Technology Review for Carbon Neutrality

Perspective

Risks of increased ultrafine particles associated with transition to a carbon-neutral world

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ABSTRACT

Decades of successful air quality policies have significantly reduced fine particulate matter ($PM_{2.5}$) concentrations, a major public health achievement. This success, however, presents an atmospheric paradox. The reduction in $PM_{2.5}$ mass has lowered the atmospheric condensation sink, which normally scavenges the molecular clusters that initiate new particle formation (NPF). This creates more favourable conditions for the formation of smaller, potentially more hazardous, ultrafine particles (UFPs). Furthermore, technologies central to net-zero strategies, such as amine-based carbon capture, risk creating new, concentrated sources of potent NPF precursors. This confluence of factors exposes a critical blind spot in air quality management. Current regulations and industrial risk assessments are almost exclusively mass-based, overlooking particle number concentrations and the associated health risks of UFPs. This article argues that the pursuit of climate goals must not create unforeseen public health burdens. It calls for the strategic integration of particle number and size distribution measurements into existing air quality networks to build the evidence base needed to validate models, inform future policy, and ensure that climate solutions do not inadvertently establish a new generation of localised air pollution problems.

KEYWORDS

Aerosol; pollution; nucleation; amine

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Received: 30 September 2025
Revised: 08 November 2025
Accepted: 10 November 2025
https://doi.org/10.26599/TRCN.2025.9550015

For decades, the story of air quality in the developed world has been one of remarkable success. Driven by stringent regulations, technological innovation, and a growing public awareness of the health impacts of pollution, many countries have systematically reduced emissions from vehicle exhausts, industrial smokestacks, and power plants both across the Western world[1] and China[2]. Concentrations of major pollutants, particularly fine particulate matter ($PM_{2.5}$, particles with a diameter <2.5 μm), have steadily declined, marking a significant public health achievement[3]. Yet, as countries push towards a carbon-neutral future, an atmospheric paradox is emerging: the success in cleaning the air of larger particles is inadvertently creating more favourable conditions for the formation of smaller, potentially more hazardous, ultrafine particles (UFPs, particles with a diameter <100 nm).

UFPs possess a greater toxicity per-unit-mass than $PM_{2.5}$. This is likely due to their physical properties, such as a high surface area per unit mass, and their small size and high diffusivity. Due to the latter two of these, they can circumvent primary airway defenses and can enter the alveoli more easily than their larger counterparts, after which they can translocate to almost all organs[4,5]. Alongside this, these secondary UFPs have both direct and indirect effects on climate, capable of absorbing and scattering incoming solar radiation, as well as acting as cloud condensation nuclei (CCN), particles capable of forming cloud seeds. High numbers of CCN affect cloud albedo and lifetime, thereby changing the radiative balance of the planet[6]. These particles possess relatively little mass, but large number concentrations, often in excess of tens of thousands per cubic centimetre. Policies designed to achieve carbon neutrality risk establishing a regulatory blind spot where the unintended consequences could lead to new, localised air quality problems. Understanding this paradox is the first step towards ensuring that pursuit of a stable climate does not create unforeseen public health burdens.

1. Why less pollution can mean more particles

The formation of new atmospheric particles—a process known as new particle formation (NPF)—is a delicate balance of chemical and physical processes. It begins when precursor gases, such as sulfuric acid, amines, and highly oxygenated organic molecules, form stable molecular clusters just over a nanometre in size[7]. Given sufficient time, these particles can themselves grow to have a substantial contribution to $PM_{2.5}$ mass[8,9] For these clusters to survive and grow into larger particles, they must avoid being scavenged by the existing population of much larger aerosol particles already in the atmosphere[10]. The smaller the cluster or particle is, the more diffusive it is, and the shorter its lifetime with respect to collision with a larger particle. For this reason, the growth from 1 to 10 nm has been dubbed the "valley of death" for new particles[11].

The condensation sink (CS) is a measure of the rate at which vapours and clusters are lost to collisions with pre-existing particles, and the coagulation sink (CoagS) is the rate at which smaller particles are lost to collisions with larger particles. The strength of these sinks is a function of the entire aerosol size distribution. However, they are strongly correlated with the total aerosol surface area, and therefore generally scale with the $PM_{2.5}$ mass concentration (Fig. 1). High pollution environments are therefore also high CS environments, and vice versa[10]. This high-CS environment is a powerful sink, efficiently removing the tiny, newly formed molecular clusters and the vapours that would otherwise fuel their growth. Reducing the CS by 50% increases the atmospheric lifetime of NPF precursors by a factor of two, increasing the likelihood that they will form new particles as opposed to being lost to pre-existing particle surface, with changes of a similar magnitude for new particles with respect to the CoagS. The probability that new particles will survive the valley of death is often below 1%, and small changes to their rate of growth or the CoagS can have a disproportionate effect on this probability[12].

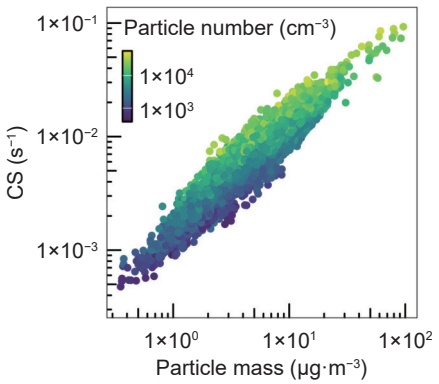

Fig. 1. Condensation sink (CS) scales with particle mass. Correlation between CS and particle mass, coloured by the particle number concentration, all as calculated from the number size distribution. R^2=0.85. Data taken from Demokritos, Athens.

However, decades of successful air quality policy have fundamentally altered this baseline by significantly reducing the mass of $PM_{2.5}$ in the atmosphere. While this is an unequivocal good for public health, it has also caused a steady decline in the CS. With fewer large particles to act as a sink, the atmosphere has become a much more suitable environment for NPF. In Beijing, it has been shown that when the $PM_{2.5}$ mass concentration drops below 10 $\mu g \cdot m^{-3}$, the likelihood of a visually identifiable NPF event is almost 100%[10]. The molecular clusters that would have once been lost now have a greater chance of survival, allowing them to grow into UFPs outside of the valley of death.

Long-term atmospheric monitoring data from sites across the globe show a clear trend. We have taken the results of Kecorius et al. (2024)[13], the most comprehensive identification of NPF to-date, covering 551 years of data across 65 sites. We took all the roadside, urban, and suburban sites with a span of data greater than three years (n = 14), and selected those where there was a statistically significant ($p < 0.1$) trend in the monthly NPF frequency (n = 4). We present these trends, alongside the corresponding changes in the CS, in Fig. 2. The data reveal a clear inverse relationship, consistent with theory. In Leipzig, where the CS has steadily increased, the frequency of NPF events has significantly decreased by 5.50%·year^{-1}. Conversely, at sites experiencing a decline in pre-existing aerosol—Helsinki, Madrid, and Athens—the atmosphere has become more conducive to nucleation, resulting in a statistically significant rise in the frequency of NPF events.

2. Aerosol precursors in a changing atmosphere

The decline of the CS is only one half of the story. The other is the availability of the chemical precursors that initiate NPF. The key ingredient for particle nucleation in most environments is sulfuric acid, formed from the oxidation of SO_2. While ambient SO_2 concentrations have fallen, there is still enough in many urban and industrialised regions to initiate the process, especially under lowering CS conditions[14], although models suggest that the projected future reduction in CS could dampen NPF[15].

However, sulfuric acid rarely acts alone. The formation of stable clusters is vastly accelerated by the presence of atmospheric bases, most notably amines. Amines, nitrogen-containing organic compounds derived from ammonia, are potent nucleating agents. Even at concentrations in the parts-per-trillion range, they can increase the rate of NPF by several orders of magnitude by stabilising the initial sulfuric acid clusters[7]. These compounds are ubiquitous, with sources ranging from agriculture and waste treatment processes to vehicle emissions[16].

Here, the drive for carbon neutrality introduces a new and significant variable. A cornerstone of many national net-zero strategies is the deployment of Carbon Capture and Storage (CCS) technology at industrial facilities and power stations. The most mature and widely used method for post-combustion capture relies on amine-based solvents to scrub CO_2 from flue gas. These amines, such as monoethanolamine (MEA) and piperazine are capable of accelerating NPF via parts-per-trillion concentrations by volume[17-19]. Although these systems are designed to be closed-loop, a small fraction of the amine solvent inevitably escapes into the atmosphere through vapour loss and aerosol formation, present at parts-per-million concentrations in the depleted flue

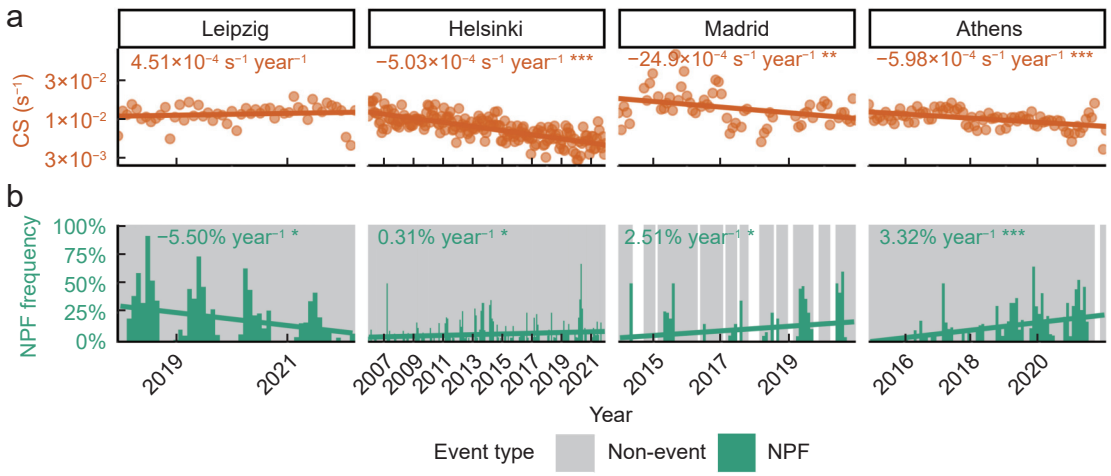

Fig. 2. Opposing trends in condensation sink (CS) and new particle formation (NPF) frequency across four European cities. (a) Monthly mean CS with an overlaid linear trend line. (b) Monthly frequency of NPF events, shown as the proportion of NPF days (green bars) to non-event days (grey bars), with an overlaid linear trend line on the NPF frequency. For both panels, the calculated annual trend and its statistical significance are annotated in the top left corner of each plot (significance levels: * for $p < 0.1$, ** for $p < 0.01$, * for $p < 0.001$).**

gas[20], and parts-per-trillion concentrations in the surrounding areas[21,22]. Interventions to limit these emissions are not always effective[23].

This means that a technology vital for climate mitigation is a potential new point source of potent NPF precursors. A critical feature of amines is their relatively short atmospheric lifetime; for MEA, this is likely on the order of hours[24,25]. This is a double-edged sword. On one hand, it means that amine-driven impacts will not be a pervasive regional issue. On the other, it implies that the effects will be highly concentrated in the immediate vicinity of CCS facilities, creating the potential for intense, localised NPF events and hotspots of high UFP concentrations.

3. A regulatory and scientific blind spot

This confluence of a declining CS and new, concentrated sources of NPF precursors exposes a significant gap in our current regulatory framework. The problem is twofold, concerning both what is measured and how it is modelled.

First, the regulatory air quality framework is almost entirely mass-based. While ultrafine particle number and size are measured extensively at specialist research sites globally, these data are not integrated into the routine, spatially-dense networks used for legal compliance and public health alerts. A location could therefore be fully compliant with $PM_{2.5}$ regulations while simultaneously experiencing frequent bursts of hundreds of thousands of UFPs per cubic centimetre. Because of their tiny size, these particles possess unique properties. They can penetrate deep into the lungs, cross into the bloodstream, and have been linked to a range of adverse health outcomes, including cardiovascular disease, respiratory issues, and neurodegenerative effects[4]. By focusing solely on mass, the regulatory system does not account for the particle number dimension of air pollution, which may be a more accurate indicator of the health risk posed by freshly formed secondary aerosol.

Second, this oversight is mirrored in the approach to risk assessment for industrial emissions. For amine-emitting facilities like CCS plants, the current regulatory focus is typically almost exclusively on the formation of carcinogenic secondary products, namely nitrosamines and nitramines. These compounds are formed in the atmosphere through the gas-phase oxidation of amines in the presence of nitrogen oxides (NO_x), with no attention given to the UFP formation potential of amines.

This is where the atmospheric chemistry becomes critical. The fate of an emitted amine molecule is dictated by a competition between several atmospheric pathways. It can be oxidised in the gas phase to form nitrosamines and nitramines. It can be taken up into existing aqueous aerosol, or, it can participate in nucleation to form a new UFP. These pathways are mutually exclusive; an amine molecule that becomes part of a nucleating cluster will likely not simultaneously form a nitrosamine. Current regulatory dispersion models used for permitting are parameterised to predict nitrosamine and nitramine formation but typically neglect or poorly represent the clustering pathway that leads to UFP production. The consequence is a fundamentally skewed risk assessment.

4. Perspective and a call for evidence

As the transition to a carbon neutral economy is progressed, it is vital that environmental assessment processes evolve with scientific understanding. The emerging challenge of secondary UFP formation highlights a potential gap between current air quality metrics and the atmospheric changes occurring as a result of decarbonisation. While the evidence suggests a potential for increased UFP events, significant uncertainties remain regarding their frequency, intensity, and ultimate health impacts in different environments.

Before comprehensive changes to atmospheric models and regulatory frameworks can be justified, a stronger evidence base is required. Therefore, the most logical first step is to bridge the gap between research and regulation. The World Health Organisation's Global Air Quality Guidelines already recommend enhanced UFP quantification. This can be achieved by strategically integrating mature measurement technologies into existing air quality networks, translating a research capability into a public health tool. We must begin to build a more complete picture of atmospheric particles that moves beyond a mass-only paradigm. Regulatory bodies should prioritise the deployment of instrumentation capable of measuring particle number concentration and size distribution, particularly in areas where future changes are anticipated, such as downwind of industrial clusters intended for CCS deployment.

This targeted monitoring would serve two critical purposes. First, it would establish a regulatory baseline and allow us to determine if, and to what extent, UFP formation is increasing in response to lower $PM_{2.5}$ levels and changing emissions profiles. Second, it would provide the ground-truth data essential for the development and validation of the next generation of air quality models—models that will eventually need to simulate the competitive atmospheric pathways and provide a more holistic risk assessment.

The journey towards cleaner air and a stable climate requires vigilance to the unintended consequences of new processes and practices. The potential for an increase in secondary UFPs is a clear signal of the atmosphere's complex response to the changes in emissions. By broadening the perspective and investing in the monitoring needed to properly understand this

phenomenon, regulators can gather the evidence required to ensure that climate solutions do not create a new generation of localised air quality problems. Sound policy must be built on a foundation of robust evidence, and the first step is to ensure that measurements are sufficient to identify and quantify potential problems.

Acknowledgements

This work was funded by the UK Natural Environment Research Council (grant NE/V001523/1, NPF-Urban) and the European Commission (grant 1010362450, RI-URBANS).

Author contribution statement

Conceptualization: Roy M. Harrison; Formal analysis: James Brean, Roy M. Harrison; Visualization: James Brean; Supervision: Roy M. Harrison; Writing – original draft: James Brean; Writing – review & editing: James Brean, Roy M. Harrison.

Data availability

The data used for the figures is freely available from the EBAS database.

Use of AI statement

None.

Declaration of competing interest

The author(s) have no competing interests to declare that are relevant to the content of this article.

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