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

Rasmus Tyge Haarløv

Technologies in Practice Research Group, IT University of Copenhagen, Denmark/rtyh@itu.dk

Mikkel Bille

The Saxo Institute, University of Copenhagen, 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 (Ellermann et al., 2022). 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, [1921] 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 (Knight, 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 (2016), 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" (Keynes in Beckert, 1996: 808). 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 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 (Jasanoff, 2012). 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. 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* (Murphy, 2006.). 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

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 (Nielsen et al., 2021: 39), but the real conditions are unknown. Meanwhile the unit consumption of all wood stoves is considered equal (Nielsen et al., 2021: 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 (Nielsen et al., 2021: 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 (Nielsen et al., 2021: 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: 70). 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 users, 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 (2018), 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 ([1921] 2018: 135-136), 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 discussion of uncertainty taking a backseat in science conducted for policy. However, the suppression 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 (Jasanoff, 2005), 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 and 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 a '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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