Making Sense of Air Pollution Modelling: Framed Uncertainty

PhD dissertation

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Abstract:
Scientific results on air pollution are often conveyed to publics in absolute numbers implying accuracy and that researchers *know* specific matters related to residential wood stove emissions, premature mortality or economic costs with precision. The movers and shakers of society, in other words, appear to know such air pollution issues with accuracy communicating unambiguous numbers in public policy. But wood stove emissions are particularly uncertain and health experts suggest that the adverse health effects that can be quantified likely represent just the visible tip of an iceberg. Numerous impact dimensions on human health, biodiversity and climate elude quantification and remain highly uncertain, which begs the question of how researchers are communicating about such uncertainties to policymakers. To answer this question, I first explore how key actors in Denmark make sense of air pollution. I find that key actors make sense of air pollution through processes that involve multiple forms of data and different political purposes. Having established the foundation for studying uncertainty in this field, I proceed to analyse how uncertainty is being treated in three case studies related to measuring ultrafine particles, calculating residential wood stove emissions, and estimating the adverse health costs of air pollution. In each of these cases, I find that unmeasurable uncertainty is conflated with measurable uncertainty, leading to the marginalisation of unmeasurable uncertainty in science conducted for policy. The implication of my analysis is that the incumbent public policy tradition which favours quantitative values as public policy input must be reconsidered. Its limitations lie in preventing public officials from acting on unmeasurable uncertainty and exploring innovative new courses of action. Because uncertainty is particularly prominent in air pollution modelling and therefore consequential at the policy level, I propose that uncertainty is foregrounded in a manner that is actionable, concentrating on harm-reduction. By foregrounding critical uncertainties in air pollution modelling, I argue that researchers can provide policymakers with a more credible and helpful understanding of the profoundly uncertain context from which they must make difficult choices.

Resumé:
Videnskabelige resultater om luftforurening bliver ofte formidlet gennem utvetydige tal, herunder beregning af samfundsøkonomiske omkostninger, for tidlige dødsfald eller brændeovnsemissioner. Når journalister, forskere og beslutningstagere kommunikerer om luftforurening med absolutte tal, lader det altså til, at de kender disse fænomener med præcision. Men brændeovnsemissioner er særdeles usikre og sundhedseksperter vurderer, at det sandsynligvis kun er den synlige top af et meget større isbjerg af sundhedsomkostninger, der kan kvantificeres. Talrige omkostningsdimensioner relateret til sundhed, biodiversitet og klima forbliver u-kvantificerbare og højst usikre, hvilket rejser spørgsmålet om, hvordan forskere kommunikerer om disse usikkerheder til beslutningstagere. For at svare på dette spørgsmål undersøger jeg først, hvordan centrale aktører i Danmark forstår luftforurening, inden jeg analyserer, hvordan spørgsmålet om usikkerhed formidles i videnskabelige rapporter til politikere. Jeg finder, at centrale aktører forstår luftforurening gennem processer, der involverer forskellige typer data og forskellige politiske formål. Efter at have etableret grundlaget for at studere usikkerhed, undersøger jeg hvordan usikkerhed behandles i tre casestudier relateret til måling af ultrafine partikler, beregning af brændeovnsemissioner og samfundsøkonomiske beregninger af sundhedsomkostninger. I hver af disse cases finder jeg, at u-kvantificerbare usikkerheder bliver sammenblandet med kvantificerbare usikkerheder, hvilket fører til at kritiske usikkerheds dimensioner marginaliseres i videnskabelige rapporter adresseret til politikere. Denne marginalisering af usikkerhed er problematisk, fordi den frarøver beslutningstageres mulighed for at handle på de mindre velkarakteriserede dimensioner af luftforureningsforskning, som er afgørende i beslutningssammenhænge. Implikationen af mine analyser er, at den eksisterende public policy tradition, som marginaliser usikkerhed, må revideres. Dens begrænsninger ligger i, at den forhindrer beslutningstagere i at udforske nye politiske tiltag og ikke mindst handle på usikkerhed. Da formidling af usikkerhed i luftforureningsmodellering har stor konsekvens på politisk niveau, foreslår jeg at den formidles på en måde, der er handlingsorienteret og fokuserer på skadesreduktion. Ved at fremhæve kritiske usikkerheder i luftforureningsmodellering kan forskere understøtte beslutningstagere på værdifulde måder og muliggøre, at de bedre kan navigere den meget usikre kontekst, hvorfra de skal træffe vanskelige beslutninger.

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Rasmus Tyge Haarløv
Copenhagen, 14/02/2024

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Part II

Research papers

Papers and status

Paper 1 Dalsgaard, S., Haarløv, R. T., & Bille, M. (2021). Data witnessing: Making sense of urban air in Copenhagen, Denmark. HAU: Journal of Ethnographic Theory, 11(2), 521–536. https://doi.org/10.1086/717018

Paper 2 Haarløv, R. Strict Uncertainty: Ordering Ultrafine Particles Spatially via Google Street View Cars in Copenhagen
Submitted to Engaging Science, Technology, and Society

Paper 3 Haarløv, R. and Bille, M. Uncomfortable Uncertainty: Modelling Residential Wood Stove Emissions in Denmark.
In review in Science and Technology Studies

Paper 4 Haarløv, R. Expected Uncertainty: Recognising the Unquantifiable Impact Dimensions of Air Pollution in Economic Valuation Practices
Submitted to Environmental Science and Policy

PART I

1. Introduction

1.1 Uncertainty in air pollution modelling

The global health costs associated with $PM_{2.5}$ pollution amount to $8, 1 trillion (World Bank, 2022), long-term exposure to $PM_{2.5}$ pollution is responsible for 417 000 premature deaths in Europe (European Environment Agency, 2020) and residential wood stoves account for 52 percent of $PM_{2.5}$ emissions in Denmark (Ellermann et al., 2022, p. 70). Such unambiguous numbers proliferate in science conducted for policy on air pollution from the national to the international and global level. They imply accuracy and that researchers *know* these matters with precision and certainty. But such estimates are highly uncertain by default, and researchers are fully aware of it. The Lancet Commission on Pollution and Health, for example, expects that the 'health effects of pollution that are currently recognised and quantified could thus be the tip of a much larger iceberg' (Landrigan et al., 2018, p. 468).

To distinguish between those adverse health effects that can be translated into economic cost estimates and those that cannot, The Lancet Commission has developed a model called the 'Pollutome' to organize scientific knowledge on pollution and its associated effects on human health. This model is visualized as an iceberg, as shown in figure 1 below (ibid.). At the top of the iceberg, zone 1 comprises the well-established health effects of well-studied pollutants that can be quantified, such as lung cancer or heart disease. Zone 2 encompasses emerging health effects of known pollutants that are still challenging to quantify. Notable effects in this zone include associations between $PM_{2.5}$ and dementia, diabetes, pre-term birth and diseases of the nervous system (ibid.). At the bottom of the iceberg, zone 3 includes inadequately characterized health effects of emerging pollutants, whose impact on human health is only beginning to be recognized (ibid.). What makes this model interesting is that the health experts suggest that the uncertain, indeterminate, and unquantifiable impact dimensions of zones 2 and 3 may be more significant than the quantifiable health effects of zone 1. Furthermore, despite the growing body of incontrovertible evidence that air pollution contributes to global warming, ecosystem deterioration, plant and crop damage, among other non-health related ill-effects (Cao et al.

2013), such costs are often not quantified in science conducted for policy due to insufficient knowledge and lack of studies. Jasanoff (1990, p. 77) characterizes science conducted for policy purposes as being typically less innovative and rarely submitted for peer review, in contrast to research science, which places great value on published papers certified by peers - a characterization that is particularly apt when the topic is air pollution. In other words, the adverse impact dimensions associated with exposure to pollution that cannot yet be quantified due to limited knowledge and high uncertainty are likely more important than those effects which can currently be translated into the flattening measuring rod of money.

Translating the multidimensional adverse effects of pollution into economics, the language of public policy (Raworth, 2017), is a challenging and highly complex exercise and such efforts likely underestimate the true economic burden due to inadequate data, poor knowledge, and lack of information concerning the long-term effects of incumbent and emerging pollutants (Landrigan et al., 2018, p. 482). Despite rapidly rising costs associated with diseases and premature deaths, pollution-related diseases are often overlooked and undercounted as they are associated with latency extending over years and decades (ibid.). The 'Pollutome' model illustrates incoherence in the relationship between existing scientific knowledge about pollution and its effects, on the one hand, and which of these effects get to be counted in quantitative economic valuation processes, on the other hand. The implication is that even though contemporary economic cost estimates of air pollution are high, they almost certainly underestimate the true costs of pollution. Against this backdrop I consider it crucial to study the problem field surrounding how contemporary valuation and communication practices treat the subject of uncertainty at the juncture where air pollution modelling intersects with policy.

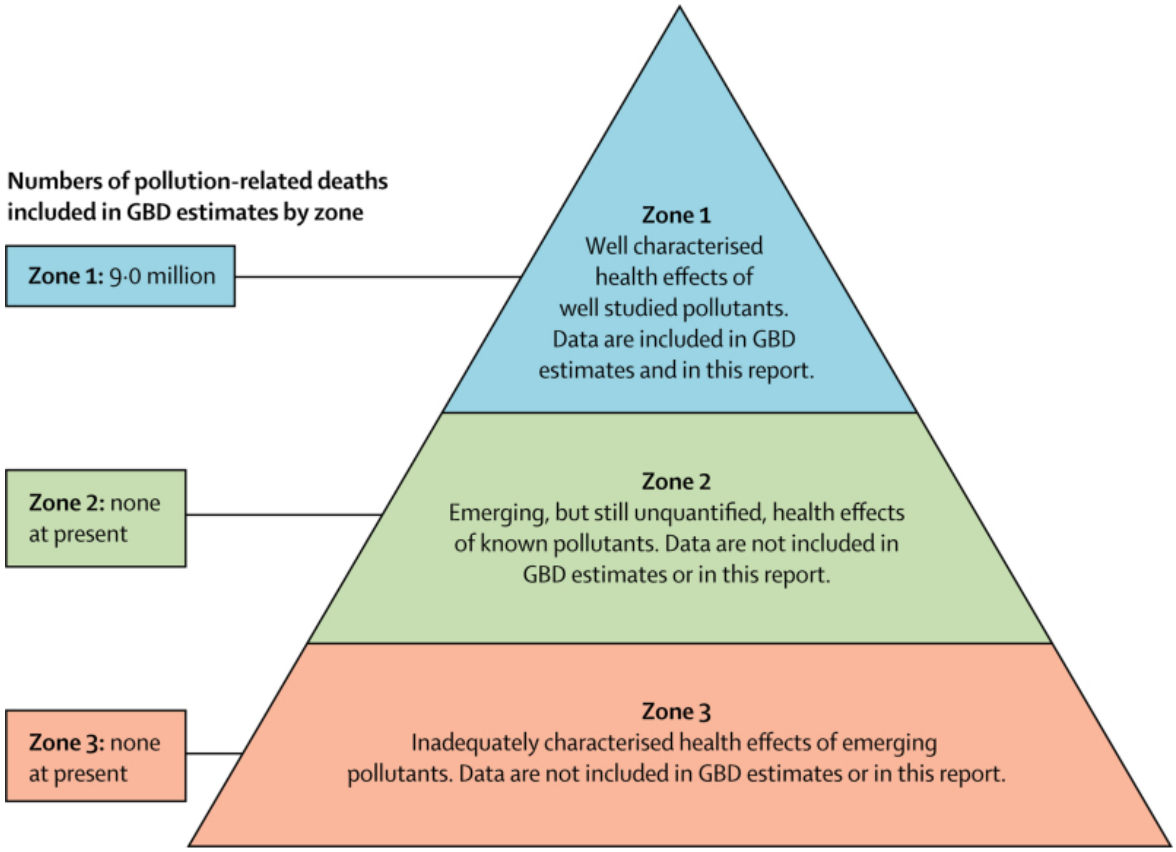

Figure 1: 'The Pollutome' in The Lancet Commission on Pollution and Health (2018, p. 468)

Air pollution researchers are constantly facing large uncertainties at the forefront of their field, which poses a challenge for them in terms of how they manage, value, and communicate about the issue to publics and policymakers. Yet, although researchers are constantly grappling with complex and large uncertainties in their everyday work, public officials and policymakers often expect that scientists and economists can deliver precise and decisive answers about complex environmental issues (Jasanoff, 2018; Pielke, 2007; Scoones & Stirling, 2020). Within the incumbent public policy tradition science often gives the impression of authority by shutting down decision dilemmas about issues which in reality remain open-ended and deeply uncertain, according to Stirling (2023 p. 2-3). In a similar vein Jasanoff (2018, p. 13) argues that the sciences over time have evolved into 'technologies of hubris' reassuring publics that contemporary issues like air pollution can indeed be measured and managed through calculative efforts. This unique public policy tradition involving researchers on the one hand, who are consistently navigating uncertainties at the forefront of their field, and public officials on the other, who seek accurate answers for policymakers, often results in discussions of uncertainty taking a backseat in science conducted for policy. However, uncertainty is particularly consequential when it intersects with policy (Jasanoff, 2022), which raises the research question addressed in this thesis:

How and why are unmeasurable uncertainties in air pollution modelling marginalised in science conducted for policy?

To answer this research question, I ask the following sub question:

How are key actors making sense of air pollution?

As a prerequisite to answering the research question, Dalsgaard, Bille and I first show how key actors embedded in research networks make sense of air pollution through processes involving multiple forms of data and collective purposes that enable actors to witness air pollution. Using this insight as a stepping stone for studying uncertainty in air pollution modelling, this dissertation argues that unmeasurable uncertainty – what Knight ([1921] 2018, p. 135-136) defines as incalculable situations where the distribution between an outcome cannot be known – is conflated with measurable uncertainty, leading to the marginalisation of unmeasurable uncertainty in air pollution modelling. More specifically, the thesis illuminates how this conflation occurs in three case studies related to measuring ultrafine particles, calculating wood stove emissions and estimating air pollution costs. Within each case, I shed light on the process by which assumptions regarding critical, yet essentially unknown parameters are translated into numerical values when researchers are faced with insufficient data. My dissertation thus contributes with new insights to STS discussions about how uncertainties which are pivotal to public policy are marginalised at the intersection where air pollution modelling meets policy. In contrast to the incumbent public policy tradition, I contend that public policy stands to gain from a more nuanced acknowledgement of uncertainty when it is conveyed in a helpful manner that enables public officials to act.

To answer the research questions, a multifaceted approach is taken, including desk research, document analysis and interviews with key actors. The research participants include fifteen senior air pollution researchers in Denmark, four municipal leaders working for Copenhagen Municipality, two citizens living near Copenhagen Airport and a chimney sweep. The research participants are involved in various kinds of air pollution work: The chimney sweep is engaged in public discussions on wood stove emissions. The concerned citizens organize to protest publicly against a proposed expansion of Copenhagen Airport, while the municipal leaders work towards mitigating urban air pollution hotspots. The air pollution researchers are involved in several large research projects concerning the adverse health effects of pollutants at different research institutions in Denmark. Several researchers take part in the production of science for policy purposes, thereby laying the foundation for policymaking. Additionally, some of my interviewees are experts who engage in public discussions on air pollution, providing valuable insights to the public on specific issues.

As a researcher inspired by Actor-Network Theory (ANT), I approach the issue of uncertainty in air pollution modelling by adopting an object-oriented sensibility towards particles, measurement instruments, epidemiological studies, and mathematical modelling systems. By focusing on incumbent air pollutants, on the one hand, and emerging pollutants, on the other, I explore the boundary between certainty and uncertainty in air pollution modelling. That is, I attend to how and why certain pollutants are being measured, modelled, and valued in science conducted for policy, while other types of pollutants and their associated effects are left marginalised due to uncertainty. To enhance my understanding of uncertainty in this field, I draw upon insights from STS and economic sociology, where uncertainty has become the centre of attention in recent years (Beckert, 2016; Callon, 2021; Jasanoff, 2022; Kay & King, 2020).

Air pollution rarely garners much public attention, despite its significant impact on public health and close entanglement with the ecological and climate crises. In Europe, the issue is governed by the European Commission and to citizens of Denmark air pollution is mostly imperceptible. Much of the air pollution floating across Denmark originates from sources outside Denmark, which reduces the potential for dealing with the problem at the national and urban level. In American cities air pollution has been labelled a 'non-issue' which continuously fails to rise to the surface of urban politics, as Crenson (1971) argued – a characterisation I still consider generally apt more than 50 years later. While the issue has certainly gained some traction among lay people and policymakers since then, it is currently being overshadowed by the ecological and climate crisis. While these issues are closely linked, making sense of air pollution modelling requires some scientific literacy and familiarization with chemical pollutants and threshold levels. But citizens may have other pressing concerns in the everyday lives, which may detract from its prominence in public discourse. Consequently, I consider the politics of the issue to be located in science conducted for policy reports rather than among lay people, as such reports typically lay the foundation for how policymakers understand the context from which they must make difficult decisions.

Before I proceed to the methodological and theoretical parts of the dissertation, I consider it useful to note the historical and empirical context of air pollution science and not least what kinds of uncertainties scientists are struggling with at the frontiers of research.

1.2 Historical context: from healthy black smoke…

Prescientific knowledge and science on air pollution has changed radically throughout history, which is the topic addressed in this section. Human-induced air pollution has existed since humanity learned to master fire, and indoor air pollution has been a severe - albeit unrecognized - issue, since pre-industrial societies lived in houses equipped with indoor hearths (Fenger, 2004). In this brief historical overview, it can be noted that in 1000-1600 AC Britain, as excavations of skeletons show, more than half of citizens living near industrial areas suffered from sinus infection in London, the symbol of urban air pollution for centuries (ibid.). Coal was essential to the rise of industrial towns, first in Britain followed by Continental Europe, US and subsequently other parts of the world. As it replaced wood in manufacturing centres like Manchester, Birmingham and Germany's Ruhrgebiet air pollution surged to unprecedented levels (Mosley, 2014, p. 148). Although coal now accounts for 'only' a third of the world's energy, it is worth noting that global production has soared from around 10 million tons in 1800 to 3,5 billion tons per year in 2000, most of which is now produced and consumed in China (ibid., p.156) and, increasingly India.

Before the chemical exploration of air was set in motion with the discovery of nitrogen and oxygen in the 1770s, air pollution was comprehended via theories such as 'miasma' and 'flogiston' (Fuller, 2019, pp. 6–7). As a result of these ideas, people were urged to light coal fires in public spaces to drive miasma away from the streets during plagues that struck London in the sixteenth and seventeenth centuries. An official investigation into air pollution by the UK House of Commons, a century later in 1859 concluded that 'the air of large towns had no effects on the lungs when compared with air supplied by nature' (ibid., pp. 9, 11). At the same time vivid descriptions from Victorian meteorologists depicted air pollution as a colossal problem in central London, where lack of daylight and permanently dark skies was not uncommon between 1881 and 1885 (ibid., p. 30). Fast-forward to the Second World War air pollution levels reached such critical levels that automobile headlights were needed during daytime in some European cities (Rothschild, 2019, p. 10).

Since the discovery of steam power, large portions of the public had generally perceived black smoke as a sign of prosperity and economic growth (Rothschild, 2019 p. 13). This conviction did not change until several major air pollution incidents, including one in London in 1952, which killed thousands of people within days (Brimblecombe, 1987). In other words, from being a largely unknown phenomenon in pre-industrial society to being a sign of prosperity during the heydays of Western industrialisation, air pollution has only relatively recently become recognized as a health issue, which leads us to how it became the target of scientific research.

1.3 …To an invisible slow disaster

The study of expertise in science brings into focus the concept of a knowledge object, which refers to an object's lack of 'objectivity' or completeness (Cetina, 1997, pp. 14–15). Knowledge objects are characterized by being things that are constantly evolving and mutating and they often co-exist in numerous variations at the same time (ibid.), which is particularly true for air pollution, as we shall see.

Scientific knowledge of air pollution levels before the twentieth century is hard to come by; there simply were no measurement instruments. Measuring urban air pollution was not possible until 1910 when, inspired by The Lancet, deposit gauges were developed (Brimblecombe, 2004, pp. 18–19). Even so, it was not until the mid-1950s, after the horrific episode mentioned above, that research into air pollution took off across Western industrialized countries. That air pollution can travel thousands of kilometres became obvious when scientists began to document the spread of pesticides (Carson [1962] 2002) and radioactive fallout to nearly every corner of the planet with the introduction of nuclear weapons testing after the Second World War (Rothschild, 2019, p. 11). The ability to measure radioactive particles, not only in the human body but also in ecosystems across the globe, advanced the idea that air pollution was not only a visible threat in the form of black smoke but also an invisible one in the form of gases (ibid., p. 10). The increasing scientific recognition of 'invisible' pollutants began with sulphur dioxide, an invisible but strong-smelling gas produced by burning fossil fuels, which became the first invisible air pollutant suspected of posing a danger to public health.

The idea of an 'environment' which works on multiple scales - local and global, from the microscopic lifeworld of an organism to the entire atmosphere - gained traction in the decades following the Second World War (Warde et al. 2019, p. 12), and when Swedish scientists first identified acid rain as a continental problem in Europe during the late 1960s that resulted in 'forest deaths' across European soils, their findings prompted the first international discussions over whether nations should work together on pollution problems via supranational institutions (Rothschild 2009, p. 11). Due to international cooperation on the problem of sulphur dioxide initiated by the OECD, levels of the gas subsequently fell sharply across the US and Europe between 1980 and 2000. Acid rain has therefore been hailed as one of the first international pollution problems to be 'solved' (ibid., p. 187).

Moving from sulphur dioxide to particulate matter (PM), this basic unit of measurable atmospheric pollution was first discovered in 1972 in Los Angeles, California, due to the deployment of newly developed instruments (Whitby et al. 1972 in Cao et al. 2013, p. 1197). Some of the first assessments of impacts and costs arrived in the late seventies and early eighties (Lave and Seskin 1977; Graves and Krumm 1981 in Rabl et al. 2014, p. 64), but it took until 1997 before the particle fraction $PM_{2.5}$ was justified as a novel air pollution indicator following the groundbreaking 'Six Cities' study on global health which proved an association between air pollution and mortality (Dockery et al., 1993). It is hard to overstate the importance of the Dockery et al. study as it still offers the best estimate for how much lives are shortened by particle pollution that is breathed across the globe (Fuller, 2019, p. 95). The methodological establishment of large cohort studies has since been very influential in advancing scientific understandings of premature mortality (Anderson 2009, p. 142), a parameter which still weighs most heavily in contemporary damage cost assessments.

In the aftermath of the Six Cities study air pollution has increasingly become recognised as a serious health problem that is now associated with economic costs equivalent in magnitude to about 6 percent of global GDP, ranging from 1.7 percent of GDP in North America to 10.3 percent in South Asia (World Bank, 2022). The OECD (2016) indicates an upward trend and estimates that the costs could increase to 9-12 percent of global GDP in 2060. Economic cost estimates evolve following new scientific discoveries of associations between adverse health effects and air pollutants (Landrigan et al., 2018); and $PM_{2.5}$ is currently the most important air pollution indicator and standard for translating mortality and morbidity into economic cost estimates (World Bank, 2022; World Health Organization, 2013).

The vantage point for understanding harmful pollution today is thus that we are living in a permanently polluted world (Liboiron, Tironi, & Calvillo, 2018), where 99 percent of the world's population is exposed to levels of air pollution that exceed WHO guidelines (World Health Organization, 2021). A helpful way in which scholars have described the temporality of a permanently polluted world is to characterise it as a slow disaster (Fortun et al., 2016; Gray- Cosgrove et al., 2015; Knowles, 2014 in Liboiron et al. 2018). In contrast to event-based disasters which typically get more public attention, slow disasters are 'neither spectacular nor instantaneous, but rather incremental and accretive, its calamitous repercussions playing out across a range of temporal scales' (ibid., p. 338). That is, slow disasters involve slow violence that is dispersed across time and space and whose impact is gradual and oftentimes out of sight (ibid.).

This brief overview of how knowledge on air pollution has changed historically to some extend reflects how air pollution scientists have understood the development of this subject. As a result, it may appear linear to some readers. However, scientific knowledge on air pollution does not follow a linear path. Science is not a transcendent mirror of reality which operates independently from public concerns and policymakers (Jasanoff 2006, p. 277); it is rather embedded in knowledge practices and co-produced by instruments and institutions, discourses and conventions that change over time (ibid., pp. 2–3). That is, although public concerns are less pronounced in my brief historical overview, it is important to note that public concerns over air pollution have likely shaped air pollution science as much as air pollution science has shaped public concerns. In summary, this short overview underscores the case that the knowledge object 'air pollution' has continued to mutate in the twentieth century from being associated with black smoke, radioactive particles and acid rain to more recently huge economic health effects. While the discovery of particle fractions (PM_{10}; $PM_{2.5}$; $PM_{0.1}$) has been critical in terms of linking air pollution to adverse health effects, scientific knowledge on air pollution is likely to remain unstable and continue to evolve moving forward.

1.4 Empirical context: the uncertainty of particle fractions

In this section, I shed light upon some of the key research topics within contemporary air pollution science that interest my interlocutors, including the researchers, municipal leaders and concerned citizens. As air pollution has become increasingly linked to adverse health effects, the World Health Organization (WHO) has emerged as the scientific authority on matters related to air pollution. The WHO (2023) defines air pollution as 'contamination of the indoor or outdoor environment by any chemical, physical or biological agent that modifies the natural characteristics of the atmosphere.' However, in this dissertation I make particle pollution my focal point, as it is currently mostly associated with adverse health effects. More specifically, my focus encompasses the incumbent $PM_{2.5}$ indicator and two emerging indicators called black carbon (BC) and ultrafine particles (UFPs), both of which are suspected of being more harmful to human health than $PM_{2.5}$.

An average human hair is about 70 micrometres in diameter – making it roughly 30 times larger than the largest $PM_{2.5}$ particles (US EPA, 2016). The $PM_{2.5}$ indicator is surrounded by a range of uncertainties and probable errors (Spash, 2002, p. 7). These include difficulties in determining citizen's actual exposure to $PM_{2.5}$ pollution in terms of timing, frequency, duration, and pollution mixture. Moreover, individual responses to pollutants can vary significantly for a range of reasons (ibid.). As a result, it remains challenging to attribute independent effects to specific pollutants or particle sizes because populations are constantly exposed to a mix of correlated pollutants (Rabl et al., 2014, p. 64). Despite the high uncertainty surrounding the $PM_{2.5}$ indicator, it is still the most widely used indicator and essential for estimating the economic health costs associated with air pollution. At this point it is important to note that scientific standards rarely remain the same (Bowker and Star 2000, p. 293).

Since $PM_{2.5}$ emerged as an object of aerial governance following its establishment as a new indicator and standard by the US Environmental Protection Agency in 1997 (Cao et al., 2013, p. 1201), air pollution scientists have debated which elements of this particle fraction cause the most harm to human health. Singling out the main culprit or component substance of what several air pollution researchers, I interviewed, describe as an ill-defined $PM_{2.5}$ 'soup' is currently the holy grail of air pollution science, as it would enable governments to implement much more efficient regulations. Researchers I interviewed are currently working under the assumption that particles from combustion processes such as black carbon (BC) may be a leading culprit. BC has been proposed by the WHO (2021) as a proxy for understanding *local* particle pollution from sources like traffic and residential wood stoves, while $PM_{2.5}$ currently operates as a proxy for understanding the *regional* background level of air pollution. Research suggests that the economic health costs associated with long-term exposure to BC can be more than four times higher than those associated with $PM_{2.5}$ exposure in Copenhagen (Jensen et al., 2021, p. 60).

Besides BC, the particle fraction ultrafine particles (UFPs or $PM_{0.1}$), with a diameter of 0,1µm or less (<100nm), has drawn attention among researchers. A currently popular hypothesis for UFPs suggests that they have greater potential to cause health damage precisely because of their small size, as this is what allows them to penetrate deeper into the lungs and translocate to all organs while carrying toxins (Schraufnagel, 2020). Although current measurement instruments have limitations in terms of measuring this particle fraction accurately, efforts are under way at the Danish Cancer Institute to identify an exposure-response function for UFPs, which would allow this particle fraction to be considered in economic cost assessments of air pollutants. If scientists can establish exposure-response functions for UFPs, the key ingredient in economic valuation practices, local sources such as residential wood stoves and traffic are likely going to account for more health effects (Jensen, et al. 2021, p. 64).

Regulation of risks to health and the environment often involves phenomena at the frontiers of science, where consensus among researchers is fragile (Jasanoff, 1987, p. 197). Moreover, during the construction of environmental models, externally defined endpoints - along with pragmatic considerations related to what can actually be measured - frequently determine the structure of knowledge output (Wynne, 1992, p. 113). These insights resonate with the emerging indicators BC and UFPs, for which scientific consensus has yet to form. This brief overview of incumbent and emerging indicators and their associated uncertainty operates as a stepping stone for my argument that it is pertinent to examine air pollution modelling through the lens of uncertainty.

The remaining parts of the thesis are structured as follows: First, I outline my method and research approach rooted in ANT. Next, drawing upon STS and Economic Sociology, I introduce the discussions and concepts related to 'uncertainty' that guide my analytical lens. Then, I outline the conclusion of the thesis and offer a perspective for further research. The Kappa is followed by the four research papers.

2. Method and research approach

In this section I cover the ideas and concepts that guide my methodological thinking. First, I outline some of the core tenets of ANT informed research related to performativity (Law & Urry, 2004), method assemblages (Law, 2004) and ‘knowledge objects’ (Cetina, 1997). Then I shed light upon how social scientists can study large-scale phenomena following Ribes (2014) before elaborating on how my research endeavour unfolded and how I approached the ‘field’ inspired by elite interview techniques (Kezar, 2003). Finally, I discuss the methodological implications of conducting research during COVID-19 lockdowns and why I find it helpful to refold concepts and theory (Krarup & Blok, 2011; Winthereik, 2023) into ANT-informed research.

2.1 ANT: performing uncertain, complex and irregular phenomena

Actor-network theory (ANT) operates as fruitful vantage point for studying air pollution because of how it puts associations between science and politics, humans and nonhumans at the centre of social inquiry (Schinkel, 2007). This intellectual tradition can be characterised as a family of methodological and conceptual sensibilities which grew out the sociology of science and technology in the late 1970s as a collective achievement of several scholars (Farias, Blok, & Roberts, 2023, p. xx). Methodologically speaking I am mostly influenced by the ANT tradition as developed by John Law, Michel Callon and Bruno Latour (Callon, 1990; Latour, 2007; Law, 1993). In what follows, I discuss how John Law’s ideas concerning methods are particularly apt for my purposes, and reflect upon how relational materialism (Law, 1993) and object-oriented sociality (Cetina, 1997) inform my methodological thinking and research approach.

The vantage point for this section is that a strict adhesion to classical social science methods is ill-advised considering twenty-first century realities (Law & Urry, 2004, p. 69) that involve ubiquitous, interrelated phenomena such as the ecological crisis, the climate crisis and air pollution, which defy national boundaries and are global in scale. The classical methods are not problematic per se; rather, it is the discourse and normativity associated with them – as well as how such discourses are being deployed to claim methodological hegemony - which raise concern for Law (2004, pp. 4–5). While standard methods are presumably good at what they do, they are ill-equipped for the study of the irregular, the indefinite and the ephemeral, multiple, complex, slippery and non-causal (Law, 2004, pp. 4–5; Law & Urry, 2004, p. 69) – all terms highly pertinent to discussions on air pollution.

To break free of the standard methodological shackles imposed by specific Euro-American assumptions, Law advises us to unmake our methodological habits and desire for certainty (Law, 2004, p. 9). Uncertainty should be accepted as the foundation of inquiry and the focal point should be on the supposed mystery of how things came to be ordered in a certain way, he argues (Law, 1993, p. 18). Orders should not be taken for granted; instead, they should rather be treated as the outcome of specific processes of ordering (ibid., p. 12). Indeed, the question of how overlapping and evolving particles are ordered into distinct categories of incumbent and emerging pollutants runs like a leitmotif throughout much of this dissertation. Law urges sociologists of associations to adopt a non-reductionist, non-dualistic and relationally materialist approach (ibid., p.95), pointing out that the social sciences have yet to develop their own ensemble of methods for 'understanding – and helping to enact – twenty-first-century realities' (Law & Urry, 2004, p. 403). Analytically, this implies treating both humans and nonhumans as equal contributors to the dynamic formation of networks. The alleged symmetry between humans and nonhumans radically challenges grand sociological theories which have shaped much of the 20th century (Farias et al., 2023, p. xxi). In contrast to grand sociological theories where agency is predominantly attributed to humans, things can be attributed with agency in ANT due to their position in a networks (Hess, 1997, p. 108). ANT, in other words, invites sociologists of association to follow the attribution of agency among both humans and nonhumans in socio-technical networks.

The enactment of reality is related to another core insight advanced by Law: that methods are performative. He explains that there are generally two views on method in science and social science. First, there is the view representing received wisdom. This approach operates under the assumption that reality has a definite form which is essentially independent of the tools deployed to research it (Law, 2009, p. 239). Following this line of thinking the job of the researcher is to uncover and describe this reality as best as possible (ibid.). Second, there is the alternative view which holds that methods are practices which tend to enact realities in addition to describing them. This alternative view treats knowledge practices as performative (ibid., p. 240). That is, instead of understanding methods as inanimate sets of procedures for reporting on a given reality, social scientists need to acknowledge that methods themselves also help to produce certain kinds of realities (Law, 2004, p. 143). In other words, the ANT view on method as advocated by Law and Urry (2004, p. 397) implies a shift from 'epistemology (where what is known depends on perspective) to ontology (what is known is also being made differently)'.

A consequence of this is that methods should not be perceived as innocent or purely technical. Methods create specific kinds of realities and non-realities, truths and non-truths, presences and absences which could have been otherwise (Law, 2004, p. 143). To the extent that the social sciences conceal their performative aspect, their claim to innocence is false, Law and Urry (2004, pp. 403–404) emphasize. Invoking Heisenberg's note that '[w]hat we observe is not nature itself, but nature exposed to our method of questioning,' Law and Urry (ibid., p. 397) propose that methods always, in some sense, enact whatever it is they try to describe; they help bring into being what they discover (ibid., p. 393). Following this line of thinking, the issue becomes one of 'ontological politics.' As methods are never innocent, they become political in the sense that they make certain ontological realities more real than others (ibid.). The question for sociologists of associations thus becomes how we want to interfere, in what ways we want to help make specific kinds of realities more real, and which realities we want to make less real (ibid.). By focusing on how air pollution scientists make certain air pollution realities more real than others in this dissertation, I analyse the embedded politics of provisional orderings of air pollution by different methods.

2.2 ANT: methods, knowledge objects and matters of concern

The claim that reality is multiple involves the idea that multiplicity is a product and effect of how networks of scientific practices and instruments situated in different laboratories produce statements about reality that may be conflicting (Law, 2004, p. 32). While reality can be considered singular under circumstances where controversies have been resolved, realities are presumably multiple during times of controversy (ibid.). Following this line of thinking, realities become manifestations of inscription devices, where the limits to reality and scientific knowledge production are set by specific sets of instruments (Latour &

Woolgar, 1979). The concept 'hinterland' refers to the idea that methods extend far beyond the limits of what is typically associated with the term and includes everything from computer software and language skills to funding bodies and overt political agendas (Law, 2004 pp. 40-41). Methods, in other words, grow out of socio-technical hinterlands that change over time and whose boundaries are porous, extending outwards in numerous directions (ibid.). Method assemblages in turn produce different kinds of objects, which are assembled and crafted by different networks and their associated hinterlands (ibid., p. 54).

While the concept of 'assemblage' can be defined in numerous ways and goes back to French philosophers Gilles Deleuze and Félix Guattari (Müller, 2015, p. 28), I subscribe to John Law's view of the concept. Assemblage according to Law (2004, p. 42) involves the process of assembling, or putting together things and elements which are not fixed in shape but rather constructed in part as they are entangled with other objects. The implication is that there cannot be general rules or fixed formula for determining good or bad method assemblages. Method assemblages both grow out hinterlands and create their own hinterlands while changing in shape through dynamic processes (ibid.). To Law (2004) there is little difference between Deleuze's concept of agencement (which translates to 'assemblage' in English) and the term actor-network. The important point is that both refer to the provisional assembly of heterogeneous and '(this is the crucial point) quite limited forms of ordering located in no larger overall order' (Law 2004, p. 146).

The study of uncertainty and scientific expertise in the field of air pollution moreover brings into focus two related concepts in the form of 'knowledge objects' and 'matters of concern.' The defining characteristics of knowledge objects are their lack of objectivity, and their changing and unfolding character (Cetina, 1997, pp. 14–15). Knowledge objects are defined by their lack of completeness, they are things that continually mutate; and they are defined as much by what they are not as by what they are (ibid.). 'Finally, knowledge objects exist simultaneously in a variety of forms, a point which becomes important in regard to their binding role for collectives,' according to Cetina (ibid.). Seen from a historical point of view, this concept encapsulates how descriptions and metaphors for speaking about air pollutants have changed and mutated over time. Taking inspiration from Cetina, I briefly summarise how the knowledge object 'air pollution' has changed in the twentieth century and how it continues to do so in the present.

Bruno Latour, addressing the ecological crisis, proposes that to be able to grasp the extent of the crisis we must recognize the proliferation of matters of concern (Latour, 2004, pp. 24–25). Unlike matters of facts, which have clear boundaries and well-defined essences (ibid., pp. 22-23), matters of concern resemble knowledge objects in the sense that they have no sharply defined boundaries or clear separation between their own essence and their associated environment (ibid., pp. 24-25). Inspired by Latour's work on this subject, I make the concerns of my interlocutors my focal point, as I explore how different measurement devices and model systems enact air pollution in ways that have different political implications. To me the methodological implication of following Law, Cetina and Latour is to adopt an object-oriented approach and trace the path of knowledge objects and matters of concern. This involves focusing on the technologies and instruments that shape the nature of emerging socio-technical networks.

2.3 ANT: studying indicators of scale

How can social scientists study an omnipresent phenomenon which disregards boundaries of all kinds, including urban, national, and regional borders, and is which mostly beyond the reach of the human senses? They can do it by focusing on the scalar indicators that natural scientists use to manage and scale a particular large-scale phenomenon (Ribes, 2014). The goal of this approach is for the ethnographer to uncover and open the black boxes of scalar indicators themselves. Confronted with a representation that indicates the size of an object, for example, an ethnographer would aim to study the enormous technical and organizational work set in motion to generate the indicator in the first place (ibid., p. 161), it is argued. The social scientist, in other words, turns their attention to the assembly of tools, instruments, and representational conventions that actors use to know and manage a particular object (ibid.). In contrast to the alternative ethnographic approach for studying large-scale phenomena popularized by anthropologist George Marcus (1995) under the header 'multi-sited ethnography,' which suggests that an ethnographer should follow the research object in a select number of locations, Ribes's scaling approach resembles past ethnographic analysis of scientific practices in centres of calculation (e.g. Latour, 1983, 1986, 1987).

Ribes defines scalar devices as the representational conventions, tools and techniques used to manage, scale and know a particular research object (ibid., p. 160).

Inspired by the actor-network sensibility towards actors, associations and networks (Latour, 2007), an ethnography of scaling involves a three-dimensional analytical focus on: 'i- the development and deployment of a scalar device; ii- the resulting indicator and its reception; and iii- the down-stream consequences of indicators as they are wrapped into organizational action or design. It is across the trajectory of these activities that the scale of an enterprise comes to be represented, known and then managed' (Ribes, 2014, p. 161). Following Ribes's focus on the deployment of scalar indicators and their associated downstream consequences, I examine how air pollution is measured and modelled as well as what the potential political implications of those representations are.

A key conviction of this methodological approach is that the ethnographer asks the actors how they know and manage the problems associated with a particular indicator of scale (ibid., p. 158). The methodological implication of this conviction is thus to maintain an agnostic attitude towards the size of the research object. This instruction resembles a core tenet in ANT to the effect that a researcher's preconceptions and categories should not be allowed to dominate descriptions (Gad & Jensen, 2010, p. 76). It is thus not a concern for the ethnographer following Ribes to determine the size of an object; that is the concern of those actors who engage in knowing and managing the object (Ribes, 2014, p. 161). The role of the ethnographer here is to gain access to activities of scaling and analyse how scaling is being conducted in practice (ibid.). The question of method, in other words, resembles Callon and Latour's proposition (1981, p. 301) in the sense that it boils down to situating oneself where the forces are translated - where the difference between the technical and social is being decided. By doing so the researcher can bypass the sociological myth that macro actors are harder to study than micro actors (ibid., p. 299), to follow Callon and Latour. Inspired by this conviction, I approach the macro actor (air pollution) by attending to how the micro actors (my interlocutors) determine the size and scale of the phenomenon.

Influenced by Ribes's methodological approach for studying large scale objects, Latour's work on centres of calculation (Latour, 1986) and Edwards's (2011) focus on climate models, I approach the research object air pollution with a sensibility towards the instruments, inscription devices and model systems that scientists use to render air pollution knowable.

2.4 Interviewing key actors during COVID-19 lockdowns

To study how the problem of air pollution and its associated uncertainties are being measured and modelled at different scales and translated into science policy reports, I likewise draw upon anthropological insights regarding the study of elites. In what follows, I present how I approached the 'field' while being situated in my combined home and office during numerous COVID-19 lockdowns and outline the strategies I deployed to analyze the empirical material.

To familiarize myself with the subject of air pollution, I first spent time reading textbooks and scientific reports about the subject, as well as science conducted for policy documents produced by scientific authorities such as the European Environment Agency, the World Health Organization and the Department of Environmental Science, Aarhus University. Concurrently I researched how the problem of air pollution had developed historically and followed contemporary discussions of air pollution in international as well as Danish news outlets. On Facebook I tracked two citizen groups called 'CPH without Expansion' and 'Stay Grounded,' who are organizing pushback action against a proposed expansion of Copenhagen Airport.

Then in March 2020 – three months after I commenced the project – the COVID-19 pandemic hit Denmark. This meant a radical change to the circumstances for conducting research; my home became my office and vantage point for conducting research online as Denmark was went through different stages of lock-down through 2020-2022. Despite these circumstances, I was fortunate to be able to interview fifteen senior researchers working on air pollution situated at different research institutions in Denmark (Aarhus University, Copenhagen University, The Danish Cancer Institute, The National Center for Work Environments, and the Danish Technical University). In addition, I interviewed four public officials working with air pollution for the Municipality of Copenhagen, a chimney sweep engaged in the air pollution debate in Copenhagen and two concerned citizens living in the vicinity of Copenhagen Airport. Except for four interviews - one of which resulted in a weeklong isolation after the interlocutor turned out to be infectious - all the interviews for this dissertation were conducted online via Teams or Zoom. Whether the pandemic enhanced or diminished my chances for interviewing busy researchers, municipal leaders and concerned citizens with tight schedules remains an open question.

Having said that – and with the benefit of hindsight – it has become clearer to me that these exceptional circumstances did hamper my research efforts in significant ways. First and foremost, the lockdowns prevented me from following the actors in situated practices, which would be the prerogative in classical ANT accounts (Latour, 1983, 1987). Due to the circumstances my research approach is closer to historical ANT accounts of Aramis (Latour, 1996) or Pasteur (Latour, 1993) to the extent that I combine analysis of interviews with the study of a series of texts. Secondly, the lockdowns lead to a series of delays of conferences, PhD courses and academic workshops which resulted in increasing intellectual isolation. In other words, being unable to learn from the actors in situated practices as well as being unable to discuss research topics and ideas with colleagues and peers at work over lunch, coffee or during breaks at conferences etc., impacted my intellectual journey in a negative way.

Another significant disruption to my 'fieldwork' occurred when two of our research partners from Copenhagen Solutions Lab, a smart city initiative by Copenhagen Municipality, left their positions. They had been involved in Project Air View - a research collaboration between University of Utrecht, Google, Copenhagen Municipality and Aarhus University, which was mapping air pollutants in the streets of Copenhagen via purpose-built Google Street View cars equipped with mobile measurement equipment. Our (Dalsgaard, Bille and my) original idea was that I should study how actors in Copenhagen Municipality deploy the Copenhagen Air View map for policy and planning purposes. However, as our partners were no longer stakeholders with a sense of ownership in the project, the research network was cut (Strathern, 1996, p. 524), and I had to move on and seek empirical insights elsewhere. Whether the pandemic hampered the deployment of the Copenhagen Air View map among urban planners and public officials is likewise unclear. Due to these empirical challenges, papers 1 and 2 focus on air pollution at the urban level in Copenhagen as initially intended in the original research proposal, while papers 3 and 4 focus on air pollution modelling at the national level.

Having surveyed how air pollution was discussed among journalists and lay people, I quickly became more interested in how scientists make sense of this complex phenomenon via measurements and model systems, as well as how they translate air pollution into science for policy documents. Influenced by the methodological shift proposed by anthropologist Laura Nader (1972, p. 5) more than 50 years ago under the header of 'studying up' - which means changing the anthropologist's focal point of attention of toward the powerful rather than the suppressed – I shifted my focus to how senior researchers, professors, heads of environmental committees and leaders of citizen groups make sense of air pollution at the urban and national level. The best methodological vantage point for studying elite institutions, according to Nader, is an eclectic approach because one is unlikely to gain access to the field via participant observation (ibid., p. 23). As participant observation was completely ruled out by the pandemic, I adopt a somewhat eclectic – though not random – approach to the study of air pollution in this dissertation by combining interviews with document analysis.

With a background in anthropology, I interviewed the research participants influenced by this discipline in the sense that I often followed the lead of my interlocutors while engaging the interview situation in a casual, semi-structured, conversational manner (DeWalt & Dewalt, 2002, p. 202). As I became more attuned to what – in my view – is at stake in the field of air pollution science, my interviews began to resemble elite interviews in the sense that I arrived at a provisional analysis, which I based the interview guide on (Kezar, 2003, p. 397). As I learned how uncertainty is present in numerous branches of air pollution science, I discussed state-of-the-art research into emerging pollutant indicators with the scientists to get a better sense of the different perspectives which shape the field.

Having identified uncertainty and the associated communication thereof in science conducted for policy documents as my focal point, I introduced some of my provisional analytical points in a few interviews to test my research ideas. While some of my interlocutors found my provisional analytical points interesting and useful, others objected to them right away. After one particular interview session where I had introduced some of my provisional insights to a group of researchers, I realized there was a risk of impacting my own and other social scientists' access to the field negatively (Punch, 1986; Whyte, 1984 in Kezar, 2003, p. 398), if I persistently challenged contemporary practices concerning communication of uncertainties in science conducted for policy reports. From then on, instead of attempting to bring about change via the interview situation, as a journalists might do in an elite interview situation (Kezar, 2003, p. 398), my aim shifted to bringing about change through analytical work in the papers and subsequently through public dissemination.

As a researcher, I follow the GDPR (General Data Protection Regulation) rules as outlined by the European Commission and subscribe to the code of ethics as outlined by ASA (American Sociological Association) and AAA (American Anthropological Association) including the basic principles of doing no harm to my interlocutors, being open about my work and making my results accessible (American Anthropological Association, 2023; American Sociological Association, 2018). To honor the general principle of doing no harm to my research participants, I maintain anonymity of the people I have interviewed (DeWalt & Dewalt, 2002, p. 204). At the same time, I am well aware that 100 percent anonymity is not entirely possible among my interlocutors in a small country like Denmark, where the number of air pollution experts is so small that many of my interlocutors know each other's areas of expertise across institutions.

The development of my research orientation did not follow a straight line. Among my influences were former teachers and colleagues like Theresa Scavenius and Jens Petersen, from whom I learnt to focus on the things I do not understand and that puzzle me the most, while being attuned to 'what is at stake' in the field (personal conversation). For the work of analysis I borrowed a kind of 'staying with the trouble' propensity from Haraway (2016), which required a certain form of immersion into the empirical material (Strathern, 1999). As the pandemic prevented me from tracing associations through fieldwork, I immersed myself in scientific publications on air pollution to better understand the scientific uncertainties shaping the field. As I engaged the empirical material I was simultaneously attentive to how I could potentially enliven concepts and seek unanticipated insights (Ballestero & Winthereik, 2021, p. 4) through an iterative spiral between the empirical material and analytical concepts. During this analytical process of curiosity, struggle, and contemplation, I developed a keen interest in how air pollution and its associated uncertainties are being measured, modelled, and translated into science for policy.

2.5 Refolding theory into ANT descriptions

Actor-network theory has been criticized for encouraging sociologist to follow the heroes, those in charge, typically the heroic scientists or engineers. The point being that the resulting stories miss the work done by actors with less agency who work at the margins of scientific and technical knowledge production (Sismondo, 2009, p. 89). Along similar lines scholars have pointed out that ANT eschews to think about disparate power relations, including class, race or gender, which may impact who is able to form associations in the first place (Haraway 1991 and Star 1991 in Müller, 2015, p. 30). My concern with ANT is different though, namely that it may incline some scholars to shy away from using concepts and theory in their ANT informed accounts. While ANT contains the word 'theory', it should only be understood so in the negative sense, Latour (1999a, p. 20) stresses, providing sociologists with a vocabulary to avoid mixing up the rich vocabulary of the actors with the poor vocabulary of the social scientists. While I agree with Latour on the view that ANT is mostly a 'crude method to learn from the actors' (ibid.), I deviate from his view that we should just go on and describe the actors and their sociology. The problem is that by following Latour's ideal of empirical descriptivism we may go on producing endless descriptions without ever arriving at satisfying explanations (Müller 2015, p. 30). That is, while ANT in my view offers a strong pre-analytical vantage point for conducting research, I find its associated vocabulary ('translation', 'obligatory passage point,' 'blackbox' or 'network') insufficient in and of itself. My point is that I find it helpful to deploy concepts and theory from related fields of research in ANT descriptions to enable a higher form of reflection and understanding of the issues that are being raised by the actors.

My view on this point is close to that of Krarup & Blok (2011). While being largely sympathetic to Latour, they take issue with the problematic reliance on common sense interpretation which is embedded in the precept to 'just go on describing' (Latour, 2007). Instead, they call attention to empirical obscurities encountered by the ANT researcher when describing social phenomena such as group identities, moral codes or desires. The important point is that empirical obscurities erase their traces while simultaneously acting on the social (Krarup and Blok 2011, p. 57). Another way of putting this is to say that empirical obscurities cannot always be understood in a satisfying manner through the lens of the ANT vocabulary. They dub empirical obscurities 'quasi-actants' showing, on the one hand, how Latour's empiricism fails to deal adequately with it, and, on the other, how it might nonetheless be refolded into ANT. The implication of this view entails a rethinking of the 'description-explanation-interpretation' challenge as they call it, 'in particular creating space for more 'positive' contributions from particular forms of theory in the empiricist sociology envisaged by Latour.' (ibid.). In agreement with Latour, Krarup and Blok (ibid.) emphasize that the challenge of doing so is that if left unchecked social theory can easily transform into a deeply problematic way of silencing the voices of actors. Taking this concern seriously, they nevertheless propose that certain forms of theoretical interpretations are called for, when researchers are being confronted with empirical obscurities.

Taking the analytical frame developed by Latour as a baseline, they propose that when invoking theory, the 'ideal should be to explicate the grid of uncertain possibilities – not to act as a synthetic surrogate for silencing the multiplicity of empirical voices.' (ibid., p. 58). One way to think about the exercise of re-folding theory into ANT is to think in terms of virtual theory, they elaborate, as it constitutes an opening for dealing with empirical obscurities encountered by the researcher. Following this line of thinking the main question is to ask what further conceptual work is necessary to understand a specific quasi-actant? (ibid.). In other words, by refolding concepts and theory into ANT the sociologist of associations is led away from Latour's radical empiricism and reoriented towards a 'new interpretive descriptivism,' they declare. The implication of this is that the researcher can choose either to interpret the actors 'independently' and go on describing or choose to employ 'virtual theory' to make sense of the field. Invoking theory furthermore cannot tell the researcher what he or she is looking for; instead, it can structure the evaluation of uncertainties and possibilities (ibid., p. 59-60), they argue. In criticizing Latour from an immanent position, their point is not to slide back into classical sociology of the social, but to propose a constructive way of refolding theory into the sociological empiricism of Latour (ibid.).

In a similar fashion Winthereik (2023) argues that ANT has something on offer to those who would like to cross-over between the empirical and the analytical. Her argument is that it is instructive to think about concepts as companions or devices which can help us make sense of the puzzlements that are generated through encounters with the field (ibid., p. 29-30). Concepts it follows can establish relations with the unfamiliar and thereby help make the strange familiar. It is about following ‘the actors whose concerns you share,’ Winthereik (ibid.) argues, while recognising technological agency and the possibility of fruitful exchanges with concepts that can help the ethnographer make sense of the subject being researched. This can allow for the concepts already present in the field to engage in conversation with concepts brought by the ANT researcher which might lead to a different becoming (de la Cadena 2015 in Winthereik 2023, p. 30). As researchers bring concepts and theories to the field, concepts have the capacity to be helpful and enable the researcher to better understand unfamiliar objects or unexpected unknowns. The challenge is as noted not to impose concepts upon the actors and thereby silence their voices.

In summary, I draw upon the ANT tradition predominantly as a method and pre-analytical approach. While the COVID-19 pandemic hampered my research efforts significantly and prevented me from following the actors in critical proximity (Latour, 2007, p. 253), I instead trace air pollution indicators and their associated uncertainty through scientific documents and online interviews from my home and research base. In agreement with Winthereik (2023) and Krarup and Blok (2011), I deviate from Latour’s (2007) radical empiricism in the sense that I invoke theoretical concepts from related research traditions to enable higher forms of reflection with the unfamiliar objects I encountered in the empirical material.

3. Theoretical orientation and related work

At this point it is instructive to reiterate John Law's point that the social sciences have yet to develop their own ensemble of methods for 'understanding – and helping to enact – twenty-first-century realities' (Law & Urry, 2004, p. 403) like air pollution. On a related note, Bryan Turner (2009, p. 5-6) argues that social theory is in a state of crisis in part because it is unable to offer much insight into major modern problems like environmental pollution. Against this backdrop, my point is not that social scientists are unable to study environmental pollution, but rather to suggest that there is no straight forward or agreed upon approach for doing it. While I find the ANT vocabulary the most suitable pre-analytical tool kit for researching air pollution, I simultaneously find it necessary to draw upon related intellectual traditions to enhance my understanding of this complex subject. Taking ANT and the concerns of my interlocutors as the vantage point for my inquiry, my aim in what follows is to contextualise the thesis and bring it into conversation with researchers in related fields, notably STS and economic sociology. As I engage their work, I focus on the analytical concepts that can help me unpack and enliven concepts I encountered in my own empirical material (Ballestero & Winthereik, 2021, p. 4). While each of the four papers have their own analytical framework, this section dives deeper into select foundational discussions about the relationship between science conducted for policy purposes, on the one hand, and uncertainty in environmental science and economics, on the other. The structure on this section thus largely follows the arrangement of the papers in the sense that I begin with the discussions and concepts underpinning papers 1 and 2 before moving on to outline those of papers 3 and 4.

3.1 Sensemaking and filters

A PhD dissertation titled '*Making Sense* of Air Pollution Modelling: Framed Uncertainty' should not go without at least a brief look at what it means to make sense of something. 'Making sense' of air pollution to me first and foremost involves a focus on framing operations concerning the issue of uncertainty. Yet before I elaborate on this point, it is worth noting how the concept of 'sensemaking' fits into an ANT-informed research approach.

Developed to understand interaction and meaning creation among actors in organisations, the concept of 'sensemaking' involves a process of placing items into frameworks, constructing meaning, comprehending and patterning in the pursuit of some kind of mutual understanding according to Weick (1995, p. 6). He suggests that the value of this broad concept is that it emphasizes the invention which precedes interpretation (ibid., p. 14). While interpretation refers to an activity that is more passive and detached the activity of sensemaking implies a greater level of engagement by those actors involved in the process (ibid., p. 14). A key property of the process of sensemaking is therefore that it involves enactment (ibid., p. 17). Weick's understanding of 'enactment' is similar to John Law's (2009) idea about methods performativity in the sense that he stresses that managers and legislators in organisations often construct reality via authoritative acts (Weick 1995, p. 30-31). In other words, sensemaking according to Weick involves a process of enacting reality by placing items into a particular framework.

Another key point about sensemaking it that it takes a relative approach to truth (ibid.). That is, the criterion of accuracy is secondary to sensemaking. Sensemaking is rather about plausibility and coherence. Instead of focusing on accuracy, misperceptions or human errors, it is more productive to examine which filters people invoke, what kinds of elements the filters respectively include and exclude as well as why the actors invoke the filters in the first place, Weick highlights (ibid., p. 57). These latter points resonate with Callon (2021) and Jasanoff's (2018) research proposals that it is useful to study a) frames and overflows in processes of economisation (former) b) why some scientific objects are framed when others are not in predictive technologies (latter), discussions I return to below. In other words, the concept of 'sensemaking' as proposed by Weick (1995) fits into my STS-informed approach because it captures the processes and practices whereby networks of humans and nonhumans enact and frame realities of air pollution through authoritative scientific performances.

Taking these insights to the realm of urban air pollution in Copenhagen, Dalsgaard, Bille and I show (in paper 1) how socio technical networks of scientists and citizens make sense of air pollutants in different ways. As ambient air pollution in Copenhagen is mostly beyond the reach of the human senses, we propose that making sense of urban air involves a process of 'data witnessing' (Gray, 2019). Data witnessing refers to a process involving measurement instruments which operate as extensions to the human senses in the production of environmental data. In this field of research, we argue, that the ability to make sense of environmental change demands both data and collective efforts of interpretation and purpose. Sensemaking to us is not only about invention or enactment, as Weick (1995, p. 14) highlights. In the context of air pollution, it requires a combination of enactment and interpretation. Throughout the article we distinguish between three different types of data witnessing to understand what the combination of data and witnessing 'do' as social networks involving scientists, corporations and citizens try to make sense of air pollution (Dalsgaard, Haarløv, & Bille, 2021). In other words, making sense of urban air pollution to us involves a combination of enactment, collective interpretation and political purposes.

On a related note, the COVID-19 pandemic prevented me from witnessing these processes of sensemaking in close proximity to the actors. My ability to make sense of air pollution is in turn similar to Gray's (2019, p. 986) characterisation of how Amnesty constructs moral engagement from a far through the involvement of a multiplicity of *distant* actors. That is, instead of witnessing air pollution through personal experience - by being there with the actors – my ability to witness this phenomenon was limited to various digital data sources, including social media, research papers and online interviews. Moving from sensemaking to uncertainty, I proceed to outline how STS scholars have grappled with this issue.

3.2 Uncertainty in STS on air pollution

STS scholars working with air pollution have explored how citizens become involved in monitoring practices through the deployment of do-it-yourself devices in situations where official measurements are absent to evidence harm (Gabrys, 2017, 2018, 2022), how public knowledge about radiation hazards in Chernobyl is determined by power relations (Kuchinskaya, 2014), why measurement and modelling practices require a certain 'feeling for error' (Garnett, 2016) or how new modes of 'data sensing' enabled via design installations can produce novel forms of engagement with air pollution (Calvillo & Garnett, 2019). Scholars have studied how bodily attunement to smells allow them to enter evidentiary regimes of perception (Spackman, 2020), how air pollution is being mitigated via playground domes, masks and canned air in Beijing (Zee, 2015), how air quality indexes can be felt by the body (Liu, 2017), and how asthma sufferers navigate potentially risky atmospheres (Kenner, 2021). A common thread across this rising interest in air pollution by STS scholars concerns how this invisible substance, which is mostly beyond the reach of the human senses, becomes a matter of public concern through engagement with it at the edge of perception. Albeit the question of uncertainty lurks between the lines in much of STS work on air pollution, it is rarely tackled head-on. To better understand the origins of uncertainty in collective sense-making processes of air quality, this section delves into the work of Murphy (2006), Fortun et al. (2016) and Liboiron (2021) who examine regimes of perceptibility, critical data designs and the threshold theory of pollution.

For Michelle Murphy the question of uncertainty is multidimensional and predominantly related to chemical exposure. The vantage point for her is that the science on chemical exposure is simply unreliable, compared to contemporary scientific standards, due to the dearth of comprehensive studies on the potential adverse effects of vast numbers of chemicals being used in industries (Murphy, 2006, pp. 8–9). Disagreement among experts on the adverse effects of low-level exposure to chemicals adds to the level of uncertainty and makes it difficult to pinpoint any incidence of chemical exposure (ibid.), she elaborates. The complexity of the phenomenon itself, moreover, exacerbates the uncertainty. Considering the lack of knowledge and high uncertainty associated with sciences on chemical exposure, Murphy asserts that there is an increasing need to explore how ignorance and imperception have been generated in the history of knowledge practices (ibid.). Her commitment to feminist epistemology (Haraway 1997) often recognises the gendered dimensions of technoscientific practices.

Murphy's starting point for studying uncertainty and imperception in scientific knowledge practices is the 'historical ontology' approach which involves the question of how objects come into being (2006, pp. 7–8). Since we know, we are exposed to known chemicals, it is important to be become attuned to the likelihood that we are also exposed to unknown chemicals. By focusing on the historical ontology of things, researcher may understand how objects such as particles, diseases, immune systems and so on come into being due to historically specific modes of calculating, classifying, and measuring. Studies of historical ontology usually hold that whatever counts as true is simultaneously intrinsically tied to prevailing practices of truth telling (ibid.). By attending to the historical ontology of objects, researchers become aware of the possibility that objects which do not exist for us today could spawn in the future due to the deployment of new instruments and methods (ibid., p. 8). Adopting such a historical lens allows for a deeper contextual understanding of the dynamic development of science, technology and society over time.

Influenced by the historical ontology approach, Murphy introduces the concept 'regimes of perceptibility' to study the ability to register chemical exposure. This concept refers to the way in which an epistemological tradition or discipline perceives the world, and it is inherently tied to the delineation of what is *imperceptible* (ibid., p. 9-10). The history of how an object is rendered perceptible is thus intrinsically linked to the history of how other objects come to exist with partiality, uncertainty or not at all. Domains of (im-)perceptibility are, in other words, the inevitable outcome of the tangible ways in which 'scientists and lay people came to render chemical exposure measurable, quantifiable, assessable, and knowable in some ways and not others' (ibid., p.9). Produced by assemblages anchored in material culture, regimes of perceptibility populate the world with certain objects and not others while allowing specific actions to be performed on those objects (ibid., p. 24), Murphy contends. In other words, influenced by ANT her approach suggests a methodological openness towards examining the human and nonhuman elements that are involved in technoscientific knowledge production. While I do not focus on the gendered dimensions of scientific knowledge production, I am informed by her work when it comes to how objects come to exist with partiality and uncertainty due to specific regimes of (im-)perceptibility. Building upon her insights, Bille and I show how assumptions about key parameters related to residential wood stove emissions modelling emerge from domains of imperceptibility in Paper 3.

3.2.1 Uncertainty in pollution visualizations

Moving from the background of scientific knowledge production to the foreground of how chemical pollution can be rendered visible to the public, I proceed to focus on the challenges associated with creating pollution visualizations. In the past decades air quality indexes have become a popular means of conveying air quality information to the public. Air quality indexes, which are usually found on the websites of state agencies or affiliated research institutions, revolve around visualizing concentrations of air pollutants in a meaningful way to the public. Typically, visualisations either link pollutants to adverse health effects or specific government threshold levels. In what follows I take a closer look at Kim Fortun's work on the key design challenges to consider when air pollution data is transformed into interactive graphical visualizations. Fortun is known for her postcolonial perspective on environmental disasters (Fortun, 2004), multi-sited ethnographic and mixed methods approach (Fortun, 2011, 2012). While I neither do multi-sited fieldwork nor adopt a postcolonial perspective, the following section serves the purpose of outlining a foundational discussion underpinning Paper 1. To me her work is valuable because it aptly describes the challenges involved in rendering air pollution knowable to the public via pollution visualisations. Despite the fact that the impact of pollution visualizations is questionable (Shooter & Brimblecombe 2009, p. 319) and little studied, air quality indexes nevertheless operate as a crucial means by which the public can potentially make sense of urban air quality.

At the forefront of studying pollution visualizations, Kim Fortun describes how the aftermath of a chemical plant disaster in 1984 in Bhopal, India led to the recognition that people have a right to know about environmental problems (Fortun, 2004). These 'right-to-know' initiatives raised several difficult questions for governments concerning what kind of information should be provided to the public. What should designers of environmental information systems assume about their users? Should they communicate in simple and clear messages about the conditions of the environment, or rather provide complex open-ended datasets which users can tinker around with, explore and manipulate (ibid. p. 291), Fortun contemplates. To make sense of these novel information campaigns she introduces the concept 'informating of environmentalism' based on an analysis of 'Scorecard,' one of the first US based initiatives to offer environmental insights to the public. Informating of environmentalism refers to the double movement whereby data visualizations produce a flood of information that, on the one hand, threaten to overwhelm the user while, on the other, simultaneously offer an analytical lens through which users can potentially make at least some sense of environmental conditions (Fortun, 2004, p. 294). No longer in operation due to high maintenance costs, Scorecard was developed to provide a baseline of information on environmental problems to enable citizens to push back against polluting sources (ibid., p. 292). Although the information in Scorecard was presumably sufficient to provide users with a glimpse into pollution and health hazards, users were simultaneously consistently reminded of the presence of uncertainty and lack of information within the system (ibid.).

According to Fortun (ibid., p. 294) the goal of Scorecard was not to provide users with precise information. Rather, it was to mobilize subjects through engagement with *uncertain* information, which could then be connected to regulation and shared with other groups of citizens faced with similar environmental concerns. While much of the information in Scorecard was flagged as uncertain, users were encouraged to understand scientific efforts as contested and iterative; part of a process that rarely offers straightforward answers (ibid.), she notes. High levels of information literacy, however, were required and cultivated to make sense of the data and basic questions concerning what counted as accurate information had to be renegotiated on a continuous basis (ibid.). While the graphical user interface of Scorecard, created in 1994, resembles a dinosaur from our current IT vantage point, several of my interlocutors working with pollution visualization face the same challenges that Fortun raised then and the insight that citizens concerned with air pollution are mobilized by uncertainty is increasingly valid, as I demonstrate for the city of Copenhagen in Paper 2. In other words, the process of sensemaking of pollution via Scorecard, was to lean against Weick (1995, p. 61) not about focusing on accuracy, but rather to establish plausibility and not least energise users.

Building upon the Scorecard findings above - and influenced by John Dewey's work *The Public and its Problems* ([1927] 2012) concerning the insight that publics need to be provoked to recognize the negative effects of the state and the market - Fortun (Fortun et al., 2016) suggests that the work of contemporary data designers deserves greater attention, as they are the stewards translating complex pollution data into meaningful visualizations for the public. Rendering pollutants visible in a meaningful way is no easy task, however, as pollution data is remarkably heterogeneous. There are a vast number of heterogeneous substances collected via different devices by different organizations for different purposes which need to be connected to specific endpoints to be meaningful and actionable (ibid., p. 1-2). What is more, pollution data can sometimes be frustratingly scarce and at other times – just as frustratingly - overwhelming in its vastness of quantify (ibid.). These are a few of the challenges when it comes to how best to visualize pollutants and their associated uncertainties to the public.

Another dimension complicating the work of critical data designers involves the management of time. Whereas exposure to pollution may sometimes have immediate effects on citizens, it is more often the case that adverse effects associated with exposure to pollution emerge across weeks or months and more likely years and decades. Pollution, in other words, compounds in the tissue of the body until it eventually releases through metabolism, as Rachel Carson ([1962] 2002, p. 190) noted more than 60 years ago. Figuring out how to render the temporal dimension knowable is further complicated by the lag between time of measurement and when the data become available to researchers in laboratories. Figuring out how to characterize the temporal dimension of pollution data in relation to heterogeneous, multi-faceted adverse effects on citizens, environments and climate is a critical, yet highly complex challenge for data designers (Fortun et al., 2016, p. 2). In other words, data designers face incredible challenges when it comes to visualising the adverse effects of pollutants in a meaningful way to the public.

Since the adverse effects of pollutants on the biodiversity and climate crisis are less well understood than the effects of pollutants on human health, air pollution indexes often focus on the latter. Based on specific threshold limits outlined by governmental agencies, toxic chemicals are thus systematically allowed to enter water bodies, human bodies and environments (Liboiron et al., 2018, p. 335). The threshold theory of pollution is premised upon 'the logic of assimilative capacity in which a body - water, human, or otherwise - can handle a certain amount of contaminant before scientifically detectable harms can occur' (Liboiron, 2021, p. 19). The threshold theory, however - a hallmark of pollution regulation across the world since the 1930s (ibid.) - is increasingly being challenged by novel research which suggests that pollution causes significant harm to human health even at low levels (World Health Organization, 2021). By comparing measurements of pollutants to lax threshold levels such as those set by the EU air quality directive, public air quality indexes suggest that there is a specific point at which pollutants are no longer harmful. But the idea that there should be a point at which pollutants no longer cause harm appears increasingly scientifically outdated (Wei et al., 2022; Anderson, 2009; Kumar et al., 2014; Landrigan et al., 2018; World Health Organization, 2021), a point I explore further in Paper 2 with a focus on citizen groups and emerging pollutant indicators.

To summarize, this brief excavation of uncertainty in STS research on air pollution highlights that uncertainty is located at the limits of scientific instruments between regimes of perceptibility and domains of imperceptibility. It follows that the work of critical data designers is crucial, as such efforts facilitate at least a partial understanding of pollution for the public. Sensemaking is here less tied less to accuracy and more tied to creating credible accounts that can potentially energize the public. Drawing upon Gigerenzer, and Smith & Kida in Weick' (1995, p. 57) the work of data designers invites scholars to examine how critical data designers make sense of air pollution by inquiring into the filters they invoke, why they deploy them and what the filters include and exclude. However, such inquiries require high levels of scientific literacy and are complicated by the heterogeneous nature of pollution data and the significant uncertainties in terms of exposure and impact.

3.3 STS on uncertainty in science: overcoming the physics view

Having explored how the subject of uncertainty has been lurking between the lines within the subfield of STS on air pollution, this section proceeds by focusing on how it has been treated within STS on the science policy intersection.

Uncertainty has been a core subject in much of STS for many years (as evidenced by the work of Callon et al., 2009; Funtowicz & Ravetz, 1990; Star, 1985; Wynne, 1992). While sociologists have created panoramic big picture theories about risk and uncertainty in Western societies (Beck, 1992), to my mind, when it to comes to describing contemporary situations characterized by uncertainty, the analytical concepts developed by STS scholars are more useful (Jasanoff, 2022; Scoones & Stirling, 2020; van der Sluijs, 2016). Scholars have developed numerous helpful methods and models for how to cope with uncertainties at the science policy level (Callon et al., 2009; Funtowicz & Ravetz, 2003; Kjeldsen et al. 2022; Saltelli & Giampietro, 2016; Strand, 2017; van der Sluijs, 2017). A common theme across these studies concerns the problem that scientists often oversell scientific certainty to policymakers at the expense of exploring the unknown, indeterminate, and uncertain. Rather than deemphasizing uncertainties, these scholars suggest there is much to be gained for society if scientists engage uncertainties and explicate much more thoroughly what they do not know. In what follows I dig a little deeper into the pioneering work of Funtowicz & Ravetz (1990) and Sarewitz (2000) concerning the role of and expectations toward science in society to set the stage before shedding light upon two strategies for accommodating uncertainties at the science-policy intersection proposed by Jasanoff (2007) and Pielke (2007), I find particularly valuable.

More than thirty years ago Funtowicz and Ravetz (1990) aptly described how the expectations that policymakers and publics have of science pose challenges for researchers working with novel environmental issues. The authors argue that while a long tradition in public policy assumes that solutions to public issues must be determined by quantitative 'hard' facts in numerical form, researchers are increasingly seeing new urgent environmental threats such as chemical waste, ozone depletion and global warming as 'soft' issues in the sense that they are associated with high uncertainty (ibid., p. 7). Despite this, policymakers still expect straightforward answers and precise numbers to establish certainty. However, unlike traditional scientific problems that are researched in laboratories, these novel environmental threats are global in scale and long-term in impact; and because they are variable and highly complex, basic quantitative data on their effects are insufficient, meaning they are poorly understood, they (ibid.) assert. The best the sciences can do under these uncertain circumstances is to develop mathematical models and simulations, but these are untestable (ibid.). Due to these limitations, science provides 'soft' information which is in turn deployed as input to 'hard' policy decisions concerning novel environmental threats (ibid.). To me Funtowicz and Ravetz' descriptions resonate with how the researchers, I interviewed, who work at the science policy level, describe their current relationship to public officials. That is, according to the researchers who deliver science policy reports, public officials expect that scientists can deliver decisive and accurate answers about issues in air pollution science that are profoundly uncertain.

The challenge for scientists working at the science-policy level becomes one of quality assurance and how to cope with uncertainty, Funtowicz and Ravetz elaborate. A first step in addressing this challenge involves correcting the popular image of science so that policymakers can move beyond their dependence on magical numbers. In their view our culture has come to believe that real truth can be found in numbers and that quantitative facts are not only necessary but also sufficient as political input (ibid., p. 10). To illustrate this point, the authors invoke the physicist Lord Kelvin's statement: 'When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind' (ibid.). Sarewitz (2000, p. 92) calls this dominant view in modern culture *the physics view*. It derives from the transformative impact of science and science-based technologies on society throughout history whose method of research is aligned with the achievements and successes of physics (ibid.). When applied to policymaking, the physics view presumably 'promises to relieve humans from responsibility by generating predictions that can dictate action' (ibid., p. 92).

Sarewitz, Funtowicz and Ravetz all agree that the physics view of science in society needs to be overcome and that institutional change is necessary concerning how science is being utilised in decision-making processes. I agree with this view and return to this discussion in Paper 4. The epistemological implication of drawing upon Funtowicz and Ravetz may involve adopting a post-normal view on science (Funtowicz & Ravetz, 2003) which challenges traditional scientific objectivity because it acknowledges value judgments and multiple perspectives in decision-making processes. The methodological implication would be to encourage extended peer communities, participatory processes and the involvement of non-experts in decision-making processes. However, involving a large number of stakeholders including non-experts in political processes may not be practically feasible in a political context constrained by time. In other words, I am somewhat sceptical about the involvement of non-experts in political deliberation processes concerning air pollution, as engagement with the issue requires relatively high scientific literary in the first place. To me the value of their work is rather contextual. It resides in their apt descriptions of how science operates in society as it clearly resonates with how my interlocutors describe the public policy environment they are operating in. This leads me to the next subsection which proceeds by focusing on Sheila Jasanoff and Roger Pielke's influential work on science in policy. Their epistemological and methodological ideas on how science can accommodate uncertainties at the policy level are closer to my own view when the topic is air pollution.

3.4 Framing and humility at the science policy level

Jasanoff agrees with the characterization of the role of and expectations towards science in society outlined above. She argues that science has been successful in guarding its public image while excluding competing disciplines such as various appearances of 'pseudo-science' and religion (Jasanoff, 1987, p. 196). Much of the authority in science throughout the twentieth century derives from its successful ability to convince policymakers and the public that, unlike politics, science is indeed 'disinterested,' 'skeptical,' and 'objective,' following the Mertonian norms for science (ibid.), she elaborates. Following this line of thinking science is believed to be the only social institution capable of delivering a true picture of the world (ibid.). Over time the sciences have evolved into 'technologies of hubris' which have assured policymakers and publics that futures are indeed manageable, calculable and measurable (Jasanoff, 2018, p. 13), she asserts.

At this point, it is useful to take a step back and elaborate on Jasanoff's (2006) work on the co-production of science and technology in society where she synthesises two decades of work in STS. The starting point for her is that science is not a transcendent mirror of reality; It is rather embedded in institutions, instruments, discourses, norms, identities and social practices (ibid., p. 2-3). She develops the theme of co-production which refers to the proposition that science and technology are both products of the social world and contribute to the making of this world (ibid.). 'States, we may say, are made of knowledge, just as knowledge is constituted by states,' as she puts it (ibid., p. 3). Drawing upon Latour, Jasanoff insists that power tends to concentrate in centres of calculation (Latour, 1990) and by the same token she argues that science and technology operate as political agents in society (Jasanoff, 2006, p. 14). It follows that it does not make sense to think about science and technology as being independent of social institutions and political processes (ibid., p. 15), which implies that co-productionist accounts are starkly opposed to linear stories about scientific, technological and social progress (ibid., p. 277).

The implication of a co-productionist approach is that it offers the possibility of critique. This is most apparent when researchers are faced with an emerging order (ibid., p. 278-279). It is at the point before things are being stabilized in black boxes that one most easily can observe how phenomena are shaped by social orders. At this moment of instability several normative choices get to be made in terms of scientific conflict resolution, the classification and standardisation of scientific objects (ibid.). In other words, during phases of emergence the value of co-productionist accounts is that they can become influential in setting the stage for future development (ibid.). The normativity is here tied to the possibility for scientific alternatives and how scientific objects get (re-)framed at the science policy level. I draw upon these key insights in Paper 3 and 4.

To me the value of the co-production idiom resides in how it encourages descriptive richness and the importance of context. I am likewise inspired by this approach when it comes to the ability to reframe phenomena of the world in new ways, as it invites researchers to reflect upon ethical dimensions related to knowledge production. Having said that I do not engage in a co-productionist analysis focusing e.g. on how institutions think or classify (Douglas, 1986). Nor do I study how institutional discourses tacitly merge technical and normative dimensions of knowledge production (Jasanoff 2005, p. 41). While I largely subscribe to her co-productionist account of science, my understanding of the science policy level is limited predominantly to the researchers' point of view, including their views of public officials' preferences when it comes to communication of science and uncertainty. In other words, I do not have extensive empirical material about how science is being shaped by publics and policymakers.

Jasanoff's co-production idiom shares common ground with ANT in terms of emphasising the interconnectedness of science and society. But there are notable differences. The co-production lens highlights the contextual, discursive and institutional dimensions of knowledge construction, whereas ANT considers human and non-human as having potentially equal agency in the shaping of networks. As I focus on the networks of particles, instruments, researchers and air pollution models, my approach is closer to ANT than Jasanoff. Having said that, I nevertheless draw extensively upon her work to provide answerability into the issues raised by my interlocutors concerning how to communicate and value uncertainty in science conducted for policy.

Before introducing her analytical ingenuity concerning how to acknowledge uncertainty, it is worth noting how she considers the precautionary principle which has been the prevailing doctrine for dealing with uncertainty in science in public policy. Developed in Germany in the early 1970s, the precautionary principle instructs policymakers and public officials to act in the absence of scientific certainty to prevent serious harm to citizens and the environment (Jasanoff, 2022). Although it has been widely adopted in international agreements on the environment and was developed to justify prudent consideration of unknowns and uncertainties, it remains controversial, and critics are dismissive of it on the grounds of inertia and passivity (ibid.), she elaborates. Jasanoff argues that while this principle was presumably developed to serve the common good, it has been hard to operationalize it in productive ways. As a result, there is still a fundamental bias towards calculation and prediction in policymaking (ibid.). To compensate for the partiality of science and to overcome the ill-conceived image of how science works in the face of irreducible uncertainty, she recommends an alternative approach to the precautionary principle that is focused on framing and humility.

Inspired by actor-network theory Jasanoff (2005) exemplifies the contingency of a particular policy frame by describing how *random* road accidents on American streets where at a particular time in history reframed as *drunk driving,* oftentimes involving teenagers. As the public policy frame on road accidents shifted away from randomness to drunk driving it led to an entirely new public safety regime, including a new focus on the socio-technical aspects of driving like rules, objects and practices all enmeshed in transportation networks. The point being that under circumstances of high uncertainty (road accidents), it is worth questioning whether a public policy frame ought to be reframed. This is because if a problem is framed inadequately or on the wrong terms, then the policy solution is bound to suffer from the same deficiencies (Jasanoff 2018, p. 13). In other words, it is critical to reflect upon whether the right questions are being asked, from whose viewpoint an issue is being observed and not least whether a focus on a few sparse knowns is causing us to miss a forest of unknowns under circumstances of high uncertainty (Jasanoff 2022).

In addition to highlighting the critical role of frame analysis as an important, yet neglected, tool of policymaking, which I explore in more detail in Paper 3 and 4, Jasanoff (2012, p. 182) advocates that the contemporary 'can do' orientation of science and technology needs to be complemented with 'should do' questions concerning ethics and politics. Invoking the urgent case of global energy futures, she argues that we need to adopt a humbler approach to policymaking which reintegrates the older approaches of science and technology with 'technologies of humility' to acknowledge the normative that is lurking within calculations, to make obvious the possibility of unanticipated consequences and to recognize the need for alternative points of view (Jasanoff, 2018, p. 13). In other words, by considering uncertainties at the science policy level, we can connect the 'is' with the 'ought' and thereby reach a more enlightened view of what is known and thus a humbler approach to which solutions are possible given the gaps in contemporary science (ibid., p. 14), she contends. Inspired by Jasanoff (2012), I demonstrate in Paper 4 why air pollution economics suffers from a peripheral blindless to the uncertainties that fall outside its scope of vision. Her insights about the lack of acknowledgement of uncertainty in science conducted for policy are key to understanding why ‘many things are undervalued,’ in valuation practices of air pollutants, as one of my interlocutors stressed in an interviewed.

3.5 The linear model of science and honest brokers of policy alternatives

Influenced by Sarewitz’s (2000) idea about uncertainty being the outcome of an excess of objectivity and Jasanoff’s (1990, p. 249) point about the inseparability of science and policy, Roger Pielke (2007) develops the perhaps most useful analytical framework for understanding how scientists engage the field of public policy. To better understand why scientists often deliver unambiguous numbers to policymakers despite being aware of their associated high uncertainties, this sub-section delves more extensively into Pielke’s work. In the ‘The Honest Policy Broker: Making Sense of Science in Policy and Politics’ (2007) he invokes Lord May’s characterization of what role scientists should preferably play in society to set the stage of his main argument:

> The role of the scientist is not to determine which risks are worth taking, or deciding what choices we should take, but the scientist must be involved in indicating what the possible choices, constraints and possibilities are . . . The role of the scientist is not to decide between the possibilities but to determine what the possibilities are. (Lord May in Pielke 2007)

However, scientists rarely engage in policy as Lord May proposes they should. To characterize the differentiated roles they can play in public policy, Pielke (2007, p. 7) introduces four idealized types: the *Pure Scientist*, the *Issue Advocate*, the *Science Arbiter* and the *Honest Broker of Policy Alternatives*. He suggests that contemporary society has a noticeable shortage of the Honest Broker type, because many scientists engage the science policy level as issue advocates or pure scientists (ibid.). To better understand Pielke’s model of how scientists presumably operate at the policy level, it is useful to take a step back and outline his sources of inspiration. In what follows I therefore introduce two alternative perceptions of democracy - the Madison and the Schattschneider view, as well as two views of science: the linear model and the stakeholder model. Together, they operate as the foundation of his framework.

TABLE 2.1: *Four idealized roles for scientists in decision-making*

		View of science	
		Linear model	Stakeholder model
View of democracy	Madison	Pure Scientist	Issue Advocate
	Schattschneider	Science Arbiter	Honest Broker of Policy Alternative

(Pielke, 2007, p. 14)

Under the Madisonian view on democracy, proposed by James Madison in 1787, experts in society are expected to align themselves with their favoured interest group and offer their expertise as a resource that can be used in political battles (Pielke, 2007, pp. 11–12). From this perspective it is a virtue for the scientist to play an active and deliberate role in policymaking by using their authority and insight as an asset in political struggles (ibid.). Pielke contrasts this perspective with that of political scientist E.E. Schattschneider, who emphasizes the importance of public participation whereby a public is allowed to voice its view on alternative scientific perspectives that are being presented to it as part of the political process (ibid.). In Schattschneider's view of democracy, policy alternatives come from experts whose role it is to clarify the implications of their knowledge to decisionmakers, who may subsequently choose among alternative courses of action (ibid.). These different viewpoints on the idealized roles of scientists in democracy are complemented with two alternative views on the role of science in society in Pielke's model, see table 2.1 above.

In the aftermath of the Second World War, the United States adopted a view on science that scholars have labelled the 'linear model,' Pielke (ibid., pp. 12-13) proceeds. This model is likely familiar to many in the form of the conviction that knowledge flows 'from basic research to applied research to development and ultimately societal benefits' (ibid.). A fundamental assumption embedded in the linear model of science is that science provides a reservoir of knowledge which can be tapped and deployed for specific societal purposes when needed (ibid., p. 80). The model suggests that 'societal benefits are to be found "downstream" from the reservoir of knowledge' (ibid.). As most scientists are presumably trained in this line of reasoning, some approach public policy as pure scientists or science arbiters (ibid., p. 94). This linear view on science contrasts with Jasanoff's (2005) co-productionist account of science and technology in society as outlined above.

The second characteristic of the linear model concerns how science presumably operates in the context of decision-making. In policymaking the linear model is often evoked to suggest that it is a prerequisite for political deliberation and subsequent action that scientists reach agreement on a specific research topic (ibid.). Pielke illustrates this point by invoking how the US Environmental Protection Agency describes the role of science in the agency: 'Through research that is designed to reduce uncertainties, our understanding increases and, as a result, we change our assumptions about the impacts of environmental problems and how they should be addressed' (EPA 2006 in Pielke, 2007, pp. 12-13). The implication of this line of reasoning is that actors often use the linear model to suggest that specific facts necessitate certain policy responses (ibid.). In addition to being a rationale for explaining the consequence of science on politics, the linear model is simultaneously a strongly held general perception of how science should be connected to the broader social context (Bocking, 2004; Sarewitz, 1996; Stokes, 1997 in Pielke, 2007, p. 78). These insights resonate with how some of my interlocutors working with air pollution economics perceive scientific consensus as a prerequisite for engaging the policy level, a topic I return to in Paper 4.

After having criticized the linear model of science for being inaccurate and normatively undesirable, several scholars have developed their own alternatives (Jasanoff 1990; Nowotny et al. 2001; Sarewitz 1996; Wynne et al. 2005 in Pielke 2007, pp. 13-14). Each of these perspectives propose some kind of 'stakeholder model' that works as an alternative to the linear model concerning the relationship between decision-makers and science (ibid.). A common trait among these stakeholder models is that users of science should preferably be able to influence the production of science and that considerations concerning how science is being deployed in decision-making are a critical part of understanding the effectiveness of science in policymaking (ibid.). These alternative views on science and democracy in turn work as the foundation for Pielke's four idealized roles of how scientists operate in policymaking.

Despite its critics and more than 20 years of STS research results indicating its inadequacy, Pielke suggests that many scientists continue to subscribe to the linear model, oblivious to the critiques (ibid., p. 131). It follows that many scientists therefore approach the science policy level as pure scientist or science arbiters in the sense that they seek to stay removed from explicit considerations of politics (ibid., p. 94). Reinforced by the linear model, other scientists engage the science policy intersection as issue advocates because they subscribe to the view that winning a scientific debate leads to a privileged position in political struggles, as resolving a scientific debate resolves a political debate (ibid., pp. 124-125). Winning a scientific debate can thus be a convenient means for removing specific policy options from a political debate without deliberately acknowledging alternative scientific perspectives that would imply other kinds of politics (ibid.), he suggests. In other words, the linear model of science can be more effective at bringing politics into science than science into policy (Jasanoff 1987; Wynne 1991 in Pielke 2007, p. 124), Pielke asserts.

Invoking Bjørn Lomborg's (2001) controversial work 'The Skeptical Environmentalist: Measuring the Real State of the World,' Pielke highlights how the linear model can create pathologies in decision-making. To scientists who subscribe to the linear model Lomborg presumably could not be more provocative since, as the title indicates, his premise is that other scientific perspectives are less real. While Lomborg appears to subscribe to the linear model himself, his work may seem less provocative to STS scholars who reject the linear model of science and therefore perceive his work as a partial perspective on global warming, among numerous others who are seeking to advance their agenda through science (Funtowicz and Ravetz 1992; Herrick and Jamieson 2000; Wynne 1991 in Pielke 2007, pp. 129-130). In other words, whether a scientist subscribes to the linear model or not helps to explain why certain scholars react with fury to Lomborg's work and others with indifference (ibid.), Pielke asserts. Rather than subscribing to the linear model of science and the Madisonian view on democracy, Pielke proposes that a scientist can advantageously engage policy in a more beneficial way to society by acting as an Honest Broker of Policy Alternatives, which he defines in the following way:

> The Honest Broker of Policy Alternatives engages in decisionmaking by clarifying and, at times, seeking to expand the scope of choice available to decision-makers. Unlike the Science Arbiter, the Honest Broker of Policy Alternatives seeks explicitly to integrate scientific knowledge with stakeholder concerns in the form of alternative possible courses of action. Like the Science Arbiter, the Honest Broker of Policy Alternatives is likely to take the form of a formal, authoritative committee or assessment. […] Further, a diversity of perspectives can help to militate against issue advocacy (stealth or otherwise). The defining difference between the Issue Advocate and the Honest Broker of Policy Alternatives is that the latter seeks to place scientific understandings in the context of a smorgasbord of policy options. Such options may appeal to a wide range of interests. […] A simple way to think about the key difference between the Honest Broker of Policy Alternatives and the Issue Advocate is that the latter seeks to reduce the scope of available choice, while the former seeks to expand (or at least clarify) the scope of choice.
> (Pielke 2007, pp. 17-18)

Pielke (ibid., p. 139) argues that the realm of climate change – and, arguably air pollution policy - requires a greater role for Honest Brokers of Policy Alternatives, who can integrate scientific knowledge with stakeholder concerns and present a diverse set of scientific perspectives to policymakers. In line with most of STS work on the topic, Pielke defines uncertainty as a situation in which multiple scientific outcomes are consistent with our understandings (ibid., p. 59). Yet, because policymakers often transfer responsibility to scientists, it is crucial for science advisors to present alternative scientific perspectives which can facility policy innovation rather than focusing solely on scientific results, he asserts (ibid.,

p. 144). In line with much of the literature, Pielke argues that this becomes increasingly critical in situations with higher scientific and political uncertainty (ibid., p. 18).

Drawing upon Pielke may encourage STS researchers to analyse how scientists interact with public officials and how the involvement of scientists in political processes impact the outcome of policy decisions. The practical consequences of drawing upon his work for scientists is to improve science communication and enhance their engagement with policy processes by integrating the concerns of publics with scientific endeavours. To me the value of Pielke's account is contextual in the sense that it offers the most compelling account of why air pollution scientists typically engage public policy with unambiguous numbers despite the associated uncertainties being very high. At this point, it is noteworthy to restate that I have not interviewed public officials at the receiving end of science conducted for policy. My knowledge of how policymakers and public officials shape science communication on uncertainty is thereof limited. Nevertheless, I find his solution to the problem that science speaks with many tongues very helpful. The present thesis may thus operate as a stepping stone for studying the extent to which science advisers also act as policymakers (Jasanoff, 1990) when the issue is air pollution.

3.6 Uncertainty in economics: the conflation of risk and uncertainty

Having explored how the issue of uncertainty is treated among influential STS scholars above, this section proceeds with a focus on how the subject is (mis-)treated in the field of economics, where neo-classical ideas often operate as a foundation for public policy solutions to environmental problems and global warming (Buller, 2022, p. 24). To better understand how uncertainty is modelled in the most influential discipline of the social sciences (Fourcade, Ollion, & Algan, 2015), I first unpack how it is being conflated with risk in contemporary neo-classical mainstream economics. Next, I shed light upon how economic sociologists study the boundary between certainty and uncertainty in valuation processes before moving on to discuss how uncertainties that fall outside the scope of valuation practices can be acknowledged via expectations and narratives.

Although contemporary economists have shown some interest in the subject of uncertainty in recent years (Bernanke, 2007; Nordhaus, 2015; Pindyck, 2022), it is becoming increasingly clear that mainstream economics sits on top of micromodels that either ignore the issue of uncertainty or conflate it with risk (Beckert & Bronk, 2018, p. 8). Alongside an increasing formalization of economics as a mathematical discipline since the 1970s and a declining interest in Keynesian ideas, the subject of uncertainty has come to play a less prominent role within the field (Hodgson, 2011). It is thus partly due to the critical role of the rational actor model, which operates as the fundamental premise of current economic reasoning, that situations of uncertainty have been conflated with situations of risk in Knight's sense (Beckert, 1996, p. 814). In light of this development of the discipline, Mirowski (1991) characterizes the dominant paradigm in economics as 'econo-physics,' and Hirschman (1991) teasingly suggests that mainstream economics suffers from physics-envy.

To understand how economists used to think about uncertainty before the mathematical turn, it is helpful to invoke Frank Knight's distinction between uncertainty and risk, developed more than 100 years ago. In his treatise 'Risk, Uncertainty and Profit' ([1921] 2018) Knight explores how entrepreneurs can make profit under circumstances that resemble uncertainty. He argues that entrepreneurs can increase their wealth significantly in a short time if they use superior judgment in situations of high uncertainty, where probability calculations are impossible or meaningless (ibid., p. 177). To distinguish between different magnitudes of uncertainty, he deploys the notion of 'risk' to describe situations where the distribution between an outcome can be known through calculation (ibid., pp. 135-136). In contrast he designates the notion 'uncertainty' to instances where the situations being dealt with are in a high degree unique and therefore incalculable (ibid.). Along those lines he proposes that we may also use the term 'subjective probability' to describe situations of uncertainty and 'objective probability' to describe situations characterized by risk (ibid.). While probability distributions can potentially inform action under circumstances which resemble risk, the exercise of *judgment* is the only means to guide conduct under circumstances resembling uncertainty following Knight (ibid.). In other words, the notion 'risk' is associated with *measurable uncertainty*, whereas 'uncertainty' is associated with *unmeasurable uncertainty*. In Paper 3, I deploy Knight's concepts to make sense of the unfamiliar type of uncertainty I encountered in the case of modelling residential wood stove emissions.

The conflation of risk and uncertainty is particularly prominent in the multi-disciplinary subfield of air pollution economics, which follows the lead of the dominant economics paradigm. In *How Much is Clean Air Worth: Calculating the Benefits of Pollution Control*, Rabl et al. (2014) treat the subject of uncertainty at some length. However, despite extensive discussion of the subject, they often conflate unmeasurable uncertainty with measurable uncertainty to follow Knight (2018). This conflation is evident when, for example, they introduce numerical *assumptions* about the relative toxicity of the different components of ambient particulate matter (PM) based on 'extensive discussion' with epidemiologist and toxicologist (ibid., p. 465) to estimate the adverse health costs of air pollution. That is, numerical assumptions about key ingredients like morbidity and mortality due to ambient particle pollution enter the valuation process (ibid.), even though these numerical values are based on subjective judgment. Due to lack of data, the air pollution economists cannot establish a measurable degree of uncertainty associated with these parameters (ibid.). This relates to the fact that while concentrations of ambient $PM_{2.5}$ particles are currently the most important indicator for calculating health costs, this indicator is simultaneously surrounded by a range of uncertainties and described as a relatively ill-defined chemical soup by some of my interlocutors, as already noted. In other words, although Rabl et al. do admit that their calculation efforts rely partially on assumptions and expert judgments, they typically turn unmeasurable uncertainties into probability distributions to calculate costs (ibid., p. 482), thereby essentially conflating uncertainty with risk in the Knightian sense.

Invoking the case of integrated assessment models for climate policy, economist Pindyck (2015, p. 6) suggests that modelers have so much freedom in choosing key parameter values that such models can be used to obtain nearly any kind of result that one desires and thereby legitimize what is essentially a subjective view on climate policy. He asserts that when uncertainty is treated with arbitrary probability distributions, such models are close to useless as tools for policy analysis (ibid., p. 1). To illustrate his point, he invokes the discount rate, which is crucial to calculating the social cost of carbon. Because there is no consensus regarding the discount rate among economists, different inputs concerning this key parameter will generate wildly different estimates. This helps explains why Nordhaus (2007) and Stern (2007) come to such striklingly diverging conclusions when it comes to calculating the abatement costs of climate change (Pindyck, 2015, pp. 1-2).

While I will not go as far as Pindyck and suggest that models developed to calculate air pollution costs are close to useless, his point is nonetheless strikingly apt considering how environmental economists specialized in air pollution deploy numerical assumptions about key ingredients in quantitative valuation practices.

Although Rabl and his colleagues devote an entire chapter to the subject of uncertainty and suggest that 'communicating the uncertainties of external costs is very important' (ibid., p. 489-490) they nevertheless proclaim that it is more difficult for public officials and policymakers to deal with a number and its associated uncertainty than just a number. They suggest that numerous futile approaches for introducing uncertainties to policymakers have been attempted throughout the years, including providing high and low estimates alongside central estimates and elaborating on specific assumptions. Such efforts, they assert, have been futile as users typically disregard uncertainties and instead extract a single number, which is usually the central estimate (ibid.). Because of the alleged difficulty for users to handle uncertainties, they do not consider it beneficial to explicate irreducible uncertainties to policymakers. Although concern is growing about how uncertainty which eludes quantification is treated within the discipline (Kay & King, 2020; Pindyck, 2022; Tanzi, 2022), mainstream neo-classical approaches still downplay unmeasurable uncertainty or conflate it with risk.

To me the work of Pindyck (2015), Beckert & Bronk (2018) and Hodgson, (2011) is valuable contextually speaking as they offer credible accounts of why uncertainty is treated the way it is in neo-classical economics. Analytically, Frank Knight's work on uncertainty may encourage social scientists to study decision-making processes, qualitative aspects of economic phenomena, or how entrepreneurs deal with situations characterised by profound uncertainty. To me his theory of uncertainty is valuable because it enables me to recognise the qualitative aspects of quantitative valuation efforts of pollutants and how assumptions about critical unknown parameters are turned into numerical values in the residential wood stove emissions model.

3.7 The boundary between certainty and uncertainty in valuation practices

To better understand how economists value the adverse effects of air pollution, this section introduces some of the analytical tools deployed by market sociologists to study valuation practices. These tools enable me to examine the critical boundary between which objects (pollutants and their associated effects) get to count and which objects (pollutants and their associated effects) do not get to count due to being associated with unmeasurable uncertainty in quantitative valuation practices of air pollutants.

Since the publication of *The Laws of the Market*, where Callon (1998a) introduces the idea that 'economics, in the broad sense of the term, performs, shapes and formats the economy, rather than observing how it functions' (p. 2), scholars have been drawn to the study of valuation in diverse contexts ranging from oil spills (Fourcade, 2011) to animal slurry (Doganova & Karnøe, 2015) and luxury perfumes (Trébuchet-Breitwiller, 2015) and developed theoretical contributions to this subfield of economic sociology by shifting the conversation towards processes of 'economization' (Çalışkan & Callon, 2009), 'financialization' (Chiapello, 2015) and, more recently, 'assetization' (Birch & Muniesa, 2020). A common thread across these studies concerns an interest in how things become valuable through specific evaluative networks and processes. Drawing upon the agenda setting work of Callon (1998a) and Muniesa (2011) this sections outlines the underlying theoretical premises for studying valuation in practice.

To set the stage it is useful to invoke the philosopher John Dewey's view on valuation, who laid the foundation for this specific scholarly interest in the publication *Theory of Valuation* (Dewey, [1939] 1965). Rather than perceiving value as something that is intrinsic to an object in itself, Dewey draws attention to the act of valuing, and the conscious expression of interest (ibid., p. 5). To value means to consider and the emphasis should be on the activity, practice and process of valuation, according to Muniesa's (2011, p. 25) interpretation of Dewey. Following this line of thinking, scholars may attend to how value is being assigned, how goods and services are appreciated, honoured, rated or held precious in valuation processes that may involve comparisons via the flattening measuring rod of money (Dewey, [1939] 1965, p. 5).

To study valuation practices, Callon introduces the concept of a frame and its associated overflows. Drawing upon Goffman's description of interpersonal relationships, Callon suggests that the concept of a frame can easily be applied to the interaction of economists (Callon, 1998b, p. 250). It refers to the social and physical boundary within which interactions between actors can occur. The social aspect of a frame depends upon an agreement and commitment by the actors themselves concerning the rules of the interaction and it operates as the foundational requirement for courses of action to take place (ibid., pp. 248-248). As in a game of chess, players need to agree upon certain rules before the interaction can occur, Callon (ibid., p. 250) elaborates. In addition to being dependent upon a commitment by the actors, the framing process is simultaneously rooted in organizational and physical devices. In other words, the process of framing refers to how actors put the world in brackets and the concept can easily be applied to interactions that interest economists such as contract negotiations or commercial transactions (ibid.).

However, framings are not only costly, but also incomplete, especially within the context of externalities, because overflows happen all the time, Callon argues (ibid., p. 255). Invoking the case of global warming (2009, p. 542), he suggests that the issue is unqualifiable, not in theory but in practice, as there are no frames that can embrace the phenomenon in its entirety. The issue tends to change constantly as it spreads, which is why it cannot be contained within a frame (ibid.). Overflows are thus fed by multiple sources as they flow down multiple channels because framing operations are never complete (Callon, 1998b, p. 255). In an increasingly 'hot' world characterized by scientific uncertainties, which overflow the calculative frames of economists, who constantly seek to improve calculative devices, Callon (ibid., p. 263) proposes that an Anthropology of Science and Technology could help by improving the visibility surrounding such framing operations. By identifying overflows and keeping track of the agreements and disagreements concerning framing operations like satellite imaging systems, researchers can improve the visibility surrounding these calculative efforts and thereby endow navigators with the ability to always keep track of their positions, Callon (ibid.) asserts. Drawing upon Callon in Paper 4, I track of the overflows and uncertainties that do not get to count in economic valuation practices of air pollutants.

The consequence of overflows is a constant re-creation of new political spaces led by emerging concerned groups, he suggests (Callon in Barry & Slater, 2002, p. 287). When people become affected by uncertainties that overflow established regulatory frames, such uncertainties become a growing matter of concern because existing institutions and expertise are unable to deal with them (Callon, 2007, p. 143). When affected groups of citizens feel negatively impacted by overflows, they tend to establish new metrological devices to explore the magnitude of overflows and subsequently demand collective action, he (ibid., p. 144) elaborates. The implication of overflows is that markets constantly produce new matters of concern which are associated with high uncertainties (ibid., p. 146). Influenced by Strathern (1999), Callon describes this meshing of techno-science with economics as the 'proliferation of the social' (Callon, 2007, p. 146), which constantly produces new uncertainties about the constitution of the collective (Callon in Barry & Slater, 2002, p. 287). While economists tend to play a very dominant role in debates on externalities and the constitution of the collective, it becomes the role of anthropologists and sociologists to contribute to an articulation of this political space, where overflows and their associated uncertainties proliferate (ibid.), Callon suggests.

In summary, the most notable epistemological consequence of drawing upon Callon is related to the idea that economics is performative. His view on economic theory is similar to John Law's view on methods. Akin to how methods enact reality, economic theories not only describe economies, they also contribute to the shaping of economies. Analytically, I draw upon Callon's neologism 'passivaction' from his recent work 'Markets in the Making – Rethinking Competition, Goods, and Innovation' (2021) to analyse why certain pollutants and their associated effects are deployed in framing operations, whereas others are not. His work is valuable analytically because it offers the most apt vocabulary for understanding the complexity of environmental economics and valuation practices of pollutants in particular.

3.8 Recognising uncertainty through expectations and narratives

If uncertainties overflow quantitative framing operations of externalities all the time, then how can social scientists account for them in science conducted for policy by qualitative means? This section digs deeper into the role of economists at the science-policy level and explores how unquantifiable overflows can be recognized via strategies that rely upon language, narratives and metaphors rather than numerical assertions.

In the publication *Radical Uncertainty: Decision-Making Beyond the Numbers* (Kay & King, 2020) two economists influenced by Merton and Knight provide a refreshing critique of the mainstream view of uncertainty in economics. They proclaim that while radical uncertainty is ubiquitous and most people have learned how to deal with it, most economists find it difficult to accept the centrality of this condition. To emphasize this point, they compare the predictability with which physicists and engineers can calculate the accurate position of a spaceship with the unpredictability of economics due to human intervention. Drawing upon Merton's ([1949] 2017) work on reflexivity they point out that while the type of problems NASA deals with can be completely specified and comprehensively understood, and are therefore presumably stationary, economic relationships are inherently nonstationary and unstable due to the unpredictability of humans, whose relationships and expectations change constantly over time (Kay & King, 2020, p. 38). Kay and King's comparison of the predictive capacity of NASA and the unpredictability of economics due to human involvement provides a convincing argument for the inherent non-predictability of economics due to human reflexivity.

Faced with a world that is radically uncertain in the Knightian sense, where our understanding of the present is incomplete and our understanding of the future even more limited, Kay and King suggest that the goal of social scientists conducting science for policy is to provide policymakers with a frame and *narrative* account of the problem (Kay & King, 2020, p. 345). The value of an economic model is not so much in accurate quantitative policy guidance as in the insights it can provide through narrative reasoning into the problem (ibid., pp. 224-225), they argue. The role of economists, in other words, resembles that of firefighters, dentists, or engineers, in the sense that they can contribute to problem-solving by helping policymakers think about their problems through the exercise of expert judgment in a pragmatic fashion that is both problem-specific and context-specific (ibid., p. 335).

Moving from uncertainty in policymaking to uncertainty in capitalism, economic sociologist Jens Beckert (2016, pp. 8–9) makes uncertainty and fictional expectations his starting point for understanding contemporary capitalist dynamics. Inspired by Keynes' work on expectations, Beckert invokes his point concerning the relationship between business decisions and expectations:

> The considerations upon which expectations of prospective yields are based are partly existing facts which we can assume to be known more or less for certain, and partly future events which can only be forecasted with more or less confidence (Keynes in Beckert 2016, p. 46)

Once the idea of rational and precise forecasting is abandoned and the contingency of the market is accepted, the question becomes what indicators actors can deploy in the context of assessing business options to follow Beckert (2016, p. 46). Paraphrasing Keynes, Beckert suggests that actors can draw upon three indicators. First, actors can make decisions based on conventional thinking where the existing state of affairs presumable continues indefinitely; second, actors can base their decisions on emotions. Keynes captures this in the concept of 'animal spirits,' which refers to how actors often grossly overestimate their chances of success in economic ventures. Third, actors can base their decisions in the stock market by relying on the expectations of other investors rather than the fundamental value of a given company (Keynes in Beckert 2016, p. 46). In other words, akin to Knight, Keynes departs sharply from neoclassical economics in the sense that he emphasises the importance of qualitative aspects of the economy such as emotions or expectations.

In addition to Keynes, Beckert is heavily influenced by Dewey's ([1922] 2016) work on the process of deliberation, which involves using imaginaries of future states of the world to instill confidence in the present. By imagining competing lines of action and the consequences of those choices, actors can appraise the significance of the future, which in turn can help them overcome present obstacles and orient their decisions (Dewey 1922 in Beckert, p. 55). Dewey calls decisions based on such deliberation processes with future states of the world 'reasonable,' adding that they do not represent a final end point so much as a way to act (ibid.). Imaginaries of emerging futures make it possible to reconsider contemporary action by reconstructing them creatively to enable innovative courses of action, Beckert argues (ibid). The implication of this proposition is that actor's expectations about future outcomes need to be considered if we are to understand the movement of the economy. Following this line of thinking, imaginaries, narratives, and expectations about the future state of the world matter just as much as past events if we are to understand contemporary action in the economy (ibid., p. 58). Imaginaries and expectations thus become interpretative frames under genuinely uncertain circumstances which can orient decision-making despite the incalculability of the situation (ibid., p. 9). These points are useful to me analytically speaking when it comes to acknowledging different gradations of uncertainty in air pollution cost assessments, which I return to in Paper 4.

Like Beckert, anthropologist Douglas Holmes (2013) draws upon Keynes influential work on expectations to characterize how central bankers engage incalculable uncertain future states of the world. Holmes introduces the concept 'economy of words' to describe those situations where central bankers inform the public about the outlook for the economy via carefully constructed linguistic statements (ibid., pp. 30-31). He stresses that *words* cast in a narrative form perform a crucial role in shaping the contexts that frame statistical measures or data series (Holmes, 2009, p. 383). Holmes proposes that, just as economists model the economy mathematically, it is equally important to understand how the economy is being modelled through language and hence performed communicatively (Holmes, 2013, p. 10). Influenced by the performativity thesis (Callon, 1998b; Mackenzie, 2008), Holmes contends that carefully constructed statements about incalculable uncertainties in the economy are not merely descriptive expressions about the economy, but rather important linguistic performances that contribute to the making of the economy itself (Holmes, 2013, pp. 12–13). His point is similar to Shiller's (2019) account of how narratives can go viral and consequently shape major economic events.

The point of this theoretical deliberation into Kay and King, Beckert and Holmes serves the purpose of widening the possibilities for how unquantifiable uncertainties can be recognised in valuation practices of air pollutants. In my view their accounts of how narratives and expectations operate in advanced economies offer valuable practical guidance on how overflows can be acknowledged through words and statements in valuation practices and thereby aid public policy. To me the analytical implication of drawing upon Beckert involves inquiring into to the temporal dimensions of valuation practices, notably how scientists expect future economic air pollution costs to unfold. Methodologically his work inspires me to conduct qualitative inquiries into the stories and narratives told by air pollution scientists which shape how they expect the future to unfold.

In summary, by combining Callon (2021) with Beckert (2016) I, demonstrate how relative certainty is produced in contemporary economisation processes of air pollutants, on the one hand. On the other hand, I show how unquantifiable uncertainties that elude quantitative economisation can be refolded into economic valuation practices through the deployment of expectations cast in a narrative form. The combination of Callon and Beckert, in other words, enable me to explore the delicate boundary between certainty and uncertainty in valuation practices. My dissertation thus extends discussions of valuation practices and expectations to the hitherto unexplored field of air pollution economics.

4. Concluding discussion

4.1 The conflation of unmeasurable uncertainty with measurable uncertainty

This dissertation contributes with new empirical and theoretical insights to STS discussions on uncertainty in air pollution modelling. Informed by STS and economic sociology, I demonstrate how the politics of air pollution is intimately tied to how key actors make sense of it and how unmeasurable uncertainty is conflated with measurable uncertainty in air pollution modelling.

As a prerequisite for answering the research question – How and why are unmeasurable uncertainties in air pollution modelling marginalised in science conducted for policy? - Dalsgaard, Bille and I first characterise the process of making sense of air pollution as pertaining to a form of data witnessing. That is, witnessing air pollution requires data, on the one hand, and collective interpretation and purposes, on the other. We distinguish between three types of data witnessing involving fixed monitoring stations, Google Street view cars, handheld devices and their associated model systems to contribute to an understanding more broadly of what the combination of data and witnessing do, when state, corporate and civic actors try to make sense of air pollution. Building upon these insights, the main argument of this thesis is that unmeasurable uncertainty is conflated with measurable uncertainty, what Knight (2018) defines as situations that cannot be known through calculation, in air pollution modelling. This conflation in turn leads to the marginalisation of unmeasurable uncertainty in science conducted for policy. I show how this process unfolds in three cases related to measuring and modelling UFPs, estimating residential wood stove emissions and calculating air pollution costs.

In the case of measuring UFPs the conflation of unmeasurable uncertainty with measurable uncertainty occurs when the involved researchers multiply single digit measurements in each street segment of Copenhagen with 100 to establish annual average values. That is, despite being unable to determine degrees of probability associated with few measurements in each street segment, researchers deliberately turn situations characterised by unmeasurable uncertainty into situations that can be known with a degree of measurable uncertainty.

Similarly, in the case of modelling residential wood stove emissions, the conflation is apparent when assumptions about critical parameters which are essentially unknown are converted into numerical values when researchers are faced with lacking data. Here the construction of numerical estimates is intimately tied to expert judgements about users' firing technique, the quality of wood being combusted and the amount of wood loaded into the stove compared to its capacity.

In the case of calculating air pollution costs, the conflation of unmeasurable uncertainty with measurable uncertainty is particularly evident when economists deploy numerical assumptions about key parameters such as the toxicity of the different chemical components of particles based on discussions with toxicologists and epidemiologists. Despite lack of data, economists introduce probabilistic numerical assumptions about key ingredients in the valuation process related to mortality, morbidity and the chemical composition of particles to calculate adverse health costs (Rabl et al., 2014, p. 465).

The conflation of unmeasurable uncertainty with measurable uncertainty in each of these cases in turn leads to the marginalisation of unmeasurable uncertainty in science conducted for policy. In the case of measuring UFPs in the streets of Copenhagen, the marginalisation implies a lack of acknowledgement of annual daytime average UFP concentrations being associated with unmeasurable uncertainty. In the case of modelling residential wood stove emissions, the marginalisation involves unmeasurable uncertainty taking a backseat in science conducted for policy. That is, it disappears in the numerous numerical assumptions about critical parameters and is not acknowledged as a fundamental premise for conducting such a calculative exercise. Finally, in the case of calculating economic costs the marginalisation of unmeasurable uncertainty implies an underdeveloped acknowledgement of unquantifiable impact dimensions in science conducted for policy. While the likely tip of an iceberg is acknowledged through quantification efforts, numerous impact dimensions which defy quantification remain unacknowledged.

Despite high uncertainties, I show that science policy reports on residential wood stove emissions and air pollution costs are presented with precision to policymakers in part because air pollution scientists are encouraged by communications officers to deliver firm and decisive answers to public officials. Even though the implicated researchers are fully aware of high uncertainties associated with key estimates, they deliver unambiguous numbers to public officials due to their distinct relationship with them. This relationship, cultivated over many years, is built on a long tradition of assuming that solutions to public issues need to be determined by quantitative facts (Funtowicz & Ravetz, 1990; Jasanoff, 2007; Pielke, 2007; Scoones & Stirling, 2020). This tradition advocates that truth can be conveyed in numbers, and that numbers alone are a sufficient means of policy input (Funtowicz & Ravetz, 1990, p. 10). It follows from this tradition that knowledge is inadequate and unsatisfactory when it cannot be expressed in the form of measurements or numbers (ibid.). While Funtowicz and Ravetz identified this relationship more than 30 years ago, it has lost none of its relevance for those of my interlocutors who deliver estimates of wood stove emissions and air pollution costs to public officials. Another way of phrasing this is that air pollution science conducted for policy purposes is indeed shaped and co-produced (Jasanoff 2006) by those who pay for it at the receiving end, the policymakers, who have their own agendas and preferences regarding how uncertainty is treated by the scientists.

Despite facing criticism from both STS and scientific communities, the linear model of science remains a prevalent view on science and its relationship with broader society (Pielke, 2007, p. 131). Given that many scientists are educated in the model (ibid., p. 94), many continue to believe in it and are seemingly oblivious to its critique (ibid., p. 131). That is, due to the pervasiveness of this view on science, which suggests that scientific agreement is a necessary precondition for political deliberation, some air pollution scientists and economists engage public policy in a manner which resembles that of a *pure scientist* (ibid., p. 15), someone who seeks to stay explicitly removed from policy and politics (ibid.). This stand is most evident in the cases concerning wood stove emissions estimates and calculations of adverse health costs, where the acknowledgement of critical unmeasurable uncertainties is marginalised and underdeveloped.

However, air pollution researchers do not necessarily share the same view on how to communicate uncertainty to public officials. While some researchers prefer to engage public policy as prescribed in the incumbent tradition, others are more open towards acknowledging different gradations of uncertainty more thoroughly. Yet those in favour of acknowledging uncertainties much more operate in an environment where numerical assertions are preferred aligning with the prevailing public policy tradition. In other words, *how* air pollution researchers acknowledge different gradations of uncertainty in science conducted for policy depends partially a) on their scientific training b) institutional preferences and c) their relationship with publics and policymakers. That is, the acknowledgement of uncertainty in science conducted for policy is co-produced by the scientists, on the one hand, and the expectations of publics and institutions towards science, on the other.

The incumbent public policy tradition may be considered helpful in a context with few uncertainties where the science is settled. However, it becomes problematic when applied to profoundly uncertain issues like estimating wood stove emissions and calculating adverse health costs. First, it prevents publics and policymakers from seeing which scientific topics need to be researched moving forward. That is, publics and policymakers are deprived from understanding that numerous critical unknown parameters associated with such estimates need to be researched more to improve the knowledge foundation of science. Second, in the case of estimating wood stove emissions there is unmeasurable uncertainty associated with the socio-technical assemblage surrounding wood stoves, hindering researchers from knowing this emissions source with any degree of probability. Third, concerning the estimation of adverse health costs, health experts suggest that air pollution economists can likely only quantify a small part of a much larger problem (Landrigan et al., 2018). In both cases, I argue that critical unquantifiable dimensions are likely more significant than those elements that can be known through calculation. In other words, the incumbent public policy tradition is more effective at bringing politics into science than science into policy (Jasanoff, 1987; Wynne, 1991) because it assumes that profoundly uncertain issues must be communicated with precision, although such accuracy does not resonate with the reality, which is far more nebulous, indeterminate and unknown.

In conclusion, the three case studies examining the measurement of UFPs, the calculation of wood stove emissions and economic costs reveal a consistent pattern. The cases show how unmeasurable uncertainty is conflated with measurable uncertainty in air pollution modelling, leading to the marginalisation of unmeasurable uncertainty in the realm of science conducted for policy. This marginalisation is to a considerable extend, influenced by the prevailing tradition in public policy, which operates on the assumption that addressing complex environmental challenges, such as air pollution, necessitates numerical representation, and that numerical values alone suffice as input for policymaking. In the following, I outline the implication of my findings for public policy.

4.2 Framed uncertainty

In contrast to how uncertainty is being treated in the incumbent public policy tradition, I propose a 'framed uncertainty' approach which entails a profound reorientation in how this issue is being dealt with at the science policy level. Inspired by Jasanoff (2007) and Beckert (Beckert, 2016) my proposition for communicating uncertainty revolves around making harm mitigation a goal and presenting uncertainties in a helpful manner that enable policymakers to act. Building upon the work of Jasanoff (2018) and Callon (2021), it entails both normative and descriptive dimensions. The descriptive dimension revolves around characterising the overflows and uncertainties that fall outside a particular policy frame following Callon (2021). The normative dimension is related to the findings of this dissertation, namely that unquantifiable uncertainties are profound in air pollution modelling. The implication is that such dimensions become consequential for public policy which means that they ought to be acknowledged in science conducted for policy following Jasanoff (2018). In the following I elaborate on this proposition for communicating uncertainty.

The starting point for this endeavour is to make sure the right questions are being asked, including from whose point of view an issue is being observed (Jasanoff, 2022). Does the incumbent public policy frame on a particular air pollution issue miss a forest of unknowns compared to a few sparse knowns? Does it capture just the tip of an iceberg? In other words, being attuned to how an issue is framed in public discussions comes first in situations characterised by uncertainty, because if a problem is framed too narrowly or on the wrong terms, then the policy solution is likely going to suffer from the same defects (Jasanoff, 2018, p. 13).

Building upon these insights, I argue that estimates of residential wood stove emissions and air pollution costs ought to be reframed. First, Bille and I find that wood stove emission estimates are associated with unmeasurable uncertainty because the socio-technical assemblage surrounding stoves cannot be known with a degree of probability due to the uniqueness of the situations that researchers are trying to replicate. The implication of our finding is that rather than focusing solely on the appliance technology – the stove itself

– we argue that the policy frame ought to be reframed with a focus on the socio-technical assemblage surrounding the wood stove and indoor air pollution. This is because the interaction between users and the sociotechnical assemblage surrounding wood stoves is critical in terms of reducing emissions. By focusing on how interactions between users and the socio-technical assemblage impact indoor and outdoor emissions, policymakers are provided with opportunity to intervene and regulate emissions in novel ways.

Similarly, in the context of calculating air pollution costs, I find that unquantifiable impact dimensions which are critical to policy ought to be recognised in science conducted for policy. Invoking the framework of the 'pollutome' (Landrigan et al., 2018), which suggests that air pollution economists can likely only quantify a small part of a much larger problem, I argue that the issue ought to be reframed. Rather than focusing solely on the well-characterized health effects that can be quantified, yet likely represent just the tip of an iceberg (ibid., p.468), I contend that such efforts ought to be complemented with expectations about uncertainties cast in a narrative form. At the boundary between measurable uncertainty and unmeasurable uncertainty in valuation practices expectations can play an important role in capturing those objects and impact dimensions that overflow quantitative valuation practices due to lack of knowledge. Expectations about emerging costs can in turn help instil confidence in public officials and provoke them to act in the face of high uncertainty (Beckert, 2016). In other words, by foregrounding the critical impact dimensions that elude quantification through expectations about the 'pollutome', I argue that public officials can be provided with a more credible and open-ended understanding of the deeply uncertain subject they are dealing with.

In summary, the 'framed uncertainty' approach to communicating uncertainty in air pollution modelling involves making harm mitigation a goal and conveying critical uncertainties in manner that is actionable to policymakers. It refers to the practice of 1) analysing the policy frame through which a particular issue is being framed; 2) recognising unquantifiable impact dimensions that overflow incumbent framing operations through expectations. That is, by acknowledging different gradations, or degrees, of uncertainty much more prominently in science-policy reports, I argue that researchers can offer public officials a more credible and helpful understanding of the highly uncertain context from which they must make difficult decisions. This approach to communicating uncertainty in turn provides policymakers with more flexibility and room to act.

4.3 Overview of papers and findings

In Paper 1 Dalsgaard, Bille and I lay the foundation for this thesis by exploring how key stakeholders in Copenhagen make sense of air pollution through different modes of witnessing pollutants that are predominantly beyond the reach of the human senses. Based on online research and interviews, we employ the term 'data witnessing' (Gray, 2019) to describe the process of making sense of air pollution. This process involves pertaining to the co-production and engagement with multiple forms of data organized around political targets. We characterize three air pollution measurement methods centred around fixed monitoring stations, Google Street View cars and handheld devices. Drawing upon Haraway's (1997) work, we characterize the processes of generating and using data via fixed monitoring stations as 'modest' witnessing, which refers to the way the scientists involved are made invisible to uphold the virtue of modesty (ibid., p. 23). Similarly, inspired by Zuboff (2019), we describe the process of witnessing air pollution through Google-generated measurements as resembling an 'imperial' mode of witnessing because the company seeks to assert its dominance by subjecting the environmental world to its data empire. Finally, following Gabrys and colleagues (Gabrys, Pritchard, & Barratt, 2016), we characterize the process of witnessing air pollution through handheld devices as 'guerilla' witnessing, referring to the irregular generation and use of data that is often produced to push back against established measurement regimes via fixed monitoring stations. We argue that making sense of urban air pollution in Copenhagen is made possible through these three modes of data witnessing where data is being generated and mobilized for specific political purposes.

In paper 2, I proceed to examine how the novel measurement method centred around Google Street view cars is ordering UFPs in new spatial locations. To do this, I first analyse the degree of uncertainty associated with evoking UFPs via this approach. Drawing upon Hubbard (2020) and Knight (2018), I first show how measurement situations characterised by unmeasurable uncertainty are conflated with measurable uncertainty through the introduction of a calculative exercise. The conflation is evident when the involved researchers attempt to establish annual average concentrations of UFPs in Copenhagen. This procedure involves multiplying single digit drives in each street segment of Copenhagen with 100 to establish percentage values. In the absence of a universally accepted scientific standard method for measuring UFP formation, I argue that the researchers associated with CAV have devised a novel and independent spatial ordering of UFPs which is located in no larger scientific order (Law 2008, p. 148). The article proceeds to describe the performative effects of the associated air quality map *Copenhagen Air View* (CAV). Invoking two cases, I describe how the CAV map has been deployed among concerned groups in efforts to counter emissions from local hotspots near Copenhagen Airport and major roads. Finally, I discuss why the issue of air pollution rarely garners much public attention in Denmark and conclude that the CAV method has nevertheless contributed to making UFPs a local issue in Copenhagen by integrating public concerns with scientific knowledge practices.

Paper 3 proceeds to focus on how uncertainty is modelled in the context of residential wood stoves. Bille and I do this by focusing on the emissions of residential wood stoves, which are often highlighted as the worst source of pollution in Denmark, presumably accounting for 52 percent of the $PM_{2.5}$ pollution of national emissions in 2020 (Ellermann et al., 2022). However, despite the apparent exactness of this number (52 percent), emissions from wood stoves are exceptionally uncertain and key parameters largely unknown, as we show in this paper. Whereas the problem of wood stove emissions is typically attributed to the stove itself, we change the focus to the socio-technical assemblage surrounding the wood stove, which is often overlooked. Drawing on discussions of uncertainty (Knight, 2018; Murphy, 2006), we first illustrate how knowledge about the socio-technical assemblage is constructed based on assumptions that emerge from domains that are imperceptible. Second, we argue that kindling practices can be understood as a kind of unmeasurable uncertainty which cannot be known with any degree of probability. Building upon our analysis, we propose a ‘framed uncertainty’ approach to make sense of uncertainty in wood stove emissions modelling. This concept draws attention to limitations of the incumbent policy frame on wood stove emissions by emphasising those particles that fall outside the current lens as well as the uncertainty associated with key elements in the socio-technical assemblage surrounding wood stoves. This approach to communicating uncertainty, we argue, is more helpful to public officials as it offers novel courses of action on how to curb emissions.

In Paper 4 I turn my attention to the uncertainties associated with the multidisciplinary field of air pollution economics. Here, I examine how air pollution researchers and economists consider the adverse effects of air pollution that are beyond the reach of contemporary economic valuation practices due to high uncertainty. Inspired by discussions of economisation (Callon 2021), I first analyse the boundary between what gets to count and what does not get to count in current valuation practices. Invoking the concept of the pollutome (Landrigan et al., 2018), I find that incumbent valuation practices likely capture just a small portion of a much larger problem. The implication of my finding is that unquantifiable uncertainties that are critical to public policy ought to play a much more prominent role in air pollution cost assessments. Drawing upon Beckert (2016), I propose that unquantifiable impact dimensions become recognised via expectations. By complementing numerical estimates of well-characterised health effects with carefully constructed expectations about emerging health effects, I argue that public officials can be provided with a more credible and helpful understanding of the issue.

4.3 Perspective for further research: uncertainty in indoor air pollution

There is a great paradox within the world of air pollution science. While a great deal - relatively speaking - is known about the adverse health effects of *outdoor* air pollution, we only spend about 10 percent of our time in outdoor environments (Allen & Macomber, 2022). In contrast, little is known about *indoor* air pollution, although presumably we spend 90 percent of the time indoors (ibid.). This section elaborates on how the findings of this dissertation could inform the emerging field of indoor air pollution modelling in important ways. Without having studied this field extensively, a preliminary analysis suggests that unambiguous numbers proliferate in it and that a framed uncertainty approach would be beneficial, when scientists convey indoor air pollution results to the public.

Allen and Macomber (2022), authors of *Healthy Buildings: How Indoor Spaces Can Make You Sick—or Keep You Well*, have outlined nine foundational parameters of a healthy building, including air quality, ventilation and moisture levels. Some of the most important parameters impacting the quality of indoor air environments are tobacco smoke, wood stoves, and particle emissions stemming from cooking and candle flames. In addition, chemicals such as brominated flame retardants - commonly used in textiles, plastics, and electronic equipment to make products less flammable - percolate from furniture, carpets and other indoor objects, leading to worsening indoor air quality (Lottrup, 2023). However, indoor air pollution is a complex area of study due to the heterogeneity and profusion of living habits and indoor environments (Sigsgaard in Lottrup 2023). In other words, how humans interact with buildings and the socio-technical assemblages surrounding cooking, wood stoves, candle lights, furniture, ventilation systems, and so on, all need to be accounted for somehow.

Like its outdoor counterpart, indoor air pollution contributes to numerous adverse health effects, but because such a high percentage of time is spent indoors, the quality of the air inside is much more important for our overall human health, learning and work performance, as Allen and Macomber (2022) highlight. The US EPA (2022) suggests that indoor air pollution can be up to five times – and occasionally more than 100 times – higher than outdoor levels. In related studies, three of my interlocutors conducted indoor air pollution measurements in Danish homes. In one study, two of my interlocutors demonstrate that the number of UFPs can rise from approximately 2000-4000 particles per cm3 to 115.000 particles per cm3 following three hours of wood combustion in a residential wood stove. Through smaller sample studies of households equipped with wood stoves, my interlocutors thus demonstrate that levels of indoor UFPs can increase tremendously while stoves are in operation (Bruun, 2022). While such sample studies suggest that wood stoves can lead to poor indoor air quality, this phenomenon needs to be uncovered through large-scale studies.

However, comprehending indoor air pollution seems to be particularly challenging, as crucial parameters tied to socio-technical assemblages impacting indoor air quality are associated with unmeasurable uncertainty due to the unique and diverse nature of the indoor situations that researchers aim to study.

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Part II

Paper 1

Data witnessing: Making sense of urban air in Copenhagen, Denmark.

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Special section: Witnessing environments

Data witnessing

Making sense of urban air in Copenhagen, Denmark

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Taking air pollution in Copenhagen as a case of environmental change, this article discusses the different ways that data are employed in processes of witnessing this change. We distinguish between three different modes of "data witnessing"—modest, imperial, and guerrilla—in order to clarify how different scientific, corporate, or civil society actors are engaged in producing and analyzing data about air pollution from different vantage points and with different interests. Their respective data work, as well as their joint participation in collaboration and confrontation over the interpretation of data, is a crucial component in making sense of air pollution in Copenhagen, which is predominantly out of reach to the human senses. Witnessing air pollution in Copenhagen is made possible by critical data designs under circumstances where neither data, nor subjective witnessing, in itself is enough.

Keywords: data, environment, science, air pollution, Google, resistance

To citizens of Copenhagen, Denmark, making sense of "air pollution," and the related question of what "air quality" is, has become *more* rather than *less* complicated in recent years. Until recently, the only data about the status of air pollution in the city of Copenhagen came from three stationary sensors curated by environmental scientists and positioned in proximity to some of the city's busiest streets. Apart from data from these sensors, air pollution and air quality were assessed through modeling tools and computations, or by the citizens' bodily senses. Today, however, the limited range of particle measurements offered by these stationary sensors are both supplemented and challenged by new data gatherers and data types. On the one hand, Google's "Project Air View" (PAV) collaborates with the Municipality of Copenhagen to produce more dynamic data that can identify particle concentrations in the city with high precision and granularity. These data sets are produced by a specially designed Google Street View Vehicle circulating within Copenhagen equipped with particle sensors. On the other hand, citizen groups—sometimes armed with or inspired by the use of small hand-held "do-it-yourself" (DIY) forms of sensing, sometimes merely relying on their own olfactory senses—are stressing the importance of more widespread but situated accounts of air pollution at specific locations within the city. Air quality has become a political battleground between municipal politicians, health authorities, eco-movements, citizen preferences, and corporate interest.

This article scrutinizes how various actors interpret and make use of different data-making efforts as emergent practices of witnessing. Grounded in digital and analog ethnographic material about air pollution measurements in Copenhagen, we use the term "data witnessing" to refer to the way that witnessing of environmental circumstances emerges as a collective co-production enabled by an engagement with multiple data forms and data infrastructures, which both organizes and is organized by corresponding political ambitions (see Gray 2019). "Data," however, is not only one thing. It can be generated in multiple ways and involves different types of knowing and expertise. We therefore focus on how three different ways of organizing the generation and employment of data each can be defined by their different

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abilities to act as witness. One type is the stationary sensors coordinated through the general modeling by air pollution scientists in Denmark, which we characterize with inspiration from Donna Haraway (1997) as *modest witnessing*. A second is the Google-generated *imperial witnessing* aiming at subjecting the entire world to its data realm (see Zuboff 2019). And finally, we call the third *guerrilla witnessing*, referring to the irregular use of data forms and types for politically limited, specific, and situated purposes, oftentimes in resistance to established scientific, corporate, or political authorities, and sometimes working through the enhancement of bodily senses with DIY sensors (see Gabrys 2016; Pritchard, Gabrys, and Houston 2018). The three forms correspond to three groups of actors each employing their own mode of collecting and organizing air pollution data, which again affords specific types of politics. Yet they also collaborate and draw upon each other to various extents (although not always mutually). Most importantly, they are all committed to data as instrumental in how environmental changes (here air pollution) can be accessed and thus witnessed.

The article uses this differentiation between the organization of data types and witnessing to discuss the micropolitical conflicts of air pollution in Copenhagen. We have followed local debates over air pollution systematically since early 2020 through a combination of online ethnography, reading of relevant documents (policy papers, news stories, opinion pieces), and qualitative interviews.[1] We show how the conflicts between different actors and interests are put into relief by the existence of the different forms of data witnessing, and, vice versa, how these conflicts affect the employment of data. Altogether, we locate our argument in between anthropological and science and technology studies literatures dealing with the scientific and political status of environmental data and scientific monitoring. The article thus contributes to debates about witnessing environmental change by discussing how data in itself can perform in processes of witnessing.

Scientific monitoring and critical data design

The question of how scientific monitoring renders environments and thereby air pollution visible is of crucial importance for the making of political as well as everyday life decisions. A dominant trend in anthropological accounts of scientific monitoring has been to focus on climate or environmental modeling and especially the uncertainty of models (e.g., Lahsen 2005; Hastrup and Skrydstrup 2013; Barnes 2016). Other key treatments of this question have demonstrated how environments or polluting substances are made perceptible (e.g., Murphy 2006), how they can be implicated in "slow violence" (Nixon 2013), how they can be traced ethnographically (e.g., Fortun 2001; Shapiro and Kirksey 2017), or how collaborations between different forms of expertise are enacted within an unruly and changing climate (e.g., Vaughn 2017). The materiality of environmental or polluting phenomena figures prominently in this research, although with different degrees of agency ascribed to the materialities in question.

There has been less focus on questions of how data are presented and become part of testimony and practices of witnessing, which is the gap we intend to address. Two notable exceptions in anthropology and sociology respectively are worth mentioning. One is Kim Fortun's work about what she refers to as the informating of environmentalism (Fortun 2004). Fortun is concerned with how environmental information systems affect how and what people see in the environment, how they deal with environmental problems, and how specific (information) technologies are more or less appropriate for this effort. The uneven distribution of data and information pointed out by Fortun is of particular relevance to our case along with her recent discussion of the interpretative efforts involved in what she and her colleagues refer to as "critical data design" (Fortun et al. 2016). In combination with the political purpose of addressing public interest, this hermeneutic labor is critical in leveraging big scientific data sets and translating them into politically meaningful "pushbacks" through different graphical user interfaces and visualizations. This emphasizes how interpretative data design enables the crossing of different domains of knowledge.

The other notable exception is the sociologist Jennifer Gabrys's work on digital sensing and the construction of environmental data in new "technogeographies" that connect technology, environments, and people (Gabrys 2016; Pritchard, Gabrys, and Houston 2018). Of particular interest is her use of the term "withness" to criticize notions of the smart city, and to discuss and signal "modes of being and becoming together . . . such that the possibilities for both urban ontological engagements as well as urban speculative futures are undertaken" (Gabrys 2016: 242). "Withness" is not meant on

1. Participant observation has been difficult since the onset of the COVID-19 crisis in March 2020.

Gabrys's part as a wordplay on witnessing, but we choose to engage her work with such a pun in mind, because it raises "the question of how we 'possess' the world and become together, not exclusively as a matter of intelligence or rational cogitating actors, but as embodied if differently directed creatures in shared worlds" (ibid.:243).

When environmental problems are characterized by invisible pollutants, then data design has a critical ability to link public problems with the oftentimes highly complex data sets. Figuring out how pollution is best rendered visible is a challenge involving multidisciplinary efforts bridging different types of data, different types of knowing and expertise, and different political concerns (Vaughn 2017). Connecting pollution data with human health effects, ecosystem deterioration, or atmospheric conditions has historically been a challenging task as the health and pollution sciences have been separated into different government agencies and domains (Fortun et al. 2016: 2). However, through recognition of the multiple and diverse factors shaping data availability and use, data designers may invoke specific forms of politics by allowing users to witness environmental change, which would otherwise be out of reach to the human senses. Yet, this demands that the technological design is constructed with the appropriate affordances and attuned to the particular needs of the setting where it is supposed to work, as exemplified by the Scorecard website studied by Fortun (2004). The Scorecard website displays similarities to some of the data presentations made for air pollution in Denmark, which we turn to below.

Witnessing air pollution in Copenhagen

The World Health Organization estimates that nine out of ten people around the world breathe air containing pollutants exceeding their guidelines (World Health Organization 2021). In other words, human beings live and act in a "permanently polluted world" (Liboiron, Tironi, and Calvillo 2018). Yet, air pollution can be colorless, tasteless, and odorless. In many places it is an invisible threat difficult to detect by ordinary senses. As a Western capital city with approximately two million people living in the wider metropolitan area, Copenhagen exemplifies this dilemma. One could suspect that inhabitants of a city of this size would sense significant pollution from transport and industry, but the city is located favorably on the coast, for one thing, and secondly environmental regulation from 2006 has allowed Copenhagen to be a low emission zone with strict limits particularly on the exhaust from heavy-duty motor vehicles (Danish Environmental Protection Agency 2021). This has eliminated some particle types. Yet, the effect is uneven. There are sites where air pollution is a contentious issue both in the city center as well as in the suburbs, and levels of nitrogen dioxide (NO_2), for example, have in some streets repeatedly exceeded EU limits. The rapid growth of traffic in and out of the Copenhagen Airport, which is located a mere eight kilometers from the city center, has been especially subjected to critique, which we will outline below.

In order to make particle concentrations visible, the Municipality of Copenhagen has allied itself with both traditional scientific modes of measurement and the PAV introduced by Google. They stress public-private partnerships as a means to generate "smart green growth" (Copenhagen Solutions Lab 2021b), which is connected to a general political admiration and embrace of digitalization and data-driven solutions among Danish politicians and public servants aiming to make Denmark one of the most digitally advanced countries globally (Schou and Hjelholt 2018). It is within this context that data has emerged as central to practices of environmental witnessing in Copenhagen, and why data witnessing works as an apt ethnographically driven theorization of the processes of converting the three above-mentioned forms of monitoring into environmental politics through the intermediary of critical data work (see Fortun et al. 2016). Needless to say, governing air pollution in a site like Copenhagen involves a host of different techno-scientific, industrial, and political actors, each contrasting, probing, or borrowing each other's expertise (see Vaughn 2017). In order to address the difficult ontological vantage point, where multiple actors are involved in determining the health and environmental effects of a largely invisible source of pollution, we combine the focus on data with the notion of witnessing in order to make sense of the positions and the forms of knowing and action pursued by the different actors involved.

Joining the concepts of witnessing and data

The notion of witnessing is predominantly associated with being present and constructing a testimony based upon first-hand accounts of an event seen, heard, or experienced by the present people acting as witnesses (see Das 2003; Fassin 2008). In ethnographic work in particular, witnessing has conceptual overlaps with fieldwork practices of observation and participation (Reed-Danahay

2019), and Clifford Geertz (1989) most famously debated the entanglement of witnessing with the "I" of said witness. It may seem a contradiction in terms to combine this notion of witnessing associated with "subjective" human views based upon first-hand presence, with that of data, which in lay understanding is often regarded as "objective" representations of reality, even when numbers are transformed into audiovisual media, or when digital media can catch details imperceptible, distorted, or lost in human memory (Peters 2009: 24).

It is the case for air pollution in Copenhagen that it is not easily smelled. It is approached in a technologically mediated form as data about specific particles. Our argument is that this combination of data mediation and human sentience performs a new type of witnessing that engages the co-productive potentials of different data forms. While we do not want to go so far as to claim that data has gained a life of its own, we do want to emphasize how opportunities for data collection and analytics today are transforming what it means to witness something both for our interlocutors and for the ethnographic work of following their attempts to make sense of urban air. It demands an ethnography of data practices including their collection, presentation, and interpretation (Fortun et al. 2016).

Taking a cue from anthropological debates about data, it is important to stress that the recent proliferation of data as both a popular term and a focus for IT-based research practices in the social sciences has meant that data gathering practices as well as the categories of what data "is" and what data "represents" have been in need of rethinking (see, e.g., Boellstorff and Maurer 2015). As new forms of (digital) data have become central to social scientific research (e.g., Rogers 2013; Pink et al. 2016; Dalsgaard 2016; Knox and Nafus 2018), any attempt at a sharp delineation between uncertain (human) witnesses and certain (nonhuman) data has itself come into jeopardy through a critical social scientific gaze (e.g., Gitelman 2013; Kitchin 2014; Garnett 2016). Yet, the idea that data can represent a one-to-one rendering of reality has been undermined by accounts of how data is generated in practice. Just as witnesses can be unreliable, so can data. The metaphor of "raw data" has been claimed to be potentially misleading because such data are regarded by scientists as uncertain and untrustworthy because they can be filled with errors. The metaphor itself obscures the infrastructures and labor of cleaning and curation involved in generating these data and what they represent (Walford 2017: 68). As with "ordinary" witnessing, however, the testimonies made by data—raw or "cooked"—can be embroiled in partiality, situatedness, or even affect. This critical view of data is necessary to keep in mind when contending that data can be considered as performing an act of witnessing in itself.

As a basis for combining this scrutiny of data with a notion of witnessing, we lean on the work of Jonathan Gray (2019), who has proposed the term "data witnessing" to refer to the multiplication of involvement of distant actors in the witnessing of events. Gray's conceptualization draws upon a number of other witnessing labels and definitions, such as "digital witnessing" or "media witnessing," which focus on the construction of moral engagement from afar, mediated through various technologies or forms of media content. Gray analyzes the digital data practices of Amnesty International's Decoders initiative and discusses the configuration of witnessing of injustices with data from various sources (e.g., social media, satellite imagery, official reports, photographs, eyewitness interviews). This is, as we read it, an approximation of data—in an organized and assembled form—becoming implicated in the performance of witnessing in itself. The accounts Gray is concerned with do not gain their authority from the presence of individual human witnesses alone. Instead, data witnessing is about the collective yet distributed rendering of injustices as systemic. Data witnessing configures the scale of witnessing across space and time and opposes it to a focus on isolated events and "the 'thereness' of singular personal experience" (ibid.: 986).

Like the notion of "virtual witnessing" (Shapin and Schaffer 1985), which Gray draws upon, data witnessing involves the construction of collective dimensions of witnessing, and in line with Bruno Latour's work (1993) it relies upon nonhuman actors and their testimony. While Gray demonstrates this for the work of documenting and exposing injustices and violations against human beings, it is equally pertinent for environmental topics, where sensors, microscopes, and accumulation of other technological intermediaries are crucial to the natural sciences as extensions of human bodily perceptions and senses in constructing an image of environmental injustices or violations (see Shapiro and Kirksey 2017). As demonstrated by anthropologists researching environmental engagement, the data and how data are presented (through models or visualizations) does more than merely "mediate." It actively creates something (Hastrup 2013; Vaughn 2017). In our case, a sense of witnessing.

We now return to our field site of Copenhagen, where our digital ethnographic material allows us to identify three different ways of generating, organizing and employing air pollution data. Each way can be defined by its ability to produce forms of data that act as witness in relation to specific political purposes.

Modest witnessing

Air pollution scientists from the Danish Center for Environment and Energy (DCE) at the Department of Environmental Science at Aarhus University are engaged in what we, with inspiration from Haraway (1997), characterize as modest witnessing. This department has for more than thirty years been responsible for monitoring air pollution levels in Denmark in collaboration with the Danish Environmental Protection Agency and other research institutions in Denmark. The efforts of the program consist of data collection from more than twenty stationary sensors located across the country (with three in Copenhagen), supplemented by a dozen mathematical models. Some stations are located in heavily trafficked streets in the four largest cities of Denmark, others have been placed on roofs or in backyards in cities, while some measure air pollution in coastal or rural areas. The air pollution substances are recorded according to EU standards and include, but are not limited to, nitrogen oxides (NO_2, NO_x), ozone (O_3), carbon monoxide (CO), sulfur dioxide (SO_2), and particles sized PM10 and PM2.5 (also known as "fine particles"). The measurements for each can be accessed through charts and diagrams on the DCE website (DCE 2021). The stations monitor the different substances using various methods in accordance with each targeted substance. This implies that some measurements need long-term data collection which is subsequently analyzed, whereas other instruments can deliver immediate analysis of daily measurements.

In addition to the network of monitoring stations, the Department has developed a suite of twelve different air quality models, each of them built with a specific purpose in mind. The "Atmospheric dispersion model," for example, is applied for regulatory purposes, whereas the "AirGIS" model is used for urban air quality assessment. The "Economic valuation of air pollution model" is used to determine societal costs of adverse human health effects from air pollution exposure, and the "THOR model," combines other models to produce the "3-day forecast for air pollution in Denmark" (Department of Environmental Science 2021). It is an interactive, animated air pollution map of Denmark which renders visible the concentration of six different air pollution substances (ozone, NO_x, NO_2, CO, PM2.5, PM10) at a granular level of one square kilometer. Website visitors can choose a pollutant and observe how the pollution level is predicted to change on an hourly basis over the course of the next three days (Figure 1).

The major guiding principle for this scientific work is to assess particle concentrations against politically determined air quality standards outlined by the European Commission (2019). To do so, the monitoring program is organized according to classic scientific criteria. Its claim to scientific validity comes from systematic data collection with methods of measurement specifically tailored to each particular substance. The equipment is furthermore tested and calibrated according to established international standards, and the methods and results are openly available to the public through the department website. In this way it is available to interested stakeholders including citizens, NGOs, governing bodies, and experts, yet many of the representations of air pollution

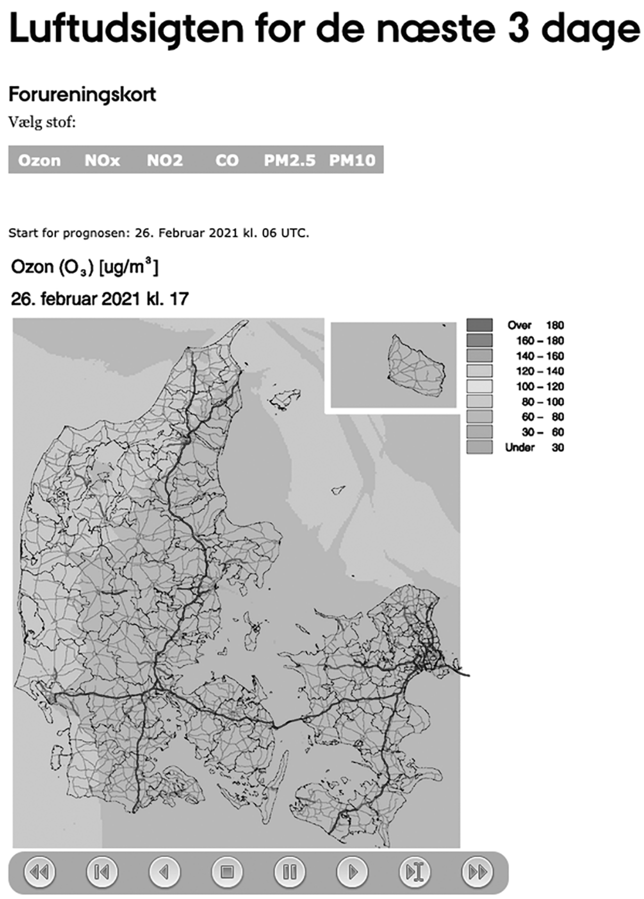

Figure 1: The DCE's 3-day forecast for air pollution in Denmark (Department of Environmental Science 2021, accessed February 26, 2021).

still require a certain level of familiarity with threshold limit values and quality standards, as well as knowledge of the scientific nature of air pollution to make sense of the data (Nafus 2018). The design of the three-day forecast for air pollution in Denmark succeeds in highlighting how air pollution in Denmark is predominantly affected by sources stemming from neighboring countries. However, in contrast to similar applications such as Scorecard (Fortun 2004), the coarse-grained nature of this map makes it more or less irrelevant for citizens of Copenhagen. It does not allow them to take any meaningful action in relation to the information provided, and it does not hold the same affordance for political mobilization as Scorecard.

While it may be a stretch to argue that the scientific work of the DCE amounts to modest witnessing in the exact sense described by Haraway (and through her also by Gray), it still does so on a number of parameters. Haraway's account has been central in the feminist destabilization of scientific assumptions of disembodied objectivity and privileged perspectives. In her book *Modest_witness@Second_Millenium.FemaleMan©_Meets_OncoMouse™* (1997), she takes the term from the work by Steven Shapin and Simon Schaffer (1985) on the seventeenth-century dispute between Thomas Hobbes and Robert Boyle, a dispute which led to the foundation of experimental science. Most importantly, Shapin and Schaffer argue that "if knowledge was to be empirically based . . . , then its experimental foundations had to be witnessed" (ibid.: 55–56). As with the overarching notion of data witnessing as described by Gray, the construction of scientific facts relied on public and collective contributions. The witnesses during the times of Boyle and Hobbes had to be gentlemen, whose moral constitution and thus their testimony could be trusted to be credible and reliable. The ideal was "a modest man," and Haraway emphasizes how the white male scientist was made invisible in order to enforce "the virtue of modesty" (1997: 23), a virtue which "guarantees that the modest witness is the legitimate and authorized ventriloquist for the object world, adding nothing from his mere opinions, from his biasing embodiment. . . . His subjectivity is his objectivity" (ibid.: 24).[2]

Neither Shapin and Schaffer nor Haraway have touched upon the status of the data produced in these experiments as such. The ontological status of data at their time of writing was naturally not what it is today, but even now, data itself is by positivist natural science often perceived to be the objective yet "raw" representation of a reality: the witnessing of reality independent of a human subject that appears when facilitated by correctly calibrated equipment and data infrastructures (see Walford 2017). Haraway could easily have concluded this when she cited Shapin and Schaffer: "The experimental philosopher could say, 'It is not I who say this; it is the machine'" (1997: 25), as if the machine was the actual witness. Because we stress this shift in focus away from the scientist and on to the data, we also stress that data witnessing implies a process (as in modest witnessing) rather than a figure (the modest witness).

The scientists of the DCE most clearly act as modest witnesses through their attempts at constructing neutrality and distancing between subject and object, that is, making invisible (transparent) the many practical operations, their scientist operators, and any relationality behind them (see Haraway 1997; Walford 2017). For example, the visualizations of the DCE's models obscure or eclipse the actual work of witnessing performed by the sensors. There is in this mode of performing data witnessing little identification with the data or with the context where the data is collected. While methods are clearly outlined, there is no elaboration of the curating of the data from "raw" to "clean" (see Walford 2017). The DCE visualizations and models resemble the Scorecard website on this parameter of only providing interactive information and not the raw data itself (Fortun 2004).

In a lay sense of the term "modest," there is furthermore a reliance on the combination of (relatively) few sensors and purpose-specific models. In spatial terms data collection is rather modest due to the relatively low number of stationary measurement stations situated across the country, but the data sets are comprehensive over time, and they record a wide variety of particle types. Yet they leave the largest job to be performed by the models. When it comes to the models, they can be deemed modest because of their limited scope and focus, and because of their inaccuracy as coarse-grained calculations rather than measurements. Of our three types of data witnessing, the modest witnessing is thus the one farthest removed from being a collective and distributed accomplishment as stressed by Gray, even if it is intended as input to policy debates and is employed by citizens for

2. To be sure, Haraway's preferred ideal for the figure of a modest witness is instead "historically specific, located in a particular time, place, and body" (1997: 20). Her version of modesty is about a critical immersion where questions about race, class, gender, and sex can be raised for the purpose of dialogue, care, and accountability.

specific purposes, as we shall see below. In comparison, the PAV, to which we now turn, has a higher granularity, and claims to be positioned closer to citizens as potential users of their air quality maps.

Imperial witnessing

The PAV was welcomed by the municipal government of Copenhagen as a way to help counter criticism from the EU Commission that the city did not live up to the EU regulations on NO_2 emissions (Saietz 2016; Krog 2018). A more fine-grained mapping of air pollution in the city was thought to be able to improve urban planning and reduce local sources of emissions. In order to provide these data, the PAV collaborated with both the researchers from Aarhus University mentioned in the previous section, as well as scientists from the University of Copenhagen's Department of Public Health, and Dutch scientists from Utrecht University, who helped equip the Street View Vehicle with state-of-the-art sensors and data collection itself.

According to the PAV, data has been collected in Copenhagen by a sensor-equipped Street View Vehicle Monday through Friday during daytime hours, typically between 9 a.m. and 6 p.m. The measurements shown in the preliminary PAV map—the Air Quality Explorer (AQE)—represent an estimation of the median pollution from November 2018 through August 2019 in individual streets. Street measurements have been repeated with multiple passes by the vehicle in order to reduce the influence of individual extreme samples and to ensure that the measurements are truly "hyperlocal."[3]

Despite claims to exhaustive coverage through mobility and "hyperlocality" mentioned in a promotional video with Country Director for Google Denmark, Malou Aamund (Make Sense Film 2018), not all streets of Copenhagen are included in the AQE. A number of narrow and mid-sized streets are not (yet) included, and a few larger streets are for unknown reasons either absent or only partially covered. The Municipality of Frederiksberg which covers a large geographic area of the city is also not included. The Copenhagen Airport (CPH)—normally expected to be a large source of pollution—is located a few kilometers south of the municipal border and also not covered. Yet the citizen group named *CPH uden udvidelse* (Danish for "CPH without expansion"; see CPH-UU 2021) has copied one the AQE maps to its website in order to argue that the Airport could do more to limit its emissions. We will return to this group below.

Furthermore, not all types of particles are presented in the AQE. Copenhagen's AQE focuses on black carbon (BC, or "soot") and ultrafine particles (UFP). At first glance, then, the witnessing appears partial at most and not holistic as Google aims for its ventures to be. However, the AQE maps display Google's attempt at covering all streets that could realistically be navigated by the Street View Vehicle, and while the publicly available preliminary maps and visualizations only refer to BC and UFP (see Figure 2 below, from Google 2021), the Street View Vehicle was also meant to measure levels of PM10, CO_2, and NO_2(Copenhagen Solutions Lab 2021a). Given Google's previous history and imperialist ambition (see Zuboff 2019), the vehicle was possibly collecting other types of data too, which allows for more nuanced forms of analysis and data presentation (cf. Apte et al. 2017).

It is unlikely that altruistic help to a municipal government has been Google's only incentive. Data is the prime resource for Google (or Alphabet, as the mother company is named). It has become notorious that the founders Larry Page and Sergey Brin aim to "organize the world's information and make it universally accessible and useful" (cited in Moore and Tambini 2018: 4). This ambition to collect and organize all the world's information has not only been accused of being an exertion of dominance over human knowledge, but also of wanting to use this knowledge to exert surveillance and make profit from the possession and curation of the multitude of data constantly generated around the world (Zuboff 2019: 115). As a popular critique has it, Google's ambition implies capturing and controlling "every cache of productive information that currently existed on, or could be ported to, the web" (Galloway 2017: 147). Search results for web content were not enough for its goals: Google has gone on to impose itself as a gatekeeper of access to locations (Google Maps), astronomical information (Google Sky), geographical information (Google Earth and Google Ocean), books (Google Library Project) and journalism (Google News), not to mention the knowledge and control of human behavior through these services.

One of the most powerful recent discussions of Google and the other tech giants' role in global capitalism is Shoshana Zuboff's *The age of surveillance capitalism* (2019). She labels Google as "the pioneer, discoverer,

3. A description of the methodology that was used in Oakland, California, has been outlined by Apte et al. 2017.

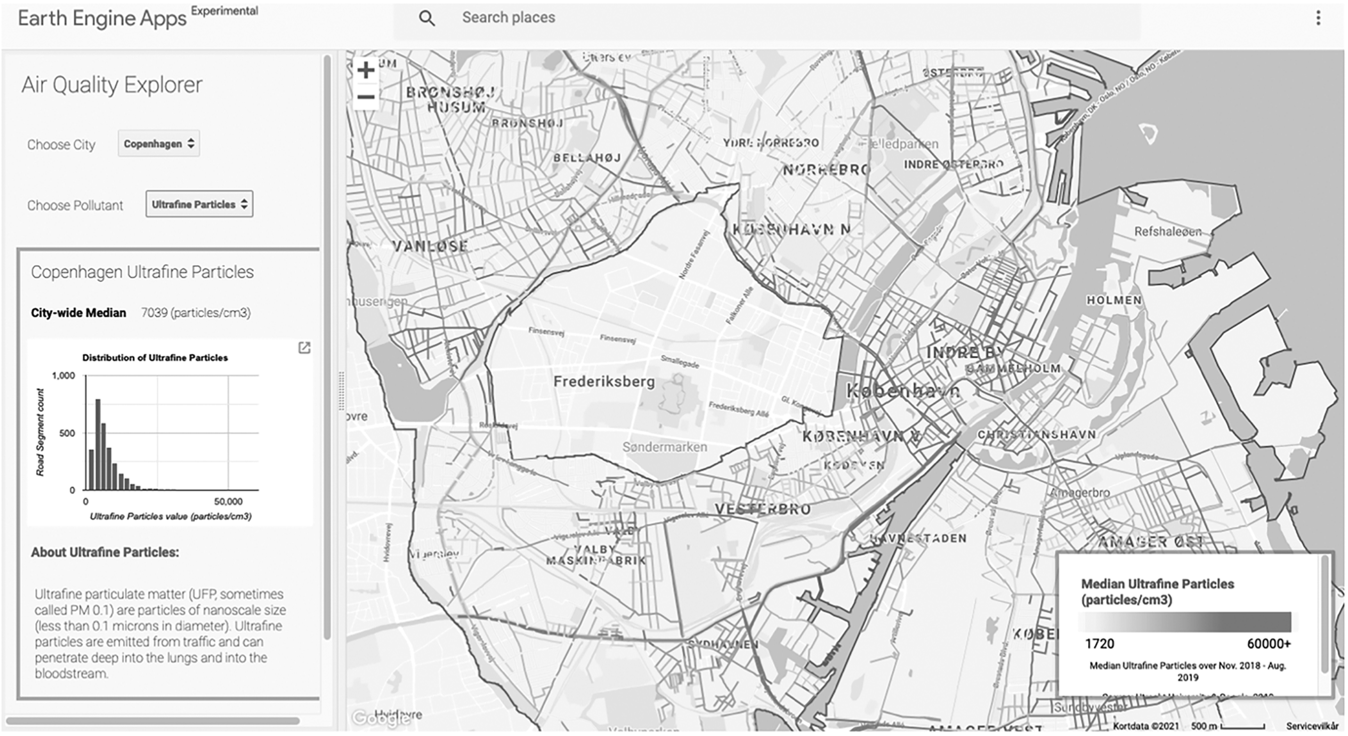

Figure 2: Google Environmental Insights Explorer. From https://insights.sustainability.google/labs/airquality, as of March 2021. Utrecht University and Google, 2021, via Google Environmental Insights Explorer (June/2021).

elaborator, experimenter, lead practitioner, role model, and diffusion hub of surveillance capitalism" (ibid.: 63). In her view, the company's data accumulation stems from a "surveillance-based logic of accumulation" (2019: 115), which not only depends upon a process of digital dispossession, but also actions, materials, and techniques defending this business model from democratic oversight (ibid.: 99–100). In its enterprises, Google aims at mapping its data objects exhaustively (Zuboff 2019: 154; see also Farman 2010). Examples of the exhaustive, pervasive, and holistic nature of Google's capture of data includes how the Street View Vehicle is so comprehensive and detailed in its coverage and creation of the Google Map and the Google Street View that it has been assessed to get Google's representations to be closer to bridging the gap between the information available in the real offline world and the information of the map than any other representation available (Zuboff 2019: 149–50).

Google's Environmental Insights Explorer is one of the most recent initiatives in Google's data-imperialist ambition (see Google 2021). As of March 2021, more than three thousand cities worldwide were included in this mapping of urban environmental data. For each city Google estimates CO_2 equivalents for buildings and transport while providing a CO_2 reduction potential for cities with regards to equipping rooftops with solar panels. Within this framework, the PAV is highlighted as a new critical indicator for climate action. Copenhagen and London are currently the only "labs" for air quality measurements under the PAV, but the program is allegedly expanding to other cities across the world (Make Sense Film 2018; Google 2021). The PAV is described as a game changer by bringing novel kinds of data together in new ways, thereby making environmental problems more visible and actionable. This framing resembles other critical data designs such as the abovementioned Scorecard (no longer in operation) or the US Environmental Protection Agency's EnviroAtlas, both of which have aided decision makers and users by linking pollution data with other issues (Fortun et al. 2016: 3). The current AQE is a preview that can currently only be accessed through larger devices, while support for smartphones is in the making. The preliminary measurements are currently being tested and the final map, which has been delayed due to COVID-19, is set to launch during the summer of 2021. Google's aim is to connect the AQE to the Google Maps application to allow citizens to navigate and avoid the most polluted streets. This focus on helping citizens avoid pollution is allegedly what was meant by Aamund's reference to hyperlocality. In contrast to the DCE's coarse-grained national three-day pollution forecast renderings, Google's more intuitive and fine-grained map thus allows citizens to act upon its data presentations. Yet, such use of the application is likely to generate more data for Google about citizens' preferred routes and whereabouts, which would contribute to the expansion of their data empire. When or if citizens start to navigate differently in urban space as a result of their interaction with the PAV, its measurements and its maps, then Google will know immediately and learn how the environmental data will affect behavior, in turn generating better predictions of human behavior and more value for the company. The PAV is an attempt to create an *individualized* data witnessing rather than the collective effort emphasized by Gray (2019), and while it may be easy for citizens to appropriate it for some of their needs, it may not as such be an "appropriate technology" (Fortun 2004), to which we return shortly. Rather than embracing local perspectives, Google's form of data witnessing is more likely to be an attempt to scale and bridge the local and the global through massive data sets to further underwrite the company's imperial ambitions.

Guerrilla witnessing

The third form of data witnessing we have encountered in our ethnographic material is what we refer to as "guerrilla witnessing." Guerrilla witnessing is built upon data collection done by scientists and lay people interested in specific experimentations with sensors, data collection methods, or activist mobilization,[4] or pursued by NGOs, companies, or government agencies trying to collect data from more scattered sources. This form of witnessing thus has parallels in what is referred to as self-tracking (e.g., Eede 2015; Lupton 2016) or mundane data practices (Pink et al. 2017), and it includes (but is not limited to) the DIY measurements of air quality undertaken with a variety of mostly low-cost digital sensors (Gabrys 2016; Pritchard, Gabrys and Houston 2018). The civil society group we have followed makes use of a variety of ways of assessing air quality, and the different modes of witnessing become entangled as overlapping but also sometimes contrasting forms of expertise in their endeavor (cf. Vaughn 2017).

In March 2016, the Copenhagen Airport announced the initiation of a major expansion aiming to double the annual number of passengers. This was not welcomed by citizens living in the vicinity of the airport, and in June 2019 the citizen group CPH-UU was formed in response to news of the expansion (Flensburg 2019; CPH-UU 2021). The group is highly active in a public Facebook group where we engaged with them and have been able to follow how nuisances related to noise and smell are discussed. Some group members express their dissatisfaction with the current conditions by posting messages on the public Facebook sites of national politicians while others write opinion pieces in local newspapers. In an interview with one of the most active members, she highlighted that the increase in smell and noise in the neighborhood close to the airport had made her consider "whether it is still a good place to raise our children." During the past decades the number of passengers traveling through CPH Airport has increased from seventeen million in 1998 to thirty million in 2019 (CPH Airport 2021). Especially in the last three to four years conditions are reported to have worsened for neighbors of the airport. The number of complaints from concerned citizens and workers about air or noise pollution around the airport increased from twenty-seven in 2017 to 674 during 2019 (Bjørton 2020b). The CPH-UU group is not against the airport as such—they perceive it to be an important employer for the local community—but they are against the expansion because of the expected rise in nuisances.

In their attempt to stop the expansion, the CPH-UU has been trying to introduce both novel forms of information-gathering about noise and air pollution and new ways of mobilizing resistance. The airport produces its own measurements, but the local government has opted to bring in scientists from the DCE as consultants to conduct an independent assessment related to the concerns of the CPH-UU group (Bjørton 2020a). The combination of corporate (airport) measurements and scientific monitoring, which is largely based upon modeling, has not fully satisfied the CPH-UU. During our work with the CPH-UU group, it became clear to us that some members suspected the airport of not being fully transparent about its measurements. The group is furthermore concerned with peak occurrences, rather than the averages which count when it comes to the official threshold limit values monitored by the DCE. Due to the lack of air pollution measurements near the airport, the group has tried to bring in more measurements

4. A "guerrilla example" with the participation of social scientists is a project at Aalborg University (see Public Data Lab 2018).

from residential areas covering a larger radius than the current monitoring practices which primarily rely upon modeling (CPH-UU 2021). A complicating factor has been the difficulty of establishing a clear scientific consensus about how hazardous high concentrations of UFPs stemming from jet fuel and fossil fuel-powered vehicles actually are to human health (see Kumar et al. 2014: 7). The lack of scientific consensus means that the Danish state has not set any threshold limits for this type of particle in correspondence with EU targets. Members of CPH-UU have tried to fortify their position by bringing scientific work from other sources into the public discussion—for example, a study which documented that exposure to the exhaust of aviation fuel is as harmful to mice as that from diesel engines which are already known to have adverse health effects (Bendtsen et al. 2019; see also Fuller 2019: 127).

In a strategy aimed at raising public awareness, the CPH-UU group has stressed the vicinity of the airport to the center of Copenhagen (eight kilometers). This is less than most other airports of comparable size, and well within the radius where particles may have a significant effect on people's health (Fuller 2019: 125–26). This mobilization also includes the group's adoption of the processes of witnessing enacted by DCE and Google. The stationary measurements conducted in Copenhagen and the measurements of the Street View Vehicle are both referred to, and the map of the AQE of UFPs is reproduced on the CPH-UU website. The group's interpretation of the AQE map is that streets situated in close proximity to the airport display high levels of particle concentration because several smaller streets in the area indeed are displayed with the red color indicating a higher particle count than comparable streets in other suburban areas.

Finally, the group has developed and promoted an app called Miljømåler—CPH Uden Udvidelse (Danish for "Environmental Measurer—CPH Without Expansion"). In contrast to the data designs of the modest and imperial forms of data witnessing, which rely on sophisticated technoscientific technologies, CPH-UU's app has, according to their spokespeople, been built with the sole purpose of raising political awareness. Due to the lack of measurements near the airport, the group has felt compelled to develop the app to register and report discomfort due to noise or air pollution based on their location (see Figure 3). Once the discomfort is registered by a user, it is sent directly as a citizen complaint to the Danish Environmental Protection Agency. Using an embedded Google map, the app allows citizens to record expe-

Figure 3: Environmental Measurer—CPH-UU.[5]

riences of nuisance without using any kind of measuring device, although it is possible to add decibel volumes when sending a complaint about noise. In contrast to the DIY cases described above (Pritchard, Gabrys, and Houston 2018), users of the app can report "air nuisance"

5. The app is available in the Apple App Store and Google Play Store (https://play.google.com/store/apps/details?id=com.gmail.chholbech.cph&hl=en_US&gl=US).

or "noise nuisance" based entirely upon their individual bodily experiences.[6] The introduction of the application in November 2019 may not carry sole responsibility for the increase in complaints, but the app does enable faster and more convenient reporting of nuisances. Yet it does so in ways that are so far not integrated with scientific measurements.

It is aims and activities such as these that we see as characterizing guerrilla witnessing. By the term guerrilla we highlight how DIY sensing, but also uses of data generated elsewhere by scientific or corporate actors, is conducted through the attempted use of technoscientific tools and methods in an irregular and uncoordinated fashion by "parascientific actors" (NGOs, citizens, lobby organizations). They pursue a political purpose such as a participatory and democratic engagement with environmental issues, or the resistance to more powerful and resourced actors—state or corporate. At the same time, the term guerrilla is as much meant to emphasize the disruptive and unreliable nature of this form of sensing in comparison to scientifically validated sensing practices, in part because even "plug-and-play sensors" demand considerations of how they are to be calibrated and situated. The people or organizations employing these sensors attempt to ensure accuracy, commensurability, and interoperability of their results through a labor of calibration and adjustment to standards, but this work is riddled with complexities and differing approaches (Pritchard, Gabrys, and Houston 2018: 4534). Thus, DIY sensing as an example of guerrilla witnessing remains closer to a contextual relationship to the locality (see Gabrys 2016: 165).

The situatedness of guerrilla witnessing can here be contrasted to both the potential distancing as well as the generalizing scope performed by both the imperial witnessing (global) and the classic modest witnessing (national). Gabrys's notion of withnessing is worth emphasizing, because it points to both the characteristics of DIY sensing as a form of witnessing, and the activist use of data in resistance to distanced modes of generating records and witnessing. Withnessing is situated and localized; it works through embodiment in the witnessed world, which is more direct than the other two modes of data witnessing. It is thus closer to traditional ethnographic understandings of witnessing. Withnessing is not to be read as a mere postphenomenological understanding of the world as mediated through data and technology, though. It also emphasizes the collectivity involved in data witnessing.

It is clear from the above that the CPH-UU mobilizes a variety of regular and irregular data types and sources with the aim of generating concerns among fellow citizens in resistance to the major airport expansion. When the Environmental Protection Agency expressed annoyance about the number of complaints they were receiving through the app, the group replied in a letter shared in their public Facebook site that

> the discussion is not just about the app, but a broader discussion of what the complaints indicate, the existing guidelines and threshold limit values; the need for independent measurements and which demands one can raise against CPH in relation to noise and air pollution.[7] (our translation from Danish)

The group, in other words, tries to refer to the felt and bodily experienced interactions with air pollution as an appeal to solidarity; they attempt to turn the individual experiences into a collective withnessing, thus moving beyond the "thereness" of singular experiences (see Gray 2019: 986). This includes stressing peak measurements rather than just threshold limit values as calculated averages and prompting the need to raise concerns as a collective endeavor. The guerrilla witnessing of CPH-UU is in this sense emphasizing an embodied witnessing position in comparison to disembodied modest and imperial witnessing. Yet, it is not because the group does not want the scientific data. It is because they can neither scrutinize nor control the measurements and calculations made by the DCE on air quality, nor can they effectively see the measurements made by the airport. Being unable to sufficiently account for the daily nuisances of air and noise pollution in a scientific language, or have their area fully covered by the PAV, citizens must rely upon a combination of generally available but limited scientific work and their own bodily and mundane experiences represented through the app (cf. Pink et al. 2017).

6. Some neighbors living three kilometers from the airport were interviewed by a major Danish newspaper in July 2019 and stated that they could often "smell and taste the airport" when they were in their garden (Flensburg 2019).

7. https://www.facebook.com/groups/CPH.udenudvidelse, posted May 28, 2020.

Witnessing environmental change through data

It is clear that data alone is not enough for our actors. Each actor has their own concerns—quality of models and data, expansion of territory covered, bodily sensed noise and smell. What is needed for all of them aside from *more* data, is *more than* data. This "more than" is the establishment of data as enacting a form of witnessing which facilitates public concerns and (new) political agendas. For instance, what makes the PAV valuable in local contexts are the debates over air pollution that its presence engenders. For this, the PAV relies on collective engagement and a forging of alliances (for example between Google and the scientists of different universities including Utrecht, Aarhus, and Copenhagen). Google is potentially the most dominant actor here, because it has the resources and flexibility to expand beyond what binds the other actors. In the future we may see Google's imperial ambitions encompass new types of data encapsulated by the other modes of witnessing. Their role as a corporate empire is to sweep up everything that can be collected, packaged, and sold as data. In this way Google may as easily be an ally of the state as it may be undermining it and supporting or facilitating different forms of guerrilla witnessing.

Whereas the guerrilla witnessing taking place through situated sensing lends itself more directly to political engagement than the distance entailed by the modest ideals of science, or the imperial ambitions of Google, Gray's (2019) invitation to think about engagement with data as a form of witnessing helps us explain how the scientific results of the two latter may also generate identification or affective responses through the very mundane collective work of making complaints and sensing air or noise, as well as in debates or disputes when data are presented via enticing visualizations as displayed in the AQE or the DCE's website.

There is still much to be said about the ways the different actors perceive the witnessing of environmental change, and much that our discussion here cannot cover without continued empirical scrutiny. One point, however, is that all the actors endeavor to find not only the most *correct* but also the most *useful* data to engage in data witnessing. Whether their focus, for instance, is CO_2, BC, or UFPs depends on whether their concern is to manage climate change, monitor citizen health, mitigate noise and air nuisances or all of them at once. This should not be read as a mere cynical opportunism, but an attempt to enact the most pragmatic political and public concern, for instance in terms of helping policy makers in constructing nuanced and informed decisions about urban planning or mobility. Some may consider, for example, the PAV to be superior in this regard to both the localized monitoring of scientific stations as much as the DIY sensors because of the former's fine-grained scope and mobility. Yet without scientific consensus regarding UFPs and full transparency of what is collected and how it is curated by Google's data processing (Nafus 2018: 234), the authority of imperial witnessing may be questioned, which some members of the CPH-UU actually did in their internal discussions on Facebook. Our various actors then also search for the most authoritative form of witnessing. Whether authority of data comes from the construction of a virtue of modesty and distance to the object, or a situated perspective which acknowledges that data generation is embroiled in a political position, is an ongoing struggle.

Conclusion

All in all, the data generated by both the DCE scientists and the PAV is meant to aid urban planners, policymakers, healthcare professionals, and citizens alike in making smart decisions that contribute to welfare, health, and efficiency in Danish society. However, what is understood as smart decisions or appropriate technology (Fortun 2004) is here a matter of perspective, and one form of data witnessing alone does not suffice or carry automatic authority. The Municipality of Copenhagen is working to create data-driven solutions that suit the city and its citizens. It is thus vital for the Municipality to learn how the introduction of different types of data into public debate, planning, and policymaking generates concerns or controversies over public health in relation to the configuration of public space and infrastructures (such as location of public schools, urban mobility, and energy supply). Using data as a quantitative measure for the purpose of governing urban air may rub against bodily experiences of sensing pollution that are impacted by personal as well as collective values in Denmark, including coziness (in Danish *hygge*), comfort, or convenience (Shove 2003; Bille 2019). Or it may create data frictions when CPH-UU decides that the PAV is not the only appropriate technology for them, because they wish to submit bodily experiences as nuisance reports to the Environmental Protection Agency.

Data is frequently regarded to be a key component in understanding and witnessing environmental change. Witnessing in the traditional sense, however, is rarely enough when it comes to producing testimony about air pollution as environmental change. Witnessing the environment cannot take place in the form of singularized testimony. It makes little sense to present a single observation of a particle, or even a specific count. This field of research, we argue, is one where the ability to act as witness demands both data and a collective effort of interpretation and purpose (see also Fortun et al. 2016). Our aim in this article has been to discuss how data then operates in collective configurations of processes of witnessing. The modes we have discussed are all based on the employment of digital tools for the collection and organization of data, and they all contribute to different degrees to enacting processes of data witnessing, whereby we refer to exactly this collective configuration afforded by aggregates of data. The key argument is that data alone is not enough in this configuration, and neither is simply more data. Rather, data witnessing—in this case analytically distinguished by a modest, imperial, or guerrilla character—can help us along where we have found that other concepts were more limited, because the struggle over air pollution in Copenhagen is about *more than* data as evidence or information. The three types of data witnessing diverge in terms of the scale of their measurements, the specific types of technology employed, and in the politics that they afford, but they also intersect in the general need to have and to present data as a currency in the political domain over the definitions of air pollution and air quality (Shapiro and Kirksey 2017: 488). We here distinguish between the three different types of data witnessing in order, more broadly, to contribute to an understanding of what both data and witnessing "do" when a social network of the state, scientists, corporations, civil society, and nonhuman actors try to make sense of air pollution and environmental change. Data is embedded in such a network, and it is by paying attention to data's behavior within the network that we learn that while more data is desired by all, it is when data is mobilized in collective efforts that it becomes a powerful witness of environmental change.

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Paper 2

Strict Uncertainty: Ordering Ultrafine Particles Spatially via Google Street View Cars in Copenhagen

Haarløv, R. Strict Uncertainty: Ordering Ultrafine Particles Spatially via Google Street View Cars in Copenhagen
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Strict Uncertainty: Ordering Ultrafine Particles Spatially via Google Street View cars in Copenhagen

Abstract: In 2021, air pollution scientist launched a novel map of air pollution, detailing the spatial variation of ultrafine particle (UFP) formation. Based on mobile on the road measurements the Copenhagen Air View (CAV) map points toward a hitherto overlooked problem near Copenhagen Airport and along major highways. Drawing upon discussions of uncertainty, I first analyse the kind of uncertainty characterising this novel air pollution measurement method. I show how scientists conflate situations characterised by strict uncertainty with measurable uncertainty to establish annual average particle concentrations. In the absence of a scientific standard method for measuring UFP formation, I argue that the researchers behind CAV have constructed a new way of ordering UFPs spatially that is situated within no larger order. Then, I describe two cases in which citizen groups use the map to a) raise awareness about the health effects of being exposed to UFPs near Copenhagen Airport b) experiment with urban green designs. By integrating the concerns of citizens with scientific research practices, I argue that this new measurement method contributes to making one of the most uncertain problems in air pollution science a public problem.

Keywords: Uncertainty, Method, Air Pollution, Ultrafine Particles, Ordering, Issue

Introduction: measuring ultrafine particles via Google Street View cars

In 2021 the introduction of Copenhagen Air View (CAV), a new air quality map created by Utrecht University in collaboration with Google and Copenhagen Municipality, reinvigorated concerns over air pollution in Copenhagen, Denmark. Based on mobile street-by-street measurements conducted via a purpose-built Google Street View (GSV) car, the air quality map demonstrates that levels of pollution can be 'hyper local' in the sense that they can vary by as much as 800 percent within and between streets (Google Environmental Insights Explorer, 2023). The CAV approach to air pollution is interesting in numerous ways. First, it measures air pollutants along hitherto unexplored spatial dimensions focusing on pollutants on the roads of Copenhagen. Second, CAV enables users to zoom in and out of streets in an intuitive manner via a fine-grained, interactive platform to explore average pollution concentrations in the city. Third, it draws attention to key findings from the frontiers of research by focusing on ultrafine particles (UFPs), an emerging particle fraction suspected of being more harmful than larger particles (Schraufnagel, 2020). Just as Google is expanding its air pollution measurement operations across the globe through partnerships with research institutions and municipalities to grow its air pollution platform, this article scrutinizes the associated uncertainty of evoking UFPs in this manner.

To study the uncertainty associated with the CAV method, I draw upon insights from research on uncertainty. Scholars have increasingly turned their attention to this subject in recent years (as evidenced by the work of Beckert, 2016; Beckert & Bronk, 2018; Jasanoff, 2022; Kay & King, 2020; Scoones & Stirling, 2020; Stirling, 2023). These scholars have demonstrated that the concept of uncertainty is key to understanding diverse topics ranging from scientific policy advise, green transitions, economic futures and not least environmental risks. In contrast to the misleading perception that science can provide unambiguous answers about these complex topics, the scholars show why it is valuable to engage these issues in a more nuanced manner by focusing on different kinds and degrees of uncertainty. That is, by engaging uncertainty through narratives rather than quantification, they show that we can get a better understanding of the subject.

The vantage point for understanding the adverse health effects of air pollution is that experts can likely only quantified the tip of an iceberg and that the costs of diseases and premature deaths caused by pollution are rising rapidly (Landrigan et al., 2018, 468, 482). Since the establishment of $PM_{2.5}$ as a novel indicator and standard by the US Environmental Protection Agency in 1997 (Cao et al. 2013, 1201), air pollution researchers have debated which elements of the particle fraction cause the most harm to human health. Some researchers are pursuing the idea that black carbon (BC), a chemical substance of $PM_{2.5}$ produced by combustion processes, could be a leading health culprit that is causing several times more health damage than $PM_{2.5}$ (Jensen et al. 2021). Another popular scientific hypothesis suggests that ultrafine particles (UFPs or $PM_{0,1}$), which are likewise generated by combustion processes, may have greater potential in causing adverse health effects than their larger peers ($PM_{2.5}$) as their small size allow them to penetrate deeper into the lungs and onwards to other organs while potentially carrying large amounts of toxins (Schraufnagel, 2020). However, due to being associated with high technical uncertainty, there is no agreed upon international standard method for measuring UFPs. By the same token there are no threshold limits for this particle fraction in Europe. Against this backdrop knowledge about the spatial distribution of UFPs in urban environments can aid both epidemiologist and policymakers.

I demonstrate that air pollution researchers affiliated with the CAV method conflate situations characterised by strict uncertainty, what Hubbard (2020, 132-133) defines as situations where the probability associated with outcomes cannot be known, with situations where it can be known through calculation. That is, the researchers multiply single digit drives in each street segment with 100 to establish average annual UFP concentrations on the roads of Copenhagen. In the absence of a standard method and regulatory regime for rendering UFPs visible to the public, I argue that the CAV researchers have constructed a novel spatial ordering of UFPs which operates within no larger scientific order. Next, I describe how the CAV map has aided citizens groups in raising awareness about elevated UFPs concentrations near Copenhagen Airport and urban hotspots and discuss why the issue of air pollution rarely garners much attention in Denmark. Despite having had limited impact on urban planning initiatives within Copenhagen Municipality, I contend that the CAV map has nevertheless contributed to making UFPs a problem of the public by integrating citizen concerns with research efforts.

Method

This article takes a qualitative approach to studying air pollution in Copenhagen through 2020-2023. It is based on desk research, document analysis and interviews with fifteen air pollution scientists situated at different universities in Denmark, four environmental leaders working for the Municipality of Copenhagen and a spokesperson for a citizen group working to mitigate air pollution from Copenhagen Airport. First, I consulted newspaper articles and research reports to better understand the CAV network. Second, I interviewed the research participants on Teams and Zoom which lasted each approximately an hour. The scientists have expertise in different branches of air pollution modelling, including UFPs, atmospheric physics and epidemiology. The environmental leaders are experienced practitioners who have measured levels of UFPs in different neighbourhoods of Copenhagen for several years. The interviewees were selected based on their scientific knowledge of particle pollution and practical experience with conducting UFP measurements.

To study air pollution I lean against David Ribes' (2014) work on research infrastructures. Social scientists can study large-scale objects like air pollution by attending to how natural scientists scale a particular object (Ribes 2014). Akin to past ethnographic studies of centres of calculations (Latour 1987), this approach directs the attention of the researcher towards the technologies, methods and techniques deployed by actors to manage and know a particular object (Ribes 2014, 161). It encourages one to follow the actors and unpack the research network in situated practices. However, as COVID-19 lockdowns ruled out ethnographic research, the present study rather resembles Latours' work on microbes (Latour, 1993, 7) in the sense that I studied the CAV network remotely through online interviews and a series of texts from my combined home and office. Although largely sympathetic with the ANT tradition, I deviate from Latour's precept to 'just go on describing' (Latour 2007b). That is, I consider it necessary to draw upon concepts from related fields to enhance my understanding of the empirical obscurities I encountered in 'the field'. My approach therefore resembles 'interpretative descriptivism' (Krarup and Blok 2011) to the extent that I refold theory about 'uncertainty' into my ANT-informed account. The goal of this endeavour is not to silence the empirical voices, but rather to broaden the possibilities for understanding unfamiliar objects in the empirical material (ibid., 58).

Strict uncertainty and measurable uncertainty

This section proceeds to outline how the concept of uncertainty is treated within the social and natural sciences. When assessing the literature on uncertainty (Beckert, 1996; Best, 2008; Hubbard, 2020; Jasanoff, 2022; Knight, 2018; Mehta & Srivastava, 2020; Murphy, 2006; Wynne, 1992) it becomes evident that there is no universally agreed upon definition of the concept. Having said that it is possible to broadly distinguish between a social science perspective and a natural science perspective (Hubbard 2020).

Researchers trained in the technical and natural sciences typically advocate that uncertainty can be made knowable through calculative efforts (Aven 2014; 2019; Hubbard 2010; 2020). Invoking physicist Werner Heisenbergs's uncertainty principle, which quantified the velocity and position of a particle, Hubbard (2020, 110) argues that uncertainty refers to a condition that can be quantified and measured. This principle can be exemplified as follows, 'There is a 60 percent chance it will rain tomorrow and a 40 percent chance it won't.' That is, the 'measurement of uncertainty' refers to a situation in which a probability (60 percent) can be assigned to a possibility (it will rain) (ibid.). Having defined uncertainty as something that can be expressed in quantified probabilities, he proceeds to introduce the concept of 'strict uncertainty.' This concept refers to situations where possible outcomes have been identified but in which there is no possibility to establish probability for them. In other words, strict uncertainty, refers to a situation in which the associated uncertainty cannot be quantified (ibid., 132-133). This definition is close to Knight's version of uncertainty, as we shall see.

In contrast to natural scientists, researchers trained in STS and economic sociology are inclined to argue that uncertainty eludes reduction to quantifiable measures because of insufficient data. These scholars tend to subscribe to a version of uncertainty proposed by Frank Knight ([1921] 2018), who made a critical distinction between 'risk' and 'uncertainty,' also named measurable and unmeasurable uncertainty. In situations marked by 'risk' the distribution of an outcomes is discernible via statistical methods, aligning with the description of 'uncertainty' by Hubbard (2020) above; This contrasts with situations characterised by 'uncertainty' in which the uniqueness of a situation prevents actors from knowing the distribution of an outcome through calculation (ibid., 135-136). That is, uncertainty according to Knight is synonymous with unmeasurable uncertainty since there is no scientific foundation upon which to establish a degree of calculable probability (Kay and King 2020, 13). In other words, Knight's version of uncertainty is like Hubbard's definition of strict uncertainty. In the context of establishing environmental models under circumstances of Knightian uncertainty, researchers often rely on assumptions to construct computer simulations, the validity of which cannot be adequately determined according to van der Sluijs (2016, 160). Such practices typically involve a tendency to conflate uncertainty (in the Knightian sense) with risk, or pretending to know the probabilities when these are unknown (Scoones & Stirling 2020, 3), a key insight I return to below.

Taking the discussion of uncertainty to the realm of ANT, uncertainty is often located at the limits in scientific instruments. Foregrounding the role of instruments and settings in scientific knowledge production is a hallmark of science studies (e.g. Shapin 1988; Shapin and Schaffer 2017; Latour and Woolgar 1979; Latour 1983, 1987). Within this tradition Latour and colleagues have demonstrated how phenomena become knowable through transformation and amplification processes, whereby objects gain and lose specific properties to make them compatible with already-established centres of calculation (Latour 1999). The limits to scientific knowledge production, it is argued, are set by specific instruments (Latour and Woolgar 1979). The implication of these insights following Law (2009, 239) is that methods are not only techniques for *describing* reality but that methods actively *perform* reality in the sense that knowledge practices tend to enact realities in addition to describing them. A consequence of this is that it cannot be assumed that methods are purely technical and agenda-free. Rather they operate in ways which make certain political arrangements more likely and more real while simultaneously eroding other realities, making them less probable (Law 2004, 149). Following this line of thinking the most interesting objects of study lie at the boundary between order and disorder, where alternative orders produced by methods rub against one another (Law 2008, 144).

In summary, this section has shown how the issue of uncertainty is treated differently in the natural and social sciences. Whereas natural scientists subscribe to the view that uncertainty can be quantified, social scientists usually agree that situations characterised by uncertainty are unquantifiable due to lack of data. In the ANT tradition uncertainty is located at the edge of scientific instruments and methods perform reality in ways that have political consequences.

Conflating strict uncertainty with measurable uncertainty

> It is almost impossible to put a number on it [the variability of the measurements]
> - air pollution researcher

In the European Union member states are required to conduct measurements of air pollutants in accordance with specific standards (European Commission 2019). This involves using fixed routine monitoring stations to measure classical pollutants ($PM_{2.5}$, NO_2, O_3, etc.) on sidewalks against specific threshold limits as outlined by the Ambient Air Quality Directive set by the EU. The strength of monitoring stations is that they can capture long temporal variations of air pollution and provide policymakers with insights on annual average concentrations over time. Measuring pollutants via this approach represents the incumbent measurement standard and such measurements are not only used to oversee threshold limits but are also being deployed in epidemiological research to estimate adverse health costs. The weakness of fixed monitoring stations is meanwhile that they cannot provide insights on the spatial variation of urban emissions very well (Kerckhoffs et al. 2022, 1). Traffic related pollution is for instance highly variable within and between streets which is difficult to assess via fixed monitoring stations. To capture the spatial variation of urban emissions, researchers have developed new measurement methods based on mobile sensing, an approach that has gained increased traction in recent years (Apte et al. 2017; Hankey and Marshall 2015; Hasenfratzet al. 2015; Hatzopoulou et al. 2017; Kerckhoffs et al. 2021 in Kerckhoffs et al., 2022, 1). The Copenhagen Air View project represents exactly this methodological turn to mobile measurements in air pollution science. The CAV project does not necessarily challenge the incumbent way of measuring pollutants via fixed monitoring stations; it rather complements such measurements with new insights.

The CAV project was set in motion via a partnership between Utrecht University, Google and Copenhagen Municipality in collaboration with research colleagues from Aarhus University's (AU) Centre for Environment and Energy. Together with Amsterdam, Copenhagen represents one of the first cities where GSV cars have been deployed to measure UFPs on the roads. In line with Google's ambition to expand the program to more cities, it recently announced new partnerships with city councils in Dublin, Ireland, Hamburg, Germany and Bengaluru, India (Google Earth Outreach 2023). To better understand the associated uncertainty of this method, I analyse how GSV cars are measuring UFPs in Copenhagen. To generate the CAV map, researchers use a so-called mixed-model approach, which involves three steps. First, the scientists at Utrecht University equip a GSV car with mobile sensing equipment to measure the air pollution substances: UFPs, black carbon (BC) and nitrogen dioxide (NO_2) through Nov. 2018 – Feb. 2020. Measurements were stopped abruptly in March 2020 due to the Covid-19 pandemic. The second step involves applying a land-use regression model developed by researchers at Utrecht University. This model utilises a number of geographical variables including traffic intensity, road lengths, building heights and land-use data such as population density, industry and green vegetation (Ellermann et al. 2021, 12). In the third step, measurements and model calculations are merged to design the final map. Average daytime street-by-street measurements can be explored via a user-friendly desktop interface (see figure 1. Below) (Google Environmental Insights Explorer, 2023).

Considering the level of uncertainty in the observed measurements, the mixed-model approach weighs either the land-use regression model or the statistical aggregation of measurements in a particular road segment more heavily, a lead researcher explains. The total number of drives conducted by the GSV car for each street segment (divided into 50 meters) amounts to on average seven unique drives with fewer drives on smaller roads and more frequent drives on larger roads (Kerckhoffs et al. 2022, 3). The typical measurement duration in each street segment ranges from 30 seconds to a few minutes (Ellermann et al. 2021, 11). Depending on the road segment, a fundamental risk in the data set thus consists in having conducted measurements behind a truck or high emitting vehicle for the same road segment several times, which may inflate average values. As one of the involved researchers notes, 'you measure only 10 seconds on every road and that for 6 or 7 times […] and that is off course less accurate than measurements for a full year' referring to measurements conducted by fixed monitoring stations. The situations researchers measure, in other words, resemble strict uncertainty to follow Hubbard (2020, 132–133) in the sense that while possible outcomes have been identified it is not possible to assign any degrees of probability to those outcomes.

To remedy the small number of drives, researchers multiply the mean value of the 6-7 drives in each street segment with 100 to establish percentages for the variability of UFP concentrations (Kerckhoffs et al. 2022, 4). That is, while the researchers have identified possible variations in UFP measurements for each street segment, they cannot establish a degree of measurable uncertainty associated with them without artificially multiplying the street segments mean value with 100. Drawing upon Knight (2018), this procedure resembles conflating situations characterised by being unique which are associated with unmeasurable uncertainty with situations that can determined by statistics or probability which are associated with measurable uncertainty. In other words, the conflation occurs when the mean values of the few drives in each street segment are turned into statistical entities through the multiplication of 100 to create percentage values. This helps explain, why the CAV lead researcher, as highlighted above, suggests that it is nearly impossible to put a number on the variability of the measurements. By the same token, research partners from AU characterise the CAV measurement campaign as a kind of 'snapshot' of the pollution concentrations through 2018-2020 (Ellermann et al. 2021), alluding to the short measurement duration in each street segment which prevents CAV researchers from knowing annual average concentrations of UFPs with a degree of probability.

In summary to establish annual average concentrations of UFPs in the streets of Copenhagen, CAV researchers deliberately conflate situations characterised by strict uncertainty with situations that can be determined with a degree of probability. This process involves turning a few drives in each street segment into hundreds of drives through the introduction a calculative exercise to establish percentage values. In the following I proceed to examine the technical challenges facing researchers when such measurements are compared to measurements conducted via routine measurement stations.

Incommensurable measurements at the limits of scientific knowledge production

Moving from the strict uncertainty associated with mobile measurements to counting particles in accordance with the definition of UFPs, one researcher explains the technical difficulties researchers are facing, which is worth quoting at length:

> The difficulty with Google's measurement is that it's really challenging to measure particles. It's really hard to measure them, even if you're at a stationary measuring station with some of the best equipment you have, and you know what you're doing, and you're accredited, and you quality control – basically, it's damn hard, especially ultrafine particles. The smaller they get, the worse it is because they settle in the machine's inlet, they stick to the surface, it's extremely difficult to control. Ultrafine particles are not something you can analyse in terms of composition. You have to count the number. The Detection limit is typically 7 nanometres (nm). However, most instruments don't do a decent job under 30nm, but the majority of the small particles are under 40nm. So, if you don't do it right down there, you don't get it all. It requires intense calibration, and, well, those who work with this around Europe, they have years-long series of measurements and they're still working on getting it right.
>
> - Air pollution researcher

Conducting measurements of UFPs is not new in Denmark, as the researcher alludes to above. The CAV research partners from Aarhus University have conducted routine measurements of UFPs at three locations. Measurements have been conducted since 2001 via fixed monitoring stations at an urban sidewalk & urban background location in Copenhagen and at a rural background location 30km west of Copenhagen resulting in one of the longest data sets for UFPs in the world (Ketzel et al., 2021, 6). These monitoring stations count particles ranging in size from 41nm to 480nm (Ellermann et al., 2021, 11). These measurements contrast with the mobile measurement instrument attached to the Google Street view car which has counted particles down to 7nm and includes particles with a diameter well above 100nm and no specification on the upper size limit of the device (Ellermann et al., 2021, 11; TSI, 2023). Leaning against Law (2008, 144-145) these technical translation processes involve a degree of betrayal in the sense that particles way above 100nm get to count as 'UFP'. That is both measurement methods count heterogeneously sized particles which do not strictly follow the definition of ultrafine particles (less than 100nm). The two methods, in other words, produce alternative orders that rub against one another (ibid.). Acknowledging these technical limitations, researchers prefer to speak of 'quasi-ultrafine particles' or 'particle numbers' instead of ultrafine particles. In other words, the limits to scientific knowledge production are set by these measurement instruments (Latour and Woolgar 1979), which cannot adhere to the definition of UFPs. In what follows 'UFP' refers to number concentrations of quasi-ultrafine particles.

Even though the two measurement methods are incommensurable due to having counted particles in different locations with different instruments, the research partners from Aarhus University have nevertheless compared the CAV measurements to their own measurements. The side by side comparison of on the road measurements via GSV cars and sidewalk measurements via monitoring stations is rather striking: the GSV measurements are on average twice as high as sidewalk measurements taking their different measurement approaches into consideration (Ellermann et al., 2021, 5). These findings resonate with a short term study of UFPs conducted via bicycles in Copenhagen where UFPs were measured in the breathing zone of bicyclists during rush-hours (Bergmann et al. 2022). Drawing upon Law (2008, 146), the CAV method has arguably facilitated a new way of ordering UFPs that is operating within no larger overall scientific consensus order, as there is no international or national standard method for measuring UFPs (World Health Organization, 2021, 152). UFPs are likewise not covered by any regulatory regime setting specific threshold limits. In other words, by measuring UFPs on the roads, the CAV method has constructed a new spatial reality of air pollution that has hitherto been invisible to citizens of Copenhagen. However, these efforts are incompatible with already-established centres of calculation (Latour 1999) because annual threshold limits must be measured against routine monitoring stations as defined by the EU. Despite the obvious challenges in terms of measuring UFPs, the CAV method presents a new map of ultrafine particles that is pointing towards a hitherto overlooked problem, namely that urban commuters are exposed to significantly higher levels of pollution than previously believed.

In summary, the two measurement methods based on routine monitoring stations and the Google Street View car have produced alternative ways of ordering UFPs that rub against each other temporally, spatially and technically speaking as they measure UFPs with different devices in different locations. In contrast to measuring UFPs via routine monitoring stations in accordance with the incumbent regulatory regime, the CAV method has arguably produced a novel spatial ordering of UFPs that is positioned within no larger scientific order.

Energising the public through a novel scientific order

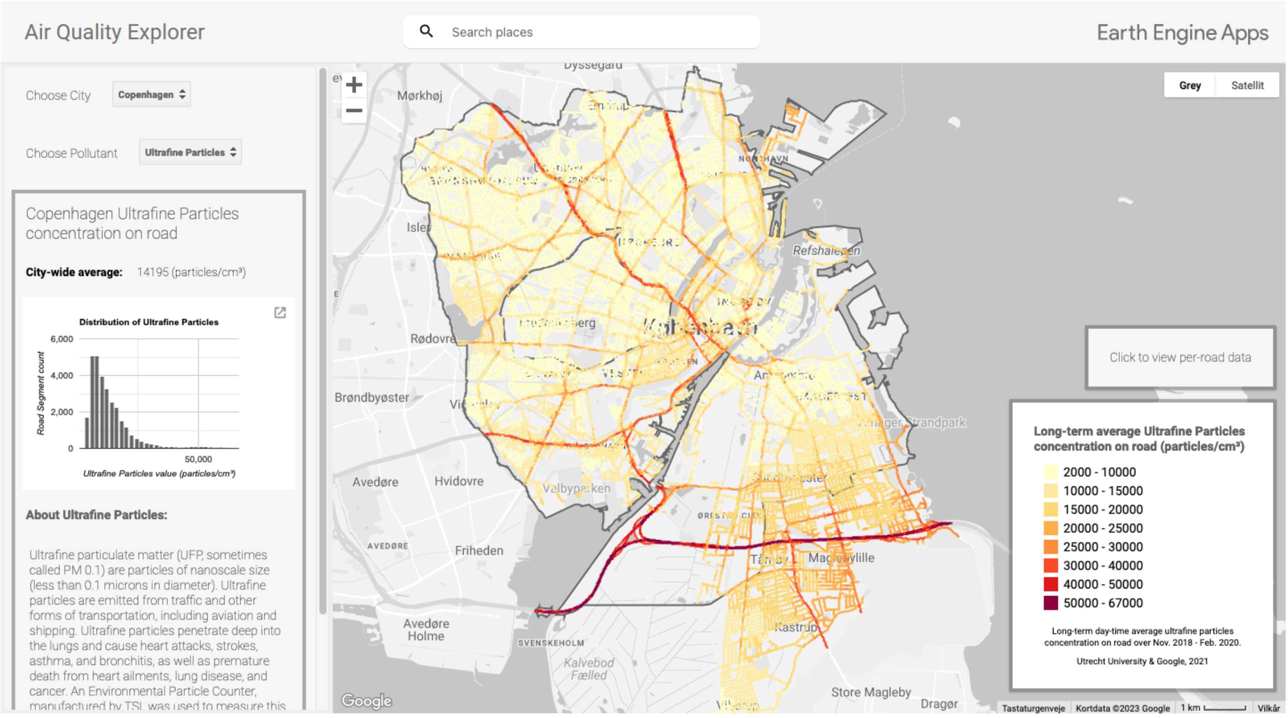

Figure 1. Copenhagen Air View

In STS science is often considered to be inherently political (Jasanoff, 1990; Latour, 2007b) and tied to how concerned groups get mobilized by uncertain knowledge which overflows incumbent regulatory regimes (Akrich and Rabeharisoa 2021; Callon 1998; Callon and Rabeharisoa 2008; Epstein 1995). Inspired by this tradition and the performativity thesis (Law 2004), this section proceeds to describe how the CAV map has aided concerned citizens in Copenhagen.

As a prerequisite for doing this, it is useful to first examine how UFPs are being ordered in the CAV map. The CAV map renders concentrations of UFPs visible through colours ranging from light yellow in smaller streets (2000-10,000 particles/cm3) to dark red along major highways (50,000-67,000 particles/cm3), see Figure 1. above. Rather than trumpeting accuracy, it visualises UFPs through different interval ranges. Using the streets of Copenhagen as background framework it demonstrates that levels of UFPs are especially high on the roads of major highways and in the neighbourhoods situated near Copenhagen Airport (which occupies the lower right corner of the map). The long-term on the road average value for UFPs in Copenhagen amounts to 9,600 particles/cm3 (Kerckhoffs et al. 2022, 4), a figure that is associated with strict uncertainty, as demonstrated above. Despite the lack of a standard method to measure UFPs, the World Health Organisation (WHO) nevertheless provides practical advice to national and regional authorities on how to distinguish between high and low particle number concentrations. Low concentrations can be considered <1000 particles/cm3 (24-hour mean), whereas high concentrations can be considered >10,000 particles/cm3 (24-hour mean). However, as the CAV method has measured long-term *daytime* average and not 24-hour mean concentrations as recommended by the WHO, it cannot be measured against the WHO practical advice.

In contrast to how colleagues overseeing the national air pollution surveillance program at Aarhus University render UFPs visible in the 'the Air on Your Street' map,[1] which was launched a few months after the introduction of CAV map, the perhaps most striking feature of the CAV map is that it shows increasing levels of UFPs near Copenhagen Airport. That is, the CAV method includes aircraft emissions which are dominated by particles in the size range 10nm – 20nm (Stacey 2019, 474), in contrast to 'the Air on Your Street' map which is based on the routine monitoring stations that count particles above 41nm (Ellermann et al., 2021, 25). Ascending and descending aircraft typically impact adjacent neighbourhoods downwind and up to 20 km (Hudda et al. 2020), which is especially pertinent for Copenhagen, whose city centre is situated only eight km from Copenhagen Airport. UFPs from aviation typically mix with UFPs from surrounding road traffic making it difficult to separate the two sources (He et al. 2020, 2) but the impact of aviation emissions on near-airport residential air quality is substantial and studies have generally found elevated pollution concentrations in residential areas downwind of major airports (Hudda et al. 2020; Stacey, 2019). As a result of how the CAV map renders UFPs visible near the airport, it has been endorsed by a vocal citizen group called 'CPH without Expansion' (CPH-UU) that is attempting to thwart a proposed expansion of Copenhagen Airport. To counter the expansion, the CPH-UU has deployed the CAV map in public debates to raise awareness about the likely health effects of being exposed to high levels of UFPs (CPH without Expansion 2021).

Building upon the insights of the CAV map, a different group of citizens decided to explore urban design solutions to mitigate pollution from road traffic. Under the banner 'Thrive Zone Amager' this project was launched by a local environmental committee in Amager, Copenhagen in collaboration with the urban design consultancy Gehl. The goal of this project was to build green design installations to shield citizens from high levels of air pollution near major roads. After having consulted citizens in the neighbourhood, the consultancy constructed a green fence next to a playground and two domes decorated with green vegetation along a bus stop and in an open park[2]. While the air pollution reducing effects of such design installations are questionable and limited, it is safe to say that green infrastructure like trees, shrubs and other vegetation can operate as passive reducers of air pollutants, as the vegetation generally improves air quality through dispersion and deposition mechanisms (Barwise & Kumar, 2020; Kumar et al. 2019). Unsurprised by the findings of the CAV method, my interlocutors emphasise that the air quality map has confirmed their suspicion about elevated levels of UFPs along major highways and near the airport. Several of my interlocutors in turn characterise the CAV map as a compelling 'awareness raising tool' which not only speaks to their concerns of elevated pollution levels but likewise offers a compelling platform for exploring street level concentrations of UFPs. The 'Thrive Zone Amager' project, in summary, encourages the deployment of green vegetation to reduce levels of street pollution.

While the two cases mentioned above, on the one hand, show how citizen groups have used the map to raise awareness about air pollution, it is, on the other hand, striking how little impact the map has had on urban planning. Even though the map consistently shows that schools, kindergartens and elderly homes are situated unfavourably close to major pollution hotspots, the Municipality of Copenhagen has to my knowledge not utilised the CAV tool to set in motion new urban planning initiatives. A project lead from Copenhagen Municipality involved in the CAV project highlighted to me in an interview that despite the ambition of the municipality to use data driven

[1] http://lpdv.spatialsuite.dk/spatialmap

[2] https://iclei-europe.org/fileadmin/user_upload/Action_Fund/Resources/Thrive-Zone-Amager_Urban-Design-Booklet_Gehl_Final-4_compressed.pdf

solutions across the organisation (Copenhagen Solutions Lab 2021), the insights of the CAV project are still not being operationalised within the organisation for unknown reasons. In summary, while the CAV map has been useful to some citizen groups in Copenhagen, it is surprising how little impact it has had on urban planning initiatives within the municipality.

Discussion: from a national non-issue to a local concern

Building upon the analysis above, it should be clear that the science of air pollution science cannot be separated from politics, as Jasanoff (1990) pointed out long ago. In contrast to the incumbent air pollution method which measures particles above 41nm, my analysis of how the CAV method measures the spatial variation of UFPs down to 7nm demonstrates that this method has contributed to make UFP pollution a local issue in Copenhagen. However, to better understand the impact and limitations of the CAV map in terms of energising the public, I discuss how the issue of air pollution has broadly evolved in recent years in Denmark.

More than 50 years ago, political scientist Matthew Crenson (1971) famously labelled air pollution a 'non-issue' in American cities which continuously failed to rise to the surface of politics. He speculated that the failure of an issue to emerge in the political domain may be an indicator that there simply is not enough discontent about the subject or that although dissatisfaction exists, citizens are failing to register their complaints with political leaders (ibid., p. 5). This description of air pollution as a 'non-issue' is – in my view - surprisingly apt at the national level in the Danish Parliament, where the issue is rarely discussed. The exception being occasional local debates in Copenhagen about nuisances related to wood stove emissions or transgressions of EU threshold limits concerning nitrogen dioxide (NO_2) (Bruun 2022; Persson 2018). That is, the issue of air pollution has arguably been overshadowed by other crisis in recent years, including the COVID-19 pandemic, the ecological and climate crises despite its deep entanglement with each of them. Another reason why the issue has likely failed to gain significant political traction is that the issue is being framed and measured against EU threshold limits. These lax threshold limits allow EU countries to emit twice as much pollution for key pollutants ($PM_{2.5}$, NO_2) compared to WHO recommendations (World Health Organization 2021). The fact air pollution has hitherto mostly been framed as a regional phenomenon via the $PM_{2.5}$ indicator in accordance with EU directives - which suggests that about 70-80 percent of air pollution in Denmark originates from neighbouring countries (Ellermann et al., 2022, 12) - has likely contributed to give concerned citizens the impression that this issue can only be dealt with at an international level.

However, with the introduction of CAV, air pollution becomes framed as an urban and local issue via the UFP indicator in a way that speaks more to the concerns of citizens in Copenhagen. By focusing on the spatial and local variability of two emerging indicators (UFP and BC both of which are suspected of being significantly more harmful than incumbent types of pollutants), the CAV method has arguably integrated the concerns of citizens with the interests of researchers working at the frontiers of scientific knowledge production. Instead of focusing on classical types of pollutants ($PM_{2.5}$, etc.) which resemble 'matters of fact' in Latour's (2005) jargon and are measured against existing regulatory frameworks, the CAV method has made the citizens 'matters of concern' (UFPs) their focal point. Leaning against the pragmatist tradition (Dewey, [1927] 2012), the CAV method has arguably taken one of one the most uncertain and confusing research topics in air pollution science and made it the public's problem (Lippmann in Latour 2007a, 4-5). That is, instead of measuring classical pollutants in the absence of any public issue, the CAV method has developed tools and methods to follow the objects that concern citizens (Latour 2007a, 4), which overflow the boundaries of the incumbent regulatory regime (European Environment Agency 2021). In other words, to grasp the object of concern raised by citizens for many years, the CAV method has focused on the spatial variability of on the road UFP formation near Copenhagen Airport and major highways.

The benefit of providing public officials and concerned groups with a diverse set of scientific perspectives on local air pollution formation (UFP; BC; NO_2) is that it expands their options for dealing with the problem. A powerful role for science in society is thus to facilitate the creation of innovative new policies (Pielke 2007), as scientific alternatives have the potential to shake up politics and, in some cases, enable novels forms of action. While it remains an open question whether the CAV method is going to enable new courses of action within Copenhagen Municipality with regards to urban planning initiatives, the CAV method has nevertheless contributed to make urban air pollution, and local UFP formation in particular, a public concern in Copenhagen.

Conclusion

In this article I have analysed the degree of uncertainty that is associated with measurements of UFPs conducted via the CAV method. First, I have demonstrated how the involved scientists conflate situations characterised by strict uncertainty (Hubbard 2020) with situations characterised by measurable uncertainty to construct annual average values of on the road UFP concentrations. They do this by deliberately multiplying few measurements in each street segment with 100 to establish percentage values, leading to the marginalisation of strict uncertainty. That is, the strict uncertainty associated with the average daytime annual UFP emissions estimate is not acknowledged to the public. Despite being associated with strict uncertainty, the CAV map has nevertheless been deployed among concerned citizens as an awareness and urban design tool to point towards a hitherto overlooked problem in the streets of Copenhagen. Against the backdrop of a lacking standard method for measuring UFPs, I argue that the CAV method produces a new spatial order of UFP formation that is situated within no larger scientific order (Law 2008, 146). In doing so the CAV method exposes significant limitations intrinsic to the incumbent measurement regime based on routine monitoring stations while pointing toward a hitherto overlooked problem on the roads. By counting UFPs down to the size of aviation emissions (10-20nm), the CAV method has integrated public concerns which scientific concerns and thereby contributed to making one of the most difficult research topics in air pollution science a public problem.

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Paper 3
Framed Uncertainty: Making Sense of Residential Wood Stove Emissions in Denmark

Haarløv, R & Bille, M. Making Sense of Residential Wood Stove Emissions in Denmark
In review in Science and Technology Studies

Framed Uncertainty: Making Sense of Residential Wood Stove Emissions in Denmark

Abstract
Residential wood stoves are often highlighted as the worst pollution source of $PM_{2.5}$ air pollution in Denmark, accounting for 52 percent of national emissions. This unambiguous number implies accuracy, and that researchers *know* how much $PM_{2.5}$ pollution can be attributed to residential wood stoves with precision. But we demonstrate in this article that emissions from wood stoves are notoriously uncertain and key parameters largely unknown. While the problem of wood stove emissions is often tied to the stove itself, this article illuminates the socio-technical assemblage surrounding wood stoves as an often overlooked aspect. Drawing upon discussions of uncertainty, we first show how knowledge about the socio-technical assemblage is constructed based on assumptions that emerge from domains of imperceptibility. Second, we argue that kindling practices can be understood as a kind of uncertainty which cannot be known with any degree of probability. To make better sense of wood stove emissions in public policy, we propose a 'framed uncertainty' lens to highlight the particular kind of uncertainty associated with key parameters in the socio-technical wood stove assemblage. Finally, we discuss the implications of changing the policy frame towards the socio-technical assemblage surrounding wood stoves in terms of reducing emissions.

Keywords: residential wood stoves, uncertainty, emissions, socio-technical assemblage, air pollution

Introduction

Air pollution researchers in Denmark claimed that residential wood stoves accounted for 52 percent of the $PM_{2.5}$ air pollution emitted in Denmark in 2019. This makes wood stoves by far the largest source of national particle pollution that is mostly associated with adverse health effects (Ellermann et al., 2022: 70). $PM_{2.5}$ pollution from wood stoves is often translated into absolute numbers regarding premature deaths and associated adverse health costs: 280 deaths and \$0,7B, in 2020 (ibid.). Journalists and pundits often use these numbers as a springboard for either shaming wood stove users, enforcing higher wood taxes, or calling for a total ban (Ankerstjerne, 2022). The detractors, in other words, appear to know exactly how much $PM_{2.5}$ pollution can be attributed to residential wood stoves, communicating accurate and unambiguous numbers (Funtowicz and Ravetz, 1990: 83–84). Emissions from wood stoves are, however, notoriously uncertain, and key parameters impacting emissions are largely unknown, we argue. In addition, 79% of the total air pollution in Denmark presumably originates from foreign sources beyond Danish borders, which means that Danish wood stove emissions actually only account for 6% of the total pollution in Denmark (Ellermann et al., 2022: 13). While the problem of wood stove emissions is typically tied solely to the appliance technology – the wood burning stove – this article examines wood stoves as a socio-technical assemblage – an aspect that is often overlooked in public debates, rendering the level of certainty less pronounced. This assemblage includes kindling and refilling practices – such as the size and quality of the pieces of wood loaded, as well as how full the chamber is made compared to its capacity – and ambient air conditions, both indoors and outdoors. It is vital to know these parameters when trying to make sense of wood stove emissions.

To shed light upon these largely unknown parameters we take inspiration from a recent upsurge in discussions of uncertainty (Beckert and Bronk, 2018; Hubbard, 2020; Jasanoff, 2018, 2022; Mehta and Srivastava, 2020; Scoones and Stirling, 2020; Stirling, 2023; van der Sluijs, 2016). Particularly within STS, economics, and sociology, the work demonstrates how our contemporary epistemic situation is defined as much by what is not known as by what is known. Rather than downplaying knowledge that is not known with certainty, this emerging body of work powerfully demonstrates how issues ranging from environmental hazards to economic futures and bureaucratic practices are shaped by different kinds of uncertainty. While uncertainty is particularly consequential at the science policy level (Jasanoff, 2022) this article focuses on those parameters in the residential wood stove emissions model that are least known.

We demonstrate that assumptions and uncertainties associated with kindling practices and socio-technical wood stove assemblages are particularly dominant phenomena in the subfield of air pollution modelling concerning residential wood stove emissions. To make better sense of residential wood stove emissions in public policy, we propose a 'framed uncertainty' approach to communicating estimates. Inspired by Jasanoff (2005) and Knight ([1921] 2018), this notion draws attention to the socio-technical assemblage surrounding wood stoves and the policy implications of the information that is unmeasurable, and that lies at the boundary of what is known and not known. To do this, we initially outline how the 'uncertainty' entails several gradations, or degrees, of certainty. We argue that average emission estimates are based on assumptions emerging from imperceptible domains, which are located beyond the reach of contemporary measurement regimes (Murphy, 2006). We then demonstrate how kindling practices can be understood as a kind of uncertainty which cannot be known with any kind of realistic probability (Knight, 2018). We conclude by discussing the public policy implications of our findings in relation to the unambiguous numbers highlighted above as well as the advantages of using the notion 'framed uncertainty' to make sense of emission estimates.

Method

To study how natural scientist produce wood stove emission estimates, we first consulted written material such as newspaper articles and policy documents to understand how the problem of wood stove emissions is being problematized in public discussions by different stakeholders. Second, we conducted semi-structured online interviews through 2020 – 2022 with a chimney sweep and 15 senior air pollution researchers. The interviews lasted approximately one hour each and were conducted mostly online via Teams or Zoom while Denmark was in different stages of lockdown during the COVID-19 pandemic. The researchers have expertise in different branches of air pollution modelling related to wood stove emissions, including emissions accounting and epidemiology. The researchers were selected as they contribute with different insights to the complex modelling process of estimating wood stove emissions. This also accounts for Danish chimney sweeps who provide key data to the researchers. The interviews enabled us to understand that key parameters surrounding the socio-technical wood stove assemblage are associated with different magnitudes of uncertainty. We have subscribed to the research ethics protocol for collecting data with human respondents as outlined by the American Anthropological Association (2023) and follow the General Data Protection Regulation (GPDR) and the Danish Code of Conduct for Research Integrity, including anonymizing all informants (Ministry of Higher Education and Science, 2014).

Coping with unmeasurable uncertainty

Research on uncertainty has grown substantially within STS, economic sociology and economics (Beckert and Bronk, 2018; Best, 2008; Callon et al., 2009; Doganova, 2018; Haldane, 2018; Jasanoff, 2022; Kay and King, 2020; Pindyck, 2022; Tanzi, 2022; van der Sluijs, 2017). These scholars have demonstrated how the notion of uncertainty is essential for understanding contemporary issues like economic modelling and discounting, scientific policy advising and not least urgent environmental problems. To better understand how the question of uncertainty is being accounted for in the emission model for residential wood stoves, we draw upon the work of economist Frank Knight ([1921] 2018) and STS scholars Sheila Jasanoff (2005, 2018, 2022) and Michelle Murphy (2006). First, we outline the distinction between measurable and unmeasurable uncertainty as proposed by Knight (2018), which is underappreciated not only in mainstream economics but also in the analytical capacities of modern states (Jasanoff, 2012). Then we show why knowledge associated with unmeasurable uncertainty is typically located in domains of imperceptibility (Murphy, 2006).

When assessing the literature on uncertainty across disciplines we find numerous interpretations of the concept and no agreed upon definition. However, learning from Hubbard (2020), we can generally distinguish between a natural science version and a social science version of uncertainty. Whereas scholars trained in the natural and technical sciences tend to subscribe to the view that uncertainty ought to be rendered knowable through calculative endeavours (Aven, 2014, 2019; Hubbard, 2010, 2020), researchers trained in STS and social science tend to subscribe to the view that uncertainties often cannot be reduced to quantifiable measures due to inadequate knowledge. The latter argue that topics associated with high uncertainty are often being mistakenly reduced to unambiguous quantitative measures across a variety of disciplines ranging from climate and disease modelling to finance and macro-economics (Beckert and Bronk, 2018; Jasanoff, 2022; Kay and King, 2020; Scoones and Stirling, 2020; Stirling, 2023). Rather than invoking precision when such knowledge in unobtainable in practice, these scholars suggest that public policy could benefit from a much stronger acknowledgement of uncertainty. In agreement with the social scientists, this article demonstrates why key parameters of the socio-technical wood stove assemblage are indeed unquantifiable due to insufficient knowledge and lack of data.

The most useful definition of uncertainty for our purpose, was developed by economist Frank Knight, who distinguished between 'risk' and 'uncertainty' or what he also calls *measurable* and *unmeasurable* uncertainty. In a situation characterized by 'measurable uncertainty' the distribution of an outcome is known through either statistics or calculation, what is commonly understood by the term 'risk.' In a situation characterized by 'unmeasurable uncertainty,' on the other hand, Knight argues that it is impossible to form a group of instances, because the situations being dealt with are in a high degree unique (2018: 233). Situations characterized by being unique are, in other words, associated with unmeasurable uncertainty because there is no scientific basis on which to form any calculable probability (Kay and King 2020:13). Only the heroic entrepreneur could steer his business through situations characterized by uncertainty, Knight suggested - and this led him to point out that radical uncertainty gives opportunity for entrepreneurship, which has since been key to understanding economic, technological, and social progress (Kay and King, 2020). Knight's contemporary, John Maynard Keynes (1921), defining uncertainty along similar lines, homes in on situations where probability 'is unknown to us through our lack of skill in arguing from given evidence' (Keynes in Beckert, 1996: 808). This, he adds, is when the evidence 'justifies a certain degree of knowledge, but the weakness of our reasoning power prevents our knowing what the degree is.' (ibid.). Knight's definition of 'uncertainty' has been criticized for going against the natural science understanding of this term, where 'uncertainty' is thought to be an issue which can be determined numerically through a set of probabilities assigned to a set of possibilities (Hubbard 2020:110). However, despite this criticism and lack of agreement between the natural and social sciences concerning the term, we find Knight's insights concerning unmeasurable uncertainty as the condition of incalculable probability, particularly apt for our purposes as we demonstrate below.

The conflation of risk and uncertainty is problematic for several reasons and yet particularly prominent in what Jasanoff (2012: 178) calls the analytic capacity of modern states, or 'technologies of hubris.' These technologies include cost-benefit analyses, climate models and risk assessments – all deployed by governments to manage areas characterized by high uncertainty in the Knightian sense. Although such modelling systems obtain their authority through disciplined approaches to analysis combined with claims of objectivity, they suffer from several deficiencies, especially regarding uncertainty and ambiguity. First, they downplay whatever falls outside their techno-scientific frame and second, they overstate whatever falls within (ibid.). The remedy, according to Jasanoff (2018: 13), is to complement 'technologies of hubris' with 'technologies of humility.' This framework revolves around foregrounding uncertainties and asking whether a problem needs to be reframed considering high uncertainties. Since uncertainties are particularly consequential at the science-policy intersection, public policy could profit from a much more thorough and genuine acknowledgment of uncertainty, she argues (Jasanoff, 2022).

While Knight and Jasanoff highlight that uncertainty is associated with a condition of incalculable probability (former) and largely ignored by the analytical capacity of modern states (latter), we also need to make sense of the phenomenon spatially. To better understand where uncertainty is located spatially in the context of modelling residential wood stove emissions, we draw upon Michelle Murphy's influential work. In her study of the 'sick building syndrome,' Murphy (2006: 9) takes the discussion of uncertainty to indoor environments and locates it in 'domains of imperceptibility,' where the subjects and objects of scientific research are rendered 'measurable, quantifiable, assessable, and knowable in some ways and *not others*'. Examining the history of how certain objects become knowable, Murphy demonstrates how this process is intrinsically tied to how other objects come not to exist, or come to exist only partially, with uncertainty or ignorance. This is what Murphy calls 'domains of imperceptibility.' In her case, chemical exposures from buildings were linked to the tangible practices of how lay people and scientists decided to render specific chemical objects such as particles knowable in specific locations and *not others* (ibid.). We use this notion to illuminate how *assumptions* in the emission model emerge from processes of establishing knowledge from domains of imperceptibility.

Before demonstrating how the distinction between measurable and unmeasurable uncertainty is neglected in the wood stove emission model, we examine how assumptions about key parameters emerge from unknown domains such as domestic house practices.

Constructing numerical assumptions based on imperceptible domains

In this section, we examine the key uncertainties researchers are facing in their daily work concerning the production of residential wood stove estimates in Denmark. The role of uncertainty as well as the nature of the scientific assignment at hand was mostly clearly articulated by an air pollution researcher: 'The task is to produce an emission estimate which represents the reality in the best possible way. That is incredible hard because of all the uncertainties. But that is nonetheless what we must deliver. That is the task [given by public officials].' In other words, the goal is to offer a number. An estimate, but nonetheless a number. Each year, air pollution researchers thus calculate the amount of $PM_{2.5}$ pollution that is being emitted by residential wood stoves in Denmark to comply with the Convention on Long-Range Transboundary Air Pollution (Nielsen et al., 2021). The preferred method for measuring particulate matter (PM) emissions factors from different types of residential wood stoves is called the 'dilution tunnel' method. Here, using a dilution tunnel about a meter from the chimney, the number of condensable particles from smoke gases are measured as they cool down. This method, used mainly in Norway and Denmark, contrasts with approaches – such as the European standard (EN13240) – that measure particles directly in the hot smoke gases within the chimney (Nielsen et al., 2021) without reference to condensable particles. A researcher interviewed said that the results garnered by the two methods can vary by anything from factor 2.5 to factor 10. The implication of this variance is that a country like Germany, for example, seems to have much lower emissions compared to Denmark, when in reality, because their methods are so different, their results are incommensurable, the researcher elaborates. Yet even though air pollution researchers clearly acknowledge the high uncertainties associated with the different measurement methods, they do not specify the magnitude of uncertainty that is associated with them in the emission model (Nielsen et al., 2021).

Residential wood stoves are as diffuse a source of emissions as cars. Yet, the official data inventory for personal vehicles is much more comprehensive, accurate and elaborate due to political attention on road traffic across several decades. Most countries require that road vehicles are registered via license plates. Interested parties can thus look up key features of any vehicle in the Danish vehicle registration database such as how large the motor is, what tires are equipped, how far it drives per litre of gasoline, roughly how far it has driven in total, which filter is attached to the vehicle following Euronorm standards. For the residential wood stove sector, equally important data is either absent or must be pieced together from disparate sources, such as sample studies, laboratory measurements, and, not least, assumptions.

In an interview, an air pollution researcher compares wood stoves with powerplants to show how difficult they are to make sense of:

> The unfortunate thing about residential wood stoves is that emissions will always remain uncertain by nature because we are talking about, you know, a thing that is situated in the living rooms of people. One thing is a powerplant, which has one chimney. It is super easy to measure. But we have 700.000 residential wood stoves, and of course it is not realistic to measure emissions from these appliances all the time. […] There is uncertainty regarding how many old stoves are there, how many new stoves are there, and how much firewood is being consumed in the old compared to the new ones. The implication is that there are many assumptions [in the model], all of which are uncertain.

While researchers are unable to measure emissions directly from Danish residential chimneys, they follow the air pollutant emissions guidebook of the European Environment Agency (2019). Average emission estimates are thus based upon laboratory measurements combined with smaller sample studies of in-situ measurements of different technology appliances where researchers try to consider and replicate the many parameters and user practices which impact emissions.

The situations that air pollution researchers simulate to measure emissions include combustion of wet and dry wood, part load and full load, as well as common misuse situations (Nielsen et al., 2021: 37-38). A key difficulty concerning firewood consumption pertains to the fact that a lot of wood is not sold via official markets, in contrast to gasoline and diesel consumption, which is registered in official databases. Some people collect their own firewood in forests or process it on their own property, which means that knowledge regarding the quality of firewood is unobtainable. Researchers are aware that burning different species such as pine, birch or beech leads to different emissions but, as one interlocutor told us, data at this level of detail is unobtainable. To construct an average assumption about the quality of firewood, researchers take into consideration that there is a spectrum from moist to dry. Based on assumptions about the moisture level in wood logs, researchers try to estimate an average emission level, which they assume to be the mean value. The assumed humidity level of wood logs in the emission model has consequently been set to 15 percent (ibid.: 39), but the real conditions are unknown. Meanwhile the unit consumption of all wood stoves is considered equal (ibid.: 13), although it differs across geographical regions and ignores categories such as inner-city apartments, suburbs, rural houses, and, not least, technological appliances. Assumptions about the quality of wood logs, in other words, emerge from a domain that is imperceptible (Murphy, 2006: 9), where scientific objects are rendered knowable via assumptions or expert judgments, as the researcher highlights above.

The study of wood stove pollution has been approached via a wide range of methods. Between 2005 – 2013 air pollution researchers collected data on wood consumption via phone sample interviews. This method was changed to online survey samples from 2015. Based on biannual surveys that have been carried out by different companies (Force Technology and Ea Energy analysis) for the Danish Energy Agency, the researchers estimated how wood consumption evolved over time since the first survey was carried out in 2005. From 2007 to 2017 firewood consumption apparently remained relatively stable in Denmark at approximately 25 PJ (petajoule) (Nielsen et al., 2021: 15). One researcher we spoke to notes that they will probably never know the consumption of firewood before 2005, there simply is no data.

Current calculations are moreover based on assumptions about worst-case and best-case user behaviour and assumptions about the quality of the wood they burn. The goal is to construct bottom-up average emission estimates for the approximately 738,000 residential wood stoves and ‘other appliances’ that are not too far from the actual emissions, a researcher elaborates. However, uncertainty is omnipresent in the emissions model. There is uncertainty associated with the very term ‘wood stove,’ as the emissions data also includes a number of ‘other appliances’ such as open fireplaces, pizza ovens, garden fire pits, barbecue grills, and sauna ovens (Nielsen et al., 2021: 31). The researchers’ estimate of “Wood stove emissions” in essence does thus not just originate from wood stoves. Although emission levels from ‘wood stoves’ and ‘other appliances’ show great variability depending upon the quality of the wood loaded, the kindling practices, and the load capacity of the appliances, the researchers do not go into detail describing the impact of uncertainty that is associated with these parameters (ibid.: 69). In other words, expert assumptions about these key parameters emerge to a large extend from domains that are imperceptible (Murphy, 2006) due to the dearth of data and large-scale measurement campaigns.

Researchers collect data on the number and age of appliances from the Association of Chimney Sweepers (DAPO), and data on wood consumption is collected via sample surveys done by the Danish Energy Agency every second year (Danish Energy Agency, 2019). Sales figures for residential wood stoves are not publicly registered. A time series has therefore been constructed based on assumptions and information obtained from the association for suppliers of fireplaces and wood stoves (Kristensen 2019 in Nielsen et al. 2021:12). Data on annual scrapping of old stoves is likewise not publicly available, and the researchers behind the emissions model have therefore constructed a replacement curve, under the assumption that most stoves are being replaced on average after 30 years (ibid.: 12). This relates to a recent regulation compelling owners to replace stoves that were installed before 2003 (Ministry of the Environment Denmark, 2022). In addition to receiving quantitative data from different sources, researchers benefit from asking chimney sweepers conversationally whether they are seeing more woodburning stoves being established than dismantled, and other questions that give a sense of how the sector is evolving. While annual figures for scrapping of old stoves is unknown, researchers *estimate* a growth rate of around two percent in the number of woodburning stoves in use for the whole sector, based on *assumptions* about the replacement of old stoves and sales data from DAPO (Nielsen et al., 2021: 28). Due to these difficulties in obtaining reliable and accurate data, emissions are thus usually less well-known compared to large-scale energy production, vehicular traffic, and most other emission source categories, and accurate and reliable assessments of residential wood stove emissions therefore remain a challenge in many countries (Kukkonen et al., 2020: 4350–4351).

This section has demonstrated how the construction of knowledge regarding emission estimates for residential wood stoves is intimately linked to expect judgments due to the absence of empirical data. It unfolds in the form of assumptions about 1) the quality of wood that is being burned (moisture content and species), often varying according to geographical location; 2) the size of the load compared to the capacity of the appliance; 3) firing techniques; and 4) expected lifetime and replacement rates of wood stoves. These assumptions derive from locations that resemble domains of imperceptibility (Murphy, 2006: 9) where information regarding the socio-technical wood stove assemblages is rendered numerical through expert judgments rather than empirically determined facts. In other words, estimates of wood stove emissions are less tied to the actual emissions of the approximately 738.000 wood stoves and other appliances in Denmark; rather, they are produced based on *assumptions* about socio-technical wood stove assemblages that shape simulated experiments and associated measurements in laboratory settings. The validity of the incumbent estimates can easily be questioned based on competing interpretations of assumptions, as we show in the section below, where we proceed with a focus on the actual use of the stove, more particularly how kindling practices shape levels of uncertainty regarding emission estimates.

The unmeasurable uncertainty of kindling practices

One of our interlocutors, a professor specialized in the adverse health effects of air pollution, succinctly captures the extent of the enigma facing researchers studying how the different appliances are operated and what is being burnt:

> Do wood stove owners burn wood? Is the wood they burn dry or wet? What else do they burn besides wood? Paper, cardboard, coke, or pizza trays? If they use wood, how do they light the fire? Using paper or fire starters? How do they air-condition? Do they put the right amount of wood into the oven? Do they burn overnight?

In other words, there are many factors that need to be considered when understanding air pollution from woodburning stoves. Burning wood overnight with little inflow of air to preserve embers for the next day, the professor notes is for example one of the worst things users can do to the environment. Similarly, burning wet wood produces far more particles than dry wood. There is currently a lack of comprehensive studies about how user behaviour impacts emissions from residential wood stoves (Reichert et al., 2016: 246), which leads us to the more fundamental question of how a wood stove should be operated to avoid high discharge of particles.

A chimney sweep, who is engaged in the particle pollution debate in Denmark, believes the correct firing technique is key to clean combustion processes. He claims wood stove owners can eliminate up to 80 percent of the particle discharge by igniting wood logs via a so-called top-down ignition method (Andersen and Hvidberg, 2017). The theory behind the top-down kindling approach is that gases originating from lower-lying wood logs in the combustion chamber are ignited by the flame at the top like a candle, the chimney sweeper explains. On top of a couple of wood logs, users should place 12-14 small wood sticks before starting the combustion process with a few starters placed on top of the small wood stick pile. While the 'correct' amount of wood loaded in the combustion chamber depends on the specific requirements of each appliance, a rule of thumb holds that the size of the firewood pieces should not exceed the size of a forearm, the chimney sweeper elaborates. The moisture level of the wood log should not exceed 18 percent. Then, a fire needs oxygen to burn properly. Depending on the appliance, a wood stove must also be supplied with sufficient air from its surroundings. Under these conditions, a fire will burn its way down through the pile in a relatively clean combustion process if the wood is sufficiently dry, according to the top-down approach.

If, on the other hand, a wood stove user ignites a fire via the bottom-up approach, the flame cools as it ascends through the different layers of wood. This leads to an increase in particle discharge due to poor combustion of gases, the chimney sweeper continues. One way of determining how clean the combustion process is, is to go outside and examine whether any visible smoke is coming out of the chimney. While some smoke is unavoidable, especially during the ignition phase, smoke from the chimney should barely be noticeable after 10-15 minutes under ideal combustion processes. Lighting a fire via the top-down approach with dry wood is, in other words, a good starting point for lowering particle discharge (Andersen and Hvidberg, 2017).

Several uncertainties concerning air conditions, the quality and amount loaded in the appliance and not least, kindling practice are raised by the chimney sweeper's top-down approach to kindling. How do researchers know which approach is more common among Danish wood stove user, let alone if users burn objects other than wood? An air pollution researcher outlines why knowledge about kindling practices is unobtainable for the time being:

> We do not know, and it is incredibly hard, as there are some who use it [the residential wood stove] a lot, some use it less, some are good at it [kindling a fire], some are bad. Some burn anything that can be burnt, whereas others use proper dry wood logs. So, the variability is enormous.

While researchers who have constructed the residential wood stove emissions model do not go into detail describing the impact of the uncertainties surrounding key parameters outlined in this section (Nielsen et al., 2021: 69), we argue that the heterogeneity of the situations prevents the researchers from managing uncertainty via calculative endeavours (Knight, [1921] 2018: 135-136). That is, there are fundamental uncertainties involved in the situations researchers are trying to simulate because each socio-technical assemblage surrounding each wood stove – firing practice, moisture levels, quality and size of load in the appliance, and air conditions – is unique. Emission estimates, in other words, are merely estimates, to follow Knight (ibid.), which implies that there is no possibility of forming quantitative determinations of probability associated with them, or any degree of measurable uncertainty.

To summarize, this section has demonstrated how the uncertainty associated with kindling practices can be understood as a kind of unmeasurable uncertainty in the Knightian sense (ibid.), as researchers arguably cannot configure quantitative determinations of probability associated with kindling practices and their associated socio-technical assemblages. Having established this vantage point for understanding residential wood stove emissions is, however, inadequate in and of itself in relation to making emissions reductions actionable in the current policy frame.

Framed uncertainty

The incumbent public policy tradition assumes that solutions to complex environmental issues like wood stove emissions need to be determined by precise quantitative statements and that numbers alone are a sufficient means of policy input (Funtowicz and Ravetz, 1990; Jasanoff, 2018). The unique relationship between public officials who expect that scientists can deliver precise answers, on the one hand, and, on the other hand, researchers who are constantly facing large uncertainties in their everyday work, results in discussions of uncertainty taking a backseat in science conducted for policy. However, the marginalisation of uncertainty is problematic because it obfuscates what is going on in science while simultaneously preventing public officials from seeing which scientific topics, locations or objects need to be researched in the future to improve the knowledge foundation for science and public policy. Informed by Knight (2018), we have demonstrated how air pollution scientists handle the uncertainty associated with key parameters in the production of wood stove emission estimates. That is, they turn expert assumptions into numerical values and thereby conflate an unmeasurable uncertainty with a measurable uncertainty that can be estimated with a degree of probability. Based on this operation wood stove emission estimates are now conveyed in the form of an unambiguous number (52%) although there is no basis on which to establish any degree of calculable probability with this number. In other words, due to the incumbent public policy tradition researchers are compelled to come up with a number – and one number only - whose associated uncertainty appears unacknowledged.

Inspired by Jasanoff (2005; 2018) and Knight (2018) we propose an alternative approach to communicating wood stove emission estimates and their associated uncertainties at the science policy level. This approach dismisses the idea that solutions to complex problems like wood stove emissions must be determined solely by quantitative facts. Rather than trumpeting accuracy, we propose a ‘framed uncertainty’ approach which implies an analytical and normative dimension. First, the analytical dimension highlights that wood stove emission estimates are merely estimates in the Knightian sense because there is no basis on which to form any degree of measurable uncertainty. This is because kindling practices and their associated heterogeneous socio-technical assemblages are in reality quite unique as we have outlined in detail above. Second, drawing upon Jasanoff’s (2022) plea for humility, ‘framed uncertainty’ involves accepting uncertainty as the foundation for public policy while making harm mitigation a goal because uncertainties are particularly consequential at the science policy intersection. It suggests that the incumbent policy frame needs to be continuously questioned to draw attention to whatever falls outside the frame.

Drawing upon actor-network theory, Jasanoff demonstrates the contingency of a particular policy frame by highlighting how traffic accidents, which were once perceived as random accidents involving typically young people and teenagers, were at a certain time in American history reinscribed in the national consciousness as drunk driving. To illustrate this point Jasanoff invokes Gusfield’s (1997) account of drunk driving by emphasizing the socio-technical elements of driving. As the frame of social attention shifted away from random accidents, the car emerged as a socio-technical assemblage tied to hard and soft components including practices, objects, rules and actors all entangled in complex networks of transportation (Jasanoff, 2005: 24). The impact of the novel policy frame on car accidents is worth citing at length:

> As if endowing its users with x-ray vision, the frame of drunk driving permitted society's movers and shakers to detect all kinds of once invisible nodes in the network where intervention now seemed possible in the interest of saving lives: raising the drinking age; penalizing innkeepers and even private party-givers who allowed drinkers to go on the road; mandating seatbelts use; reducing speed limits; and requiring cars themselves to be engineered with new safety features such as airbags and antilock brakes. (Jasanoff 2005, p. 24)

As the different elements of the socio-technical car assemblage became obvious to public officials, it produced a novel regime of safety regulation surrounding the car (ibid.), she emphasizes. In other words, attending to the way in which a particular issue is framed under circumstances of high uncertainty, pays off when it comes to analysing scientific uncertainties at the science policy level (Jasanoff, 2018: 13). Akin to Jasanoff’s insights above, our analysis allows us to propose that wood stove emissions emerge from heterogeneous socio-technical assemblages tied to soft and hard components including firing techniques, indoor and outdoor air conditions, wood moisture, load in the appliance and of course the wood stove technology in itself. By stressing that emissions are determined by the interaction between users and their heterogeneous socio-technical wood stove assemblages, this approach to understanding woodstove emissions provides policymakers with opportunity to intervene and regulate emissions in new ways.

While combustion of wood in residential wood stoves undoubtedly leads to outdoor emissions, novel sample measurements of indoor particle discharge point toward a hitherto overlooked problem. Sample studies are few and small in scope (Bruun, 2022; Jensen et al., 2012; Olesen et al., 2010) but collectively, they demonstrate that indoor environments often become polluted with particles during combustion processes. Indoor particle discharge typically occurs during the early ignition phase, when firewood is combusted in a cold oven, with slightly open oven door (Olesen et al., 2010). Opening of wood stove levers during refills, sudden wind blows, use of ventilation systems or extractor hoods can also contribute to indoor particle discharge (Jensen et al., 2012: 45). A common theme for these studies is that significant spikes of particle discharge typically occur during the kindling and refilling phases when the lid of the stove is open. Discharge of particles into living rooms is potentially more dangerous, as particles are emitted directly into the living rooms of wood stove users is not mixed with outdoor air. When harm mitigation is the goal of communicating about wood stove estimates to public officials, then the implication of these emerging studies is that the incumbent policy frame centred on outdoor emission ought to be complemented with an acknowledgement of those indoor particles that fall outside its current scope of vision. By acknowledging the likely dangers of indoor particle discharge, an emerging issue which needs to be uncovered through large-scale measurement campaigns, the limitations of the current policy frame can be conveyed to policymakers.

In summary the 'framed uncertainty' approach to communicating wood stove estimates at the public policy level draws attention to the unmeasurable uncertainties associated with key parameters in the socio-technical assemblage surrounding the production of wood stove emissions estimates. It highlights that estimates are merely estimates in the Knightian senses because there is no basis on which to form any calculable probability. More importantly by accepting uncertainty as the foundation for public policy while having harm mitigation as a goal, this approach to communicating wood stove emissions to public officials stresses the limitations of the incumbent policy frame by foregrounding those particles and practices that fall outside its scope of vision.

Conclusion and public policy implications

Although our analysis has focused on how uncertainty is an integral part of the science of air pollution, our point is not to relativize the scientific output of researchers. On the contrary, it is to highlight that the researchers are fully aware of the many uncertainties implicated in their studies. Yet, they are also under pressure to comply with politically determined regulations. In that process they produce specific answers and unambiguous numbers concerning how much residential wood stoves contribute to national $PM_{2.5}$ pollution – the 52 percent. The proliferation of precise numbers in public discussions of wood stove emissions, premature deaths and associated costs, however, do not resonate with the reality, which is far more nebulous, unmeasurable, and unknown, as we have shown. In other words, our analysis demonstrates that the knowledge foundation for having public discussions about unambiguous wood stove emission estimates rest upon a fragile house of cards built on unmeasurable, uncertain assumptions. It is a house of cards that is not wrong, but it is solely based on elements that to some extend can offer an exact number. The implication is that in efforts to reduce particle emissions, the wood stove is targeted, albeit, in reality, the researchers' "emission estimate" encompasses a much wider category of other appliances not encompassed by the policy. By trumpeting accuracy in discussions of wood stove emissions public officials fail to recognise that emissions are intimately entangled with user practices and the socio-technical assemblage surrounding stoves and that 'wood stove emissions' are likely also on indoor issue.

Whereas incumbent public policy responses to reducing emissions are focused on technological fixes and economic incentives, the implication of our analysis is that there are ample opportunities to reduce emissions by also focusing on the interaction between users, stoves and the heterogeneous socio-technical assemblage surrounding stoves. Rather than trumpeting accuracy when there is none – and in reality, cannot be any – we argue that it is more helpful to make sense of wood stove emissions through the lens of 'framed uncertainty' when conveying estimates to public officials. This approach embraces the high uncertainties as the foundation for policy responses. Rather than limiting policy responses to technological fixes and taxation, our study offers opportunity to regulate emissions in new ways by focusing on the practices and interactions between users and stoves to save lives while accepting that such policies are applied without the possibility of determining emissions with accuracy.

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The authors declare no potential conflict of interest.

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Paper 4
Expected Uncertainty: Recognising the Unquantifiable Impact Dimensions of Air Pollution in Economic Valuation Practices

Haarløv, R. Expected Uncertainty: Recognising the Unquantifiable Impact Dimensions of Air Pollution in Economic Valuation Practices
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Expected Uncertainty: Recognising the Unquantifiable Impact Dimensions of Air Pollution in Economic Valuation Practices

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Abstract

Each year researchers calculate the costs of air pollution to Danish society, which amounted to $11B in 2022. This number implies accuracy and that researchers know the economic impact of pollution with precision. But health experts suggest that those effects that can be quantified likely only scratch the surface of a much larger problem. Drawing upon discussions of economization and uncertainty, I first analyse the boundary between what gets counted – and, more importantly, what does not - in economic valuation practices. Invoking the concept of the 'pollutome,' I show that contemporary valuation efforts underestimate the adverse health costs of air pollution profoundly, as economists can likely only quantify the tip of an iceberg. The implication of my analysis is that the incumbent public policy tradition ought to be revised and that expectations about uncertainties ought to play a much stronger role in public policy. By utilising the agency of expectations alongside numbers in valuation practices, I argue that public officials can be provided with a more credible and flexible understanding of the highly uncertain context from which they must make difficult decisions.

Keywords: air pollution, economization, uncertainty, expectations, narratives, numbers

Introduction: uncertainty in air pollution economics

Each year, air pollution researchers in Denmark calculate the costs of air pollution to Danish society. The adverse effects of pollutants are typically translated into absolute numbers concerning premature deaths and associated adverse health costs: 4030 deaths and $11B, in 2020 (Ellermann et al., 2022, p. 112). Policymakers and journalists often use these numbers as a springboard for discussing the issue of air pollution (Ritzau, 2020). The movers and shakers of society thus appear to know the economic costs of air pollution with precision, communicating precise and unambiguous numbers in public discussions (Funtowicz & Ravetz, 1990, pp. 83–84). But health experts suggest that the adverse effects that can currently be quantified likely represent just the tip of an iceberg (Landrigan et al., 2018, p. 468-469). While the public policy frame on air pollution is tied to those health effects that can be quantified, I examine the unquantifiable cost dimensions that are usually overlooked in public debates. These dimensions include pre-term birth, dementia in elderly, autism in children or diabetes among other pollution disease pairs where evidence of causation is building (ibid.). Understanding these dimensions is key to making sense of air pollution costs.

To illuminate the unquantifiable cost dimensions associated with air pollutants, I examine how researchers assess phenomena at the limits of quantitative valuation efforts. Drawing upon discussions of economization and framings (Çalışkan & Callon, 2010; Callon, 2021), I first analyse the boundary between which adverse health effects get to count – and, more importantly, which effects do *not* - in economic valuation practices of pollutants. Next, inspired by discussions of expectations and narratives (Beckert, 2016; Holmes, 2013; Kay & King, 2020), I show that unquantifiable economic impact dimensions are particularly dominant phenomena in the subfield of air pollution economics. Invoking the concept of the 'pollutome' (Landrigan et al., 2018), my analysis demonstrates that quantitative economic valuation practices almost certainly underestimate the economic impact of pollution significantly due to insufficient knowledge (ibid., p. 487). Because uncertainty is particularly consequential at the science policy level (Jasanoff, 2022), it follows that unquantifiable cost dimensions ought to play a much stronger role in public policy. By complementing quantitative estimates of well-characterised health effects with expectations and illustrations about the emerging effects that elude quantification, I contend that public officials can be provided with a more credible and flexible understanding of air pollution costs.

The vantage point of contemporary mainstream economics regarding externalities like air pollution and climate change is that the 'price is wrong' in the sense that prices do not reflect social costs (Nordhaus, 2021, p. 22; Stern, 2007). Logically, then, the remedy would be to correct prices and then proceed with business as usual (Nordhaus, 2021, p. 74). However, in practice, calculating the costs of air pollution is extremely difficult because data is sparse at best, and more often missing altogether (ibid., p. 86). The implication of this is becoming increasingly clear: mainstream economic models cannot handle genuine uncertainty (Beckert & Bronk, 2018, p. 8), and while uncertainties continue to play an important role in the real world, they still play a very marginal role in economic theory compared to risky events which can be statistically determined (Tanzi, 2022, p. 126). A result of this is that environmental policies often lag many years behind scientific findings (Nordhaus, 2021, p. 168), which in turn exacerbates the already dire environmental crisis.

The article proceeds as follows: First I briefly describe my methodology before situating the article within discussions on framings (Çalışkan & Callon, 2010; Callon, 2021; Jasanoff, 2012, 2022). Then I outline strategies for acknowledging uncertainty via expectations and narratives (Beckert, 2016; Kay & King, 2020) before analysing key phenomena that operate at the limits of calculation and measurement concerning emerging adverse health effects. The analysis is followed by a discussion of the agency of numbers and narratives in public policy. Finally, the conclusion summarises the key findings of this article.

Method

My research is informed by a qualitative approach. It relies upon document analysis and interviews with air pollution experts. To study how air pollution becomes an object of valuation, I first consulted newspaper articles and policy documents to better understand how the issue is being problematizing in public discussions of air pollution. Next, I carried out 15 semi-structured online interviews with senior air pollution researchers and economists situated at different universities in Denmark through 2021 and 2022. The researchers have expertise in different branches of air pollution modelling, including neo-classical environmental economics, epidemiology and atmospheric physics. The interviews enabled me to better understand the critical boundary between which adverse effects gets to count and more importantly which do not get to count in contemporary valuation practices of air pollutants. As I learned about uncertainty in air pollution economics, my interviews started to resemble elite interviews (Kezar, 2003, p. 397) in the sense that I arrived at a provisional analysis, which I used as a vantage point for the interview guide. The interviews lasted approximately one hour each and were conducted over Teams and Zoom during different stages of COVID-19 lockdown in Denmark.

Economic valuation of intangible objects

Economics is the language of public policy , and calculative agencies and the numbers they produce significantly contribute to shaping the realities they appear to only represent (Callon, 2021, p. 171; Rose, 1999, p. 198). Mainstream economics is heavily indebted intellectually to classical physics; the field of finance and macroeconomics, too, tread firmly down the path cut by Popper and Newton (Haldane, 2018, p. 147). Some scholars diagnose the current paradigm as suffering from physics-envy (Hirschman, 1991), while others have even coined the term econo-physics (Mirowski, 1991). One result of this physics turn in mainstream economics has been a systemic suppression of the subject of uncertainty (Ravetz, 1994). Inspired by discussions initiated by Callon (2021) and Jasanoff (2012) this section homes in on discussions of 'economisation' and 'predictive technologies' to make better sense of those phenomena which are left unconsidered in economic valuation practices. To set the stage it is useful to examine how the issue of uncertainty is being treated in the field.

The literature on uncertainty spans numerous disciplines and is unsettled (Hubbard, 2020), but a critical distinction between 'uncertainty' and 'risk' was emphasized long ago by economist Frank Knight ([1921] 2018). Under situations of 'risk' actors know the possibly outcomes and can calculate their probability. 'Uncertainty', on the other hand, is where actors are unsure about key parameters of a particular outcome and therefore cannot calculate a degree of probability. Since the 1970s economists have increasingly ignored this critical distinction (Hodgson, 2011) and agencies involved in science assessments of environmental issues typically conflate uncertainty with risk (Scoones & Stirling, 2020b). The conflation of uncertainty with risk is likewise evident in the subfield of air pollution economics, where economists establish numerical values regarding key parameters based on expert judgments (Rabl, Spadaro, & Holland, 2014 p. 465). Neoclassical mainstream economic ideas are, moreover, the essential foundation of most policy solutions to environmental problems in the Global North (Buller, 2022, p. 22). But how do mainstream economists determine the costs of contemporary environmental problems?

The usual approach is 'methodological individualism,' according to which collective phenomena can be understood through individual behaviour or preferences (Tirole, 2017, p. 87), and money is usually a good enough metric for the 'utility' that individuals get from commodities (Fourcade, 2011, pp. 1721–1722). While certain scholars adopt the view that non-marketed objects like air pollutants are better apprehended though alternative metrics of worth (Boltanski & Thévenot, 2006), and therefore best kept separate from the measuring rod of money, I follow the lead of Dewey (1965) and Callon (1998a) by focusing on valuation practices. Instead of denouncing the simplistic and selfish homo economicus figure in order to disqualify economic theory – or, antithetical, to celebrate the proliferation of markets outside of conventional ones (Callon, 1998, p. 51) - the goal of this inquiry is to understand the $11B number through an evaluative frame that can be traced back to specific techno-scientific and institutional configurations.

In complex processes of economization the goal is precisely to identify and characterize specific entities that have been 'economized' (Çalışkan & Callon, 2009, p. 391). When objects such as air pollutants are rendered 'economic' it is the outcome of specific historical, disputable and contingent framing processes (Muniesa et al. 2017, p. 3). In other words, as valuation networks ascribe a certain value to a given object, one may easily think of it as an undisputed fact, but objects may be recategorized as valuable or not, which leads to new framings (ibid.). To study framing operations Callon proposes the neologism *market-oriented passiva(c)tion*. This notion refers to a process whereby an object is detached from those qualities that render it immobile and simultaneously imbued with qualities that make it apt for economic courses of action that are somewhat predictable and controllable (Callon, 2021, pp. 57–58). Following Callon, the key question of this inquiry revolves around how the economic valuation model developed by air pollution researchers and economists rooted in neoclassical economics frames the world of air pollution by putting it in brackets. Which states of air pollution are reflected in damage cost assessments and which, more importantly, are left out due to uncertainty?

In congruence with how valuation researchers are interested in understanding the overflows of particular framings (Barry, 2002; Best, 2012; Lohmann, 2009), Jasanoff (2012, p. 178) depicts how 'predictive methods' such as cost-benefit analyses or climate models focus on the known at the expense of the unknown. Jasanoff argues that predictive technologies which achieve power through claims to objectivity have evolved into 'technologies of hubris' that suffer from a peripheral blindness towards indeterminate long-term risks while giving little weight to whatever falls outside their scope of vision (ibid.). This boundary work, whereby certain phenomena are demarcated as belonging to the realm of objective knowledge, is often conducted by experts, which means that the politics of differentiation is locked away from criticism and public scrutiny. Following Jasanoff, the genuinely uncertain, indeterminate, lesser-known aspects of science and technology remain largely unaccounted for in policymaking (2012, pp. 178–179). A commonality across institutions involved in the management of global environmental issues is thus to claim precision and control, even if such performances are a pretence and issues remain open-ended (Scoones & Stirling, 2020a, p. 12). But uncertainty is especially consequential when it converges with political power (Jasanoff, 2022), which begs the question of how overflows in valuation framings can be accounted for in science conducted for policy.

Acknowledging uncertainty through expectations and illustrations

Across science and technology studies, economic sociology and, to a lesser degree economics, researchers have increasingly made uncertainty their driving concept (Beckert & Bronk, 2018; Haldane, 2018; Mehta & Srivastava, 2020; Scoones & Stirling, 2020b; Tanzi, 2022; J. P. van der Sluijs, 2017). These scholars have demonstrated why uncertainty is key to understanding contemporary issues ranging from climate modelling to future disasters and economic theory. In the following section, I focus on how different degrees of uncertainty can be acknowledged at the limits of quantitative valuation efforts via narratives, expectations and illustrations.

In the refreshing publication 'Radical Uncertainty: Decision-making Beyond the Numbers,' economists John Kay and Mervyn King (2020) argue that public servants and policymakers are required to act under conditions which resemble radical uncertainty. Under such conditions the public role of social scientists is to provide a *narrative* that is credible and coherent while establishing the context from which decisions can be made (ibid., p. 335). Narrative reasoning is the most compelling approach to organizing imperfect knowledge in the face of high uncertainties. The choice of narrative is problem- and context-specific, and narratives are neither true nor false, but helpful or unhelpful and they depend upon judgment (ibid.), the authors suggest. Because the accuracy of a model following Kay and King (ibid. p., 224-225) is only well founded within the context of the model itself, its value lies not so much in its pretence of providing precise quantitative estimates as it does in framing a problem via coherent and credible narratives to provide insights concerning the context and problems facing policymakers.

Starting from a similar vantage point of genuine uncertainty, sociologist Jens Beckert (2016, p. 9) proposes the concept 'fictional expectations' to better understand how economic actors are oriented toward the future. Fictional expectations, he contends, 'refers to the images actors form as they consider future states of the world, the way they visualize causal relations, and the ways they perceive their actions influencing outcomes' (ibid.). Expectations become interpretative frames that depict how future states of the world will likely unfold told from the current state of affairs (ibid., pp 9-10). Based on the credibility of such expectations and imaginaries which take a narrative form as stories, investors are persuaded to act and invest their resources, Beckert (ibid., p. 176) asserts. Expectations can, in other words, help instil confidence in situations characterized by uncertainty and thereby provoke actors to make decisions about those imaginaries while moving reality toward the kind of future that is envisioned (ibid., pp. 186, 242).

Besides expressing uncertainty via expectations and narratives, uncertainty can likewise be conveyed through maps, illustrations and figures (Funtowicz & Ravetz, 1990). While the incumbent public policy tradition - also known as the 'physics view of science' - holds that quantitative assertions are a sufficient means of policy input concerning environmental issues, Funtowicz and Ravetz (1990, pp.83-84) suggest that 'hard' numbers need to be qualified through 'soft' maps, especially when it comes to environmental pollutants. Phenomenologically speaking they propose that numbers and maps can be understood as complementary vehicles of information. By its appearance, a map can encompass uncertainty as it expresses vagueness; in contrast to a number which is precise and unambiguous (ibid.). Due to this dialectical relation between numbers and maps, a study of the properties associated with a map can shed light upon the properties of a number and vice versa, they assert (ibid., p. 84). The merit of a map involves enabling users to grasp the presence of patterns and totality of a particular issue in contrast to an isolated number which is less suited for this (ibid., p. 97). In summary, this section has outlined a variety of strategies for how uncertainties can be recognized and made actionable via narratives, expectations, and maps.

A cautious number: quantifying economic costs

One researcher I interviewed, specialised in economic valuation of pollution, describes the air pollution cost estimate for adverse health effects ($11B) in the following way:

> 'I assert with confidence that we are on the cautious side of things with the [economic] numbers, we put out. I mean, I believe we would be considered untrustworthy if we tried to exaggerate. I mean, it is better to be on the cautious side and then let the politicians use the precautionary principle on top of that. We try to set a foundation by saying that we feel safe to say that they [air pollution costs] are with confidence as high as we say and perhaps somewhat more.'

Jasanoff (2022) contends that the precautionary principle, which has been widely adopted in international agreements on the environment since the 1970s, is difficult for policymakers to use it in productive ways. As a result, there is still a fundamental bias towards prediction and quantification in public policy. To compensate for the partiality of science, she recommends an alternative approach focused on uncertainties and frame analysis (ibid.). Inspired by her approach, the aim of this analysis is to explore the extent to which air pollution cost estimates are on the cautious side of things. To do this, I analyse which pollutants and associated adverse health effects are being deployed in the economic valuation frame and, more importantly, which are not. To set the stage, I first outline how the economic valuation system was developed and how the uncertainties associated with such quantitative efforts can be understood.

Developing an economic valuation model for air pollutants was not an easy undertaking, according to one of my interviewees who was involved in its birth. The model was created during a time when Denmark was led by the climate change-sceptical government headed by prime minister Anders Fogh Rasmussen. The political environment at the time was hostile towards environmental research, and the government was openly critical of researchers studying climate change. Despite this, the researchers developed a Danish valuation model of air pollutants in 2004 that was built on a European model, ECOSENSE[1], which estimated the health and environmental impacts caused by air pollution. The European model allowed users to type in coordinates for a specific power plant and subsequently perform a calculation, which then determined the damage inflicted upon humans, nature, and buildings. Initially my interlocutors began to use this model, but they quickly started to question the scientific assumptions embedded in the system. Two of the researchers thus decided to build a foundation for their own equivalent system.

The Danish economic valuation model has been built around a so-called impact-pathway chain, which presumably draws upon state-of-the-art research input at each different layer of the model system (Rabl et al. 2014). At its core the model system is about identifying the pathway from the moment when toxic substances and their precursors are emitted into the atmosphere to when they cause damage. Calculating the costs of the damage caused by air pollution is a highly multi-disciplinary effort, requiring expertise in environmental modelling, epidemiology, economics, ecology, physics, chemistry and more (ibid.). The baseline level of uncertainty associated with estimating adverse health costs is by default +/-50 percent (Lelieveld et al., 2019, p. 1593). In other words, a profound level of uncertainty. In air pollution damage cost assessments, health impacts weigh most heavily, as knowledge in this area has advanced the most. In contrast, less is currently known about how air pollution affects nature (Nordhaus, 2021, pp. 86–87).

Following an extensive review of the adverse health effects of air pollutants, the WHO provides recommendations for concentration-response functions for key pollutants that can be used in the economic valuation model. The WHO recommendations for concentration-response functions work as a vantage point for how my interlocutors work on damage costs. The recommendations include exposure-response functions for particulate matter (PM), ozone (O3) and nitrogen dioxide (NO2) (WHO Regional Office for Europe, 2013; World Health Organization, 2013). The health effects which are currently being monetized in the model system include: premature mortality due to long-term exposure,

[1] https://www.reeem.org/ecosense/

acute mortality due to short term exposure, lung cancer, hospital admission due to cardiovascular diseases, sick days, asthma and bronchitis among other (Jensen et al. 2020, p. 19). Between 2016 to 2018 the average exposure of the Danish population to fine particles ($PM_{2.5}$) accounted for approximately 90% of all premature deaths, whereas NO_2 accounted for about 7,7% and O_3 for about 1,6% (Ellermann et al. 2021, p. 98). The adverse health effects of $PM_{2.5}$, NO_2 and to a lesser degree O_3 are thus the predominant entities being framed (Callon, 2021, p. 58) as apt for courses of action in economic damage cost assessments. The researchers acknowledge that cost estimates are associated with +/-50 percent uncertainty and they state that novel research indicates an upward trend in cost estimates (Ellermann et al., 2022, p. 123), but they do not recognise the unquantifiable impact dimensions associated with the estimate ($11B), which I return to below.

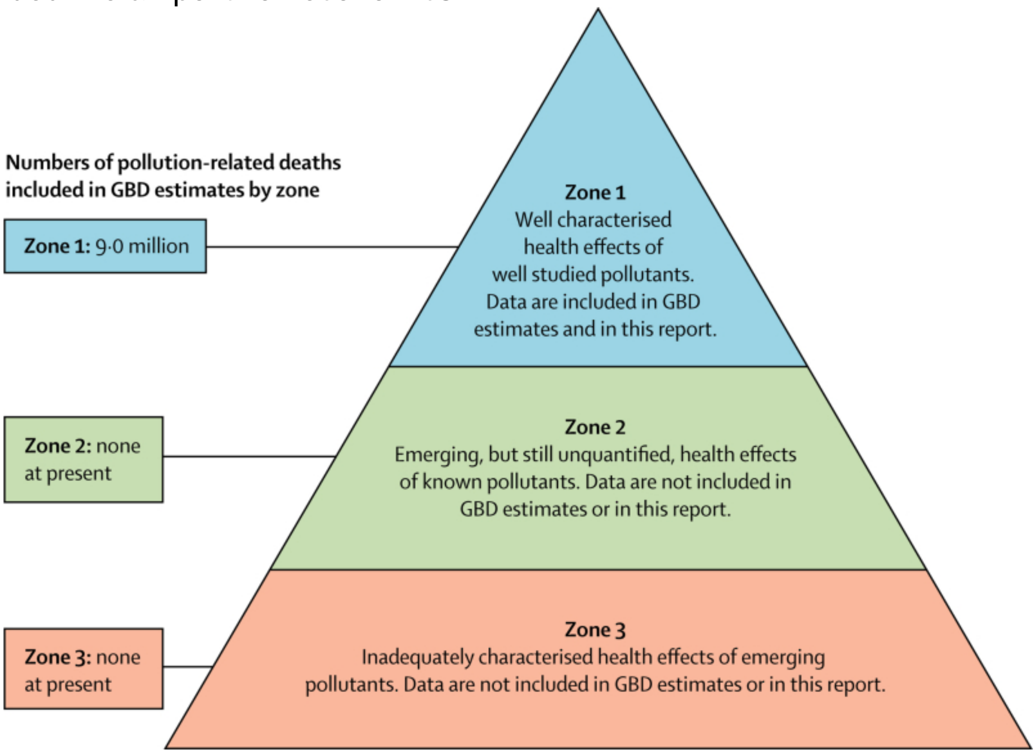
In summary, the approach whereby Danish air pollution researchers and economists lean on consolidated recommendations proposed by the World Health Organization for calculating air pollution costs can be considered a pragmatic way of dealing with the problem that science speaks with multiple tongues. By 'speaking consensus to power and policy' (van der Sluijs 2016, pp. 158-159) scientists assume that they need to produce a quantitative policy input because that is expected of science. In this line of reasoning, they achieve robustness by finding the highest common denominator in all the peer-reviewed articles to date (ibid.). Air pollution costs are thus conveyed via precise numbers in a way that is presumable cautious, as the researcher highlights above. But how are politicians supposed to operationalize the precautionary principle on top of the number whose associated uncertainty remains underdeveloped? That remains unclear. In the next section, I proceed to illuminate the context and limitations associated with contemporary valuation practices.

Expected uncertainty: contextualising the number

> I have tried this myself several times, where I also had to communicate with some politicians, where our communications officer told me that I should use very, very short sentences, and really like – that goes against my nature. On the other hand, I can also see that they could remember the number, right? They really could because I had sort of emphasized that particular number, and then that's what they went home and…I actually felt that it had an impact because they went home and negotiated some new things. - Air pollution researcher

In addition to being puzzled about how to convey uncertainty in air pollution modelling to public officials, the researcher quoted above went on to suggest that there is clearly a problem associated with how they communicate about uncertainty to public officials. That is, while the researcher clearly favours articulating different degrees of uncertainty in science conducted for policy, the researcher is instructed by a communications officer to convey scientific results in a simple manner preferably in numbers. This approach to communicating science to public officials resembles the incumbent public policy tradition, which assumes that complex environmental issues must be determined by numerical facts (Jasanoff, 2018; Scoones & Stirling, 2020b). It follows from this tradition a) that truth is best expressed in numbers b) that numbers are a sufficient means of policy input and c) that knowledge is weak and insufficient when it cannot be conveyed numerically (Funtowicz & Ravetz, 1990,

p. 10). The implication for the present case is that unquantifiable impact dimensions are marginalised in science conducted for policy. Invoking the concept of the 'pollutome,' I demonstrate below why this public policy tradition is ill-advised when the science is limited and open-ended like air pollution economics.



The 'Pollutome' (Landrigan et al., 2018, p. 468)

The Lancet Commission on pollution and health (Landrigan et al., 2018, pp. 468–469) has developed a framework called the 'Pollutome' to organize scientific knowledge on pollutants and their associated effects on human health. They define it 'as the totality of all forms of pollution that have the potential to harm human health' (ibid.). What makes this framework pertinent is that it suggests that the emerging but still unquantifiable health effects of zone 2 and 3 could be more important than the well characterized health effects of known pollutants, zone 1. The health effects that are not (yet) rendered apt for economization purposes include 1) emerging effects of known pollutants ($PM_{2.5}$, NO_2, O_3, etc.), where associations between diseases and exposure are not fully understood, but where causation is building; and 2) the adverse effects of emerging pollutants that are inadequately characterized (ibid.). Examples of pollution disease pairs from zone 2 include pre-term birth, autism in children, dementia in elderly and diseases of the central nervous system (ibid.). Several new and emerging chemicals from zone 3 such as nano particles, new classes of pesticides and developmental neurotoxicants are furthermore detectable in most bodies of the persons who have been examined in national surveys in the US, but the health effects of these pollutants are only beginning to be recognised (ibid.). To the health experts the implication of the pollutome is that '*the health effects which are currently recognized and quantified could just be the tip of a much larger iceberg*' (ibid., p. 468). In other words, while the economic valuation model analysed above claims objectivity and precision concerning zone 1 ($11B), it simultaneously neglects the adverse effects that fall outside of its scope of vision (Jasanoff, 2012, p. 178), zone 2 and 3. This helps explain, why one of the researchers highlighted to me in an interview 'that many things are undervalued,' referring to the condition that numerous impact dimensions cannot be quantified.

The bottom line concerning research into the adverse health effects of pollutants is that the list of diseases that can be associated with pollution is likely to continue to grow as new exposure-disease relationships are fully characterized (Landrigan et al., 2018, p. 468). The costs of premature deaths and diseases caused by pollution are thus not only rising rapidly but also often undercounted and overlooked because they are associated with non-communicable diseases that have long latency extending over several years which are not captured by standard economic indicators (ibid., p. 482). That is, although non-communicable pollution-related diseases can have large impacts on health care systems, such costs are typically hidden in productivity reports, hospital budgets and general health care expenditures and not considered to be associated with pollution (ibid.). While a growing body of research suggests a relationship between the abovementioned emerging diseases and air pollutants (World Health Organization 2021, p. 11; Landrigan et al. 2018, pp. 468-469), they are not considered apt for courses of action (Callon, 2021, p. 58) in valuation practices. In other words, the proliferation of precise numbers detailing premature deaths and associated economic costs in public debates does not reflect the profoundly uncertain, multi-dimensional, and open-ended nature of the problem, as I have shown above.

My argument is that although these emerging adverse impact dimensions cannot be quantified (yet), they ought to be recognized as potential harms because uncertainties are particularly consequential when science intersects with policy (Jasanoff, 2022). That is, while these uncertainties defy quantification efforts, they ought to be acknowledged by illustrations and expectations. First, the 'pollutome' figure illustrates the significant limitations to contemporary economic quantification efforts in forceful ways. It contextualises the estimate ($11B) and offers a lens for how to understand the totality of the phenomenon (Funtowicz & Ravetz, 1990, p. 97). More specifically, the properties of the pollutome shed light upon the properties (ibid., p. 84) of the number ($11B). Second, the rapidly rising economic cost dimensions of zone 2 and 3 (Landrigan et al., 2018, p. 468; 482) can be captured through expectations cast in a narrative form. By stating that current quantification efforts of adverse health effects likely represent 'just the tip of an iceberg' (ibid.), researchers can help instil confidence in public officials and more importantly provoke them to act (Beckert 2016 pp. 186, 242) on those uncertainties that are envisioned. That is, expectations become interpretative frames (ibid.) which propose how future economic impact dimensions will likely unfold. In other words, expectations and illustrations ought to be deployed in valuation practices to acknowledge critical impact dimensions which elude quantification.

Discussion: the agency of numbers and expectations in public policy

Besides being a major health issue air pollution is intimately entangled with the ecological and climate crisis and it contributes to the deterioration of the planetary boundaries (Richardson et al., 2023). The researchers, I interviewed, are currently working towards incorporating 'nature' in economic valuation practices via neo-classical methods. Yet such impact dimensions likewise remain unacknowledged in current valuation practices due lack of consensus on how to quantify such effects. My argument underscores the need to be more cognizant about what kind of narrative is being composed by scientists to public officials when the issue is air pollution costs. Should the narrative solely focus on those effects that can be quantified as is currently the case? Or should the narrative acknowledge unquantifiable impact dimensions as well? To better understand the challenges involved with altering the incumbent public policy narrative on air pollution costs, I discuss the agency of numbers and narratives in public policy below and why scientists usually shy away from using narrative accounts about uncertainties.

Acknowledging the limitations to precision might be inconvenient for scientific institutions that strive to maintain an illusion of control over uncertainties (Scoones & Stirling, 2020a, p. 12). Abandoning the pretence of precision can furthermore create opportunity for regressive forces to exploit uncertainty (ibid., p. 14). Oreske and Conway (2011) have for example shown how a small group of scientists affiliated with the coal and tobacco industry successfully sowed doubt about scientific results to thwart regulation. That is, in the incumbent public policy tradition, it is possible for regressive actors employed by industry to use arguments like 'the science is not settled' to suggest that more science is needed to resolve uncertainty. While such deceptive arguments have successfully obstructed and delayed regulation in the past, this line of reasoning is flawed not least because more environmental science rarely decreases uncertainty (Sarewitz, 2000; van der Sluijs et al. 1998). Having said that, the COVID-19 pandemic may have made publics more receptive to uncertain knowledge. That is, researchers studying the communication of uncertainty by health authorities in Scandinavia during lockdowns suggest that health experts widely agree that communication of uncertainty and knowledge gaps does not erode people's trust in science (Kjeldsen, Mølster, & Ihlen, 2022, p. 86); Rather it bolster the credibility of scientists (ibid.). The lessons of recent years is thus that science cannot produce an ultimate answer, or single picture of the intricate environmental challenges of our times (Saltelli, Ravetz, & Funtowicz, 2016). Instead, it can provide a plethora of insights to public officials, enabling democratic societies to explore options for navigating these challenges (ibid.). Embracing the unknown and unquantifiable in turn presents an alternative to the certainty of both optimists and pessimists (Scoones and Stirling 2020a, p. 21.). But why is it difficult for some scientists to acknowledge uncertainty in science conducted for policy?

In Western countries numbers have become an integral part of how democracy is operationalized and numerous societies have experienced a shift from government by rules to 'governance by numbers' (Supiot in Mennicken & Espeland, 2019, p. 224). The authority of numbers stems from the widespread perception that numbers accurately represent a given phenomenon (Desrosières, 2002), are instrumental in solving problems (Porter, 1995) and embody objectivity and rationality (Daston, 1992). Numbers thus serve as essential tools for governance and administration, answering pivotal questions related to value and quantity (Mennicken & Espeland, 2019, p. 228). However, the reliance on quantification creates a peculiar modern ontology, where the measurable often becomes synonymous with the real (Espeland & Stevens, 2008). The implication of this is that quantification efforts tend to oversimplify complex environmental issues by reducing them to measurable facts. That is, while measurements are invaluable in comprehending well-known aspects of a phenomenon and facilitate action, they can limit our appraisal of value and relevance concerning the less well-known aspects of science that cannot be quantified, (ibid. p. 232), as I have demonstrated above. In this public policy tradition, where numbers are the preferred vehicle of information, expectations and narratives about uncertainties rarely play a central role in policy presumably because scientific experts are restrained through the expectation that they ought to adhere to the scientific standards of their respective fields (Krulwich 2008 in Crow & Jones, 2018, p. 224). The implication is that experts shy away from overly rhetorical approaches to communicating uncertainty (ibid.). In other words, while my interlocutors trust the agency of numbers in public policy, they are less inclined to deliberate into uncertainties via narratives due to the expectations imposed on them in the incumbent public policy tradition.

Yet, narratives are powerful sense-making devices and people's preferred way of meaning-making (Jones et al. in Crow and Jones, 2018, p. 217-218). In the context of public policy narratives have agency as they promote specific forms of action or inaction through the objects and values which they emphasize (Constantino & Weber, 2021, p. 156). Narratives and the expectations embedded in them thus have the capacity to create and dismantle specific pathways in public policy (ibid., p. 154). This is because expectations can help create allies and build mutually binding agendas among regulators (Borup et al. 2006, p. 289). Not only can expectations help actors understand the context they are dealing with, but they can also strongly perform that same world (Holmes, 2013). Expectations about uncertain economic states of the world should in turn not be seen as antagonistic or indifferent to the realm of numbers (Holmes, 2009, pp. 384–385). Economic expectations are indeed shaped by the limitations and predicaments of quantitative measures or different forms of statistical analysis (ibid.). When it comes to uncertain states of the economy, expectations about uncertainties cast by scientific authorities with deep technical knowledge thus have the capacity to play a decisive role in establishing the context that frame a particular statistical measure (ibid., p. 383). In other words, carefully composed expectations cast in a narrative form supported by quantitative data 'can serve as analytical bridges to the near future' (Holmes, 2013, pp. 30–31).

In summary, the agency of expectations and narratives should not be underestimated in public policy. Such linguistic practices can be deployed in close coordination with numbers to help bridge the cleavage between the small part of a problem that can be quantified (Pollutome, zone 1) and the impact dimensions eluding quantification (zone 2 and 3) that represent a much larger problem. Communication of uncertainty does not eradicate people's trust in science; rather it strengthens the trustworthiness of scientists (Kjeldsen et al. 2022). The core message, to summarize, is that uncertainty has many dimensions, and that it ought to be foregrounded rather than marginalised in science conducted for policy when the issue is air pollution costs. By doing so the movers and shakers of society can get a more credible and flexible understanding of the profoundly uncertain issue they are dealing.

Conclusion: expected uncertainty in air pollution economics

This article draws attention to the deep uncertainty associated with incumbent economic valuation practices of air pollutants, revealing a multitude of unquantifiable impact dimensions. Utilising the concept of the pollutome, my analysis demonstrates that numerical assertions about costs likely underestimate the adverse impact of air pollution as only the surface of the issue is likely quantifiable, akin to the visible tip of an iceberg. That is, unquantifiable impact dimensions which are critical for policy remain underdeveloped and marginalised in science conducted for policy. Health cost estimates rooted in scientific consensus approaches are not wrong, but when the discipline, air pollution economics, can likely only quantify a small part of a much bigger problem, it becomes problematic to throw unambiguous numbers into the realm of public policy without acknowledging much more carefully the critical dimensions that elude quantification.

Addressing the challenge of qualifying uncertainty in economic valuation practices of air pollutants necessitates a shift in the prevailing perception of how science and economics informs public policy. A first step in this process involves moving beyond the idea that numbers alone are a sufficient means of policy input when it comes to complex environmental issues. A second step involves considering the agency of numbers alongside the agency of expectations and illustrations to acknowledge critical uncertainties. In essence, the prevailing public policy tradition must be revised, as it fails to grasp the partiality of science and the open-ended nature of intricate environmental challenges like valuing the costs of air pollution. Because unquantifiable impact dimensions in air pollution economics are particularly profound and therefore consequential at the public policy level, I propose that numerical estimates of well-known effects ought to be complemented by expectations and illustrations about the likely emerging harms that elude quantification. Illustrations like the pollutome can offer policymakers with a lens to make sense of the totality of the phenomenon. Similarly, expectations about emerging health effects can operate as interpretative frames and help orient decision-making despite the incalculability of the situation (Beckert 2016). This approach to communicating uncertainty in turn accepts the condition that accuracy concerning costs is unobtainable due to the significant limitations and knowledge gaps in epidemiology and environmental economics. More importantly, it is less policy-prescriptive, offering policymakers with more room to act.

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