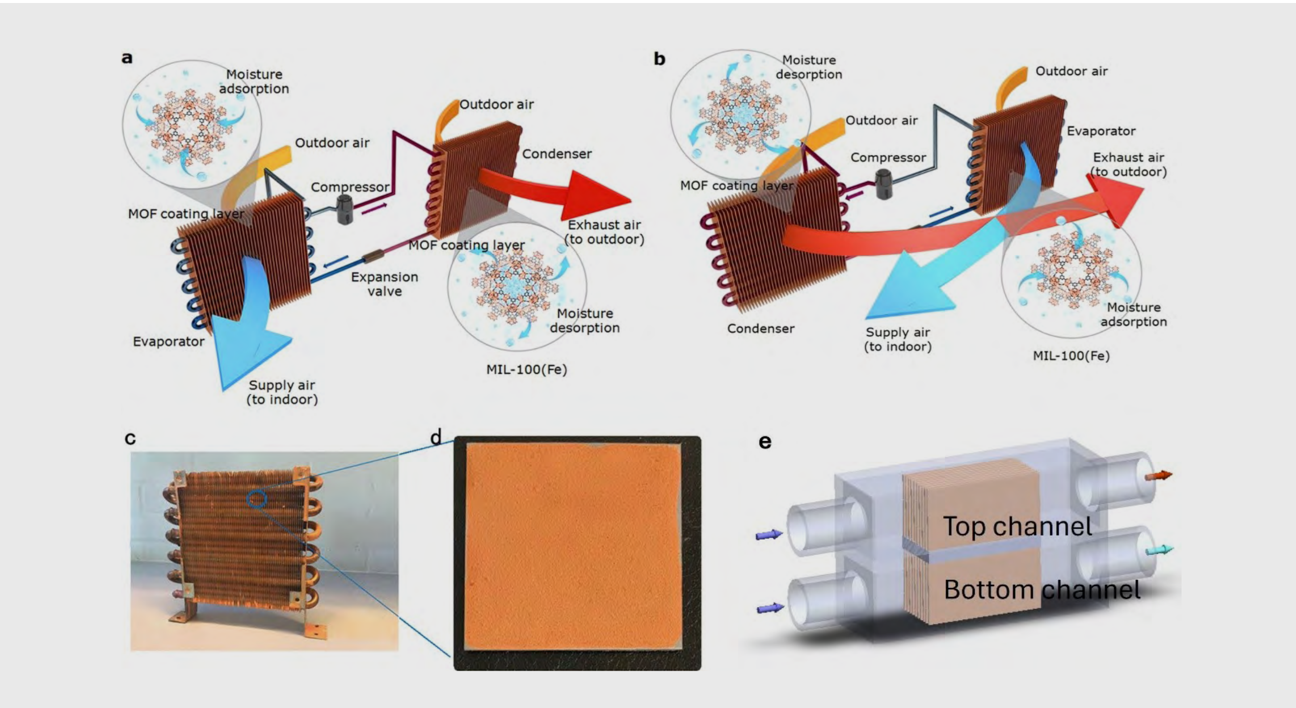
MOFs for cooling/heating and dehumidification

As highly efficient water adsorbents, many MOFs hold great promise for cooling and humidity control applications in buildings. Their organic-inorganic hybrid characteristics lead to a uniquely steep water vapor uptake. The exceptional chemical and structural diversity of MOFs allows for precise tuning of the hydrophilic/hydrophobic balance, often enabling easier water release within a narrow range of relative pressures due to their S-shaped isotherms, and at moderate temperatures (40–80 °C) owing to their amphiphilic environment, together with high working capacities of up to 2 g of water vapor per gram of MOF under practical conditions. Importantly, MOFs have also demonstrated remarkable long-term stability over repeated heating and cooling cycles leading recently to the first commercial applications in the field of dehumidification and cooling.

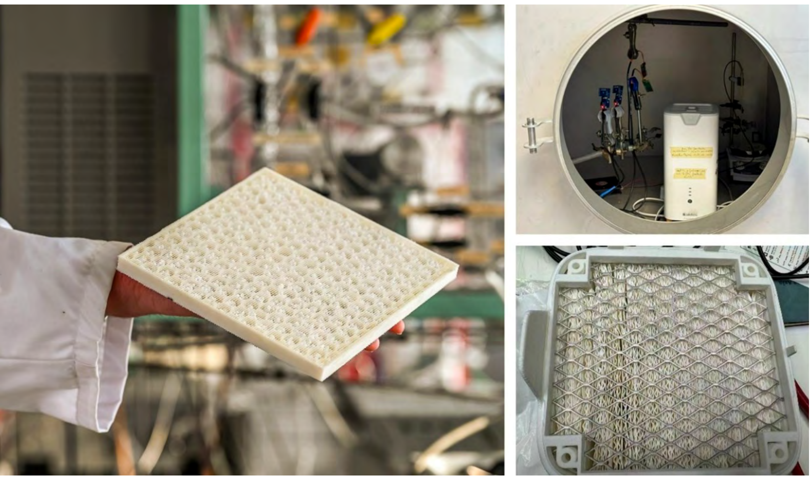
These properties enable MOFs to outperform most conventional sorbents, making them highly attractive for energy-efficient technologies that use water as a safe and environmentally friendly working fluid, often powered by low-grade renewable or waste heat. Emerging applications include autonomous indoor dehumidification (i. e., precise control of indoor relative humidity within desired ranges), adsorption heat pumps and chillers, air conditioning, thermal energy storage, and even atmospheric water harvesting. Reflecting this growing potential, many research groups and startups worldwide are now developing MOF-based technologies to translate these innovations from the laboratory into real-world building systems.

MOFs for indoor air purification

Another important application of MOFs in buildings is the removal of gaseous indoor pollutants. Owing to their exceptionally high surface areas, tunable pore structures, and adjustable surface chemistry, MOFs can selectively capture a broad spectrum of indoor contaminants at very low concentrations. At the laboratory scale, researchers have developed functional, scalable, and robust MOFs capable of removing or degrading volatile organic compounds (VOCs) (formaldehyde, acids…), carbon oxides, nitrogen oxides, sulfur oxides, ammonia, hydrogen sulfide, ozone, and even radon under ambient conditions. Some MOFs can maintain strong adsorption performance under typical indoor relative humidity levels of 40–60%.



(a–b) MOF-based heat pump systems; (c–d) MOF-coated heat exchanger; (e) MOF-based humidity pump.
Source: Sci. Rep. 8, 15284 (2018) and Build. Environ. 187, 107396 (2021)



MOF-based filters and air cleaner
Source: Nicolas Sadovnik

Among these materials, aluminum-based MOFs such as Al-3,5-PDA or MOF-303 have demonstrated outstanding potential for formaldehyde capture, a major indoor toxin released from furniture, coatings, and building materials. In particular, Al-3,5-PDA exhibits significantly higher formaldehyde removal capacity than conventional sorbents under both low- and high-humidity conditions, with a maximum adsorption capacity about six times greater than that of modified activated carbons. In addition to their high selectivity and capacity, these MOFs can be regenerated easily either through simple water soaking or heating at moderate temperatures, enabling repeated use without producing harmful by-products. Meanwhile, both academia and industry are advancing large-scale manufacturing methods, supporting their practical integration into HVAC systems and stand-alone air purifiers. As scalable synthesis continues to mature, MOFs are expected to play an increasingly important role in next-generation indoor air-cleaning technologies.

Given the broad application potential of MOFs in buildings, many leading research institutions and companies worldwide are already pursuing independent research in this area. EBC Annex 92 aims to establish a cross-disciplinary international platform that brings together top experts from chemistry, materials science, building physics, and the built environment to drive coordinated innovation and accelerate the translation of MOFs from fundamental research, to laboratory-scale design, and ultimately to early-stage industrial deployment. The initiative is also expected to open up a new research direction and frontier for building physics and building technologies. The superior sorption capability of MOFs for targeted pollutants (such as formaldehyde) also makes it an ideal material for developing reliable low-cost sensors for indoor air quality control.

The main activities of EBC Annex 92 include systematically reviewing, analyzing, and evaluating emerging smart materials (with a focus on MOFs [or COFs]) for different applications and climates, and establishing selection criteria tailored to specific use cases. The initiative will further optimize the performance of selected materials and develop suitable shaping and fabrication methods to meet application requirements. In parallel, innovative sorption-based heating/cooling systems, air purification approaches, and thermal energy storage concepts will be developed and validated. Laboratory-scale experiments will be combined with numerical modeling and optimization to quantify performance and identify key design parameters. Ultimately, the initiative will deliver practical guidelines, models, and tools to support the design, operation, and management of novel HVAC and indoor environmental control systems, complemented by case studies to demonstrate and refine the proposed solutions. The expected audiences include researchers and professionals in building engineering, chemistry and materials science, and mechanical engineering; HVAC and materials manufacturers; building designers and consultants; policy, regulatory, and standards bodies; as well as building owners and end users.

Looking ahead, MOFs and other smart functional materials are expected to become key enabling technologies for next-generation buildings, supporting deep integration with HVAC systems, building envelopes, and thermal energy storage technologies. By designing and leveraging the unique functional properties of these emerging materials, it will be possible to achieve more precise control of indoor temperature, humidity, and air quality with substantially lower energy input. As a result, these materials are poised to play an important role in advancing sustainable, healthy, and resilient built environments.

Further information
www.iea-ebc.org

Menghao Qin, Christian Serre, Guillaume Maurin, Xin Zhang, Jianshun Zhang (EBC Annex 92)

Smart Materials for Energy-efficient Heating, Cooling and Indoor Air Quality Control in Residential Buildings

EBC ANNEX 92

The rapid increase in the use of heating, ventilation, and air-conditioning (HVAC) systems in buildings worldwide has become a major driver of global energy demand. Heating alone accounts for approximately 45% of building-related emissions, with more than 55% of its final energy consumption still reliant on fossil fuels. Meanwhile, cooling primarily relies on the compression of volatile fluorinated gases. The core technology of mechanical cooling has seen little change since its invention over a century ago. However, these traditional systems are neither energy-efficient nor environmentally friendly. Combined, space and process heating and cooling constitute the largest contributors to global energy consumption and greenhouse gas emissions. Transforming heating and cooling technologies through the use of innovative functional materials and advanced physical-chemical processes offers a significant opportunity to reduce HVAC energy demand, enhance indoor air quality (IAQ), and mitigate negative environmental and climate impacts.

This project is developing energy-efficient heating, cooling and air purification strategies by using novel smart materials, especially advanced sorbents, such as metal-organic frameworks (MOFs) – awarded the Nobel Prize in Chemistry in 2025 – phase change materials (PCMs), hydrogel and their related composites, through cross-disciplinary international collaboration. The project is gathering the existing scientific knowledge and data on novel sorbent materials for heating, cooling and dehumidification, pollutant removal, and thermal energy storage. It is studying current and innovative use of these materials in heating, air-conditioning, air purification, and thermal storage systems. It is also identifying and bridging the knowledge gaps by establishing links between different disciplines. In the project, experts from building science, materials chemistry, mechanical engineering, material sciences, and environmental health are working together with other stakeholders to accelerate the development of better and more energy-efficient heating, cooling, and IAQ control systems by using advanced materials.

The 1st International Symposium on Smart Materials for Built Environment Control (SMBEC2025), Paris, France, 10–11 June 2025.
Source: Menghao Qin

Objectives

The main aim of the project is to develop energy-efficient heating, cooling and air purification strategies by using novel smart materials, especially advanced sorbents (MOFs, PCMs and hydrogels) and their related composites, through a cross-disciplinary international collaboration.

The specific project objectives are to:

- establish a cross-disciplinary international collaboration platform to develop breakthrough cooling/heating technologies by using smart materials;
- review, analyze, and evaluate novel sorbent materials suitable for energy-efficient heating, cooling, and air purification, with selection criteria to be set up for different applications.
- develop or further improve the performance of the selected materials for specific applications in different climates;
- develop suitable shaping methods of the best sorbents to adapt to the criteria of the different applications;
- identify or further develop innovative sorption heating and cooling systems using new materials;
- develop innovative air purification systems using new sorbent materials. Both the active system and passive approaches will be studied.
- develop innovative heat storage systems using new sorbent materials;
- carry out laboratory tests to measure the performance of the new solid-state heating and cooling, and air purification systems–numerical modeling and optimization is also being conducted;
- develop guidelines regarding design and control strategies for novel heating, cooling, and air purification systems using novel sorbent materials;
- identify or further develop models and tools that will be needed to assist designers and managers of buildings in using the guidelines;
- identify and investigate relevant case studies where the above-mentioned performances can be examined and optimized; and
- disseminate each of the above findings.

Deliverables

The project's planned delivetables are:

- A project summary report (Target group: researchers and professionals, HVAC and materials manufacturers, building designers and consultants, policy, regulatory and standards bodies).
- An overview report on methods and tools for selecting smart materials for energy-efficient heating, cooling, IAQ control, and thermal energy storage strategies (Target group: HVAC and materials manufacturers, building designers and consultants, researchers and professionals).
- A collection of case studies and demonstrations of energy-efficient heating, cooling air cleaning, and thermal energy storage using smart materials (Target group: HVAC and materials manufacturers, building designers and consultants, researchers and professionals).
- A collection of scientific publications in high-level journals (Target group: researchers and professionals).

Progress

Annex 92 organized the 1st International Symposium on Smart Materials for Built Environment Control (SMBEC2025) in Paris from 10 to 11 June. The symposium brought together over 120 leading experts and scholars from top universities and institutions worldwide to explore the forefront of advanced materials for energy-efficient built environment control, an emerging field of growing global importance.

The research on MOFs was awarded the Nobel Prize in Chemistry in October 2025. Some of the Annex 92 participants have close collaborations with two Nobel laureates – Prof. O. Yaghi and Prof. S. Kitagawa. Annex 92 is the first and, to date, the largest international collaboration project on MOFs for energy-efficient buildings. New MOF materials were developed and characterized for cooling, autonomous humidity control, and IAQ control applications. In 2025, 12 publications were produced in leading journals and conference proceedings.

Meetings

- June 2025: The 1st International Symposium on Smart Materials for Built Environment Control (SMBEC2025, Paris.
- June 2025: 1st expert meeting in Paris, France.
- October 2025: 2nd expert meeting at the Technical University of Denmark, Copenhagen, Denmark.
- November 2025: A workshop for Danish industry participants.

Project duration
2024–2028

Operating Agent
Menghao Qin, Technical University of Denmark (DTU), Denmark

Participating countries
Belgium, Canada, P.R. China, Denmark, France, Germany, R. Korea, Portugal, Spain, Sweden, UK, USA
Observers: UAE, India

Further information
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