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Emissions from wood stoves and health impacts assessments - A critical review

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As wood stoves are widely used for space heating, they also contribute significantly to health impacts through emissions to air, alongside several other emission sources, e.g. traffic. These emissions have various health impacts, on a short to a very long timescale. It would be very valuable to be able to accurately quantify the contribution of a specific emission source or emission producing technology to specific health impacts to assess corresponding health costs and the effect of technology improvements on the reduction of these costs and the improvement of human health. Several efforts have been done to quantify health impacts of air pollution in general and the contribution from different emissions sectors, as done annually by the European Environment Agency (EEA) for Europe and the individual countries based on mainly data from emission monitoring stations in the different countries and emission factors for the different emission sectors. More specific studies have also been carried out, trying to assess the impact of individual emission sources and technologies, e.g. the specific contribution by emissions from wood stoves to attributable (premature) deaths and years of life lost for a city. Such an assessment includes many assumptions in addition to relying on emission data resulting from limited emission measurements or atmospheric dispersion modelling. Consequently, large uncertainties are connected to the assessment outcome, and these uncertainties are usually not properly communicated. This gives a reader the impression that the results are more trustworthy than they are, which again can result in serious implications. Therefore, a critical review is needed targeting the data quality and assumptions going into the health impacts assessments, focussing on the contribution of emissions from wood stoves.

* 1. Introduction

Wood stoves are widely used in cold climates and provides energy security and relieves the pressure on the electricity grid, especially on cold winter days. As such they have a natural place in the local and national energy system in many countries. The goal is to minimise any negative effects on environment, climate and health due to emissions from wood stoves. Modern wood stoves of today are performing much better with respect to emissions and energy efficiency than old wood stoves (without staged air combustion, from before 1998) (Skreiberg and Seljeskog, 2018), and also compared to the first generation of stoves with staged air combustion (from 1998), due to continuous research and development efforts. This results in corresponding reduced impacts, including on health, but still today, the challenge is to reliably quantify these health impacts improvements. There is also a large variation in the actual emission factors used for different emission compounds and for different wood stove categories when reported in official national emission inventories (Skreiberg et al., 2022). These national emission inventories are taken further at the international level, for estimations of e.g. health impacts of emissions sectors, emission sources and specific emission compounds. This is based on measurement of atmospheric emission concentrations in emission monitoring stations and a relative source contribution to these based on the source dependent emission factors for the individual emission compounds. The emission factors can also be combined with atmospheric dispersion modelling to assess the health impacts of e.g. wood stove use, e.g. for a city as in Orru et al. (2022). Considerable uncertainty is also then connected to the results derived. Real life emission factors are needed, but also the modelling approaches and assumptions result in considerable uncertainties. Resulting predicted health impacts therefore are more qualitative than quantitative, primarily useful for making trends as a function of year.

Type approval testing of wood stoves according to NS94 (NS 3058:1994) has showed (Grythe et al., 2019) that the current emission factors (as the weighted average for old + new wood stoves) included in the Norwegian national emission inventory for particle emissions from wood stoves match relatively well when atmospheric emission concentrations are calculated using an established model (The MetVed model) and in combination with established emission factors for other particle emissions sources. Still, it is important and will be increasingly important to diversify between also the new wood stoves, as the new wood stoves of today achieve much lower emissions of unburnt than the new wood stoves that were introduced in 1998 (Skreiberg et al., 2023). Continuous research and development have through the last 25 years correspondingly contributed to also reduced health impacts of wood stove use. However, health impacts do not scale linearly with emission levels and commonly also a threshold concentration is set for the individual emission compounds in health impacts assessments, where below the threshold value the emission level then is considered to not result in significant health impacts, or the quantification of the health impacts becomes too uncertain. The correct establishment of such a threshold value is not easy and it may not adequately reflect the real health impacts, but primarily be a set target value to be reached, and to be tightened over time. There are considerable differences in threshold values for several emission compounds when comparing WHO threshold values (WHO, 2025a) and EU limit values (EU, 2025), where the WHO values are solely health impacts based and the EU limit values are target limit values to be reached by the EU countries. The EEA applies the WHO threshold values when assessing health impacts, which is very appropriate. The WHO threshold value (annual mean) for PM2.5 is 5 µg/m3, where lower particle concentrations in the air that you breathe are then in the calculation assumed to not result in significant health impacts. However, the current legislation in Europe regulates only the mass concentration of PM2.5, without considering the source, size distribution, physical characteristics or chemical composition of those particles. Assessing health impacts based on only a mass concentration, and as an annual mean, is a huge simplification. If you don’t follow the WHO guidelines, e.g. as in Orru et al. (2022), and don’t use a threshold value for PM2.5 but calculate health impacts from any particle emission concentration, based on the assumption that combustion generated particles are toxic at any concentration, then this becomes a very radical approach compared to applying threshold values. Independent of using a threshold value or not, it is imperative to carry out the assessment as accurately as possible, employing the current data and knowledge to its full extent, and providing corresponding uncertainty ranges. Health impacting emission compounds include NOx, NMVOCs, NH3, SO2 and PM2.5 (that results in the direct health impacting emission compounds PM2.5, NO2, SO2 and O3), but also BaP, several inorganic elements that are part of particles, and some gases as well, where national commitments exist to reduce these emissions. PM2.5 is the biggest single health concern connected to emissions to air, also from wood stoves. PM2.5 is therefore the focus of this review.

* 1. Quantifying impacts on health – Methods and tools

The way health impacts are commonly presented is to introduce the burden of disease, which describes the impact of a health outcome measured by different indicators, i.e. mortality (which can be converted to attributable/premature deaths) and morbidity (EEA, 2023). Together they add up to one indicator, disability-adjusted life years (DALYs). Mortality is expressed as years of life lost (YLL) while morbidity is expressed as years lived with disability (YLD). Hence, DALY = YLD + YLL. Several different methods and tools are used when calculating health impacts. EEA uses the Global Burden of Disease approach/tool, while WHO uses AirQ+ (WHO, 2025b). A large number of studies using such health impacts assessment tools are available in the literature. Sacks et al. (2020) and Lehtomäki et al. (2020) analysed established health impacts assessment tools and found significant differences in predicted health impacts. Hence, different tools and the methods that they have implemented give different outcomes. However, it is the input data quality, models used, and assumptions made that result in very large differences in predicted health impacts. Amini et al. (2024) reviewed 286 studies and found that many studies included serious flaws making them very unreliable. EEA calculates the health impacts of emissions in EU and in the EEA countries, including in Norway. For PM2.5, the annual mean concentration in Norway in 2021 (EEA, 2023) was 5.8 µg/m3, which is only slightly above the WHO guideline of 5 µg/m3. Still 400 (rounded up from 390) attributable deaths due to PM2.5 were registered for Norway, and 4100 years of life lost. The reason is that the concentrations differ between geographical locations. Hence, it is local air pollution concentrations where people breathe the air that really matter, and then the challenge becomes even greater when relating this to short-term exceedance of concentration limits, and even from seasonal sources such as wood log firing. Clinical studies to quantify the health effects of such emission sources becomes in practise impossible, and one must rely on epidemiological studies to assess health impacts. Resulting attributable deaths and DALY values are to be regarded as qualitative, and not quantitative. Such values should always be listed with a confidence interval (CI), typically 95%, indicating the uncertainty range connected to the value, taking all relevant uncertainties into consideration. In any case, a continuous effort of reducing emission levels from all emission sources are needed to reduce the risks of health impacts due to these sources. The focus should be on reducing emissions in areas where the emissions are high relative to the air amount in which they are diluted, and this might also happen at some specific times or for some specific atmospheric conditions. For wood stoves, this typically happens on cold winter days, with inversion in the atmosphere, at wind still conditions, and in limited locations with a relatively high wood stove density and use. Relating such unregular occurrences for specific emission sources to specific health impacts becomes then extremely challenging. EEA also divides the attributable deaths for Norway and the years of life lost into types of areas (based on measurement station locations), showing that the health impacts are mainly prevalent in densely populated areas, where human activity leads to higher emission concentrations in the ambient air. This is very logical.

* 1. Quantifying impacts on health – The case of wood stoves

One recent study (Orru et al., 2022) is especially relevant for showcasing how assessment of health impacts is, or rather can be, carried out for wood stoves, focussing only on PM2.5. The study also points out main limitations in the approach, which is good and appropriate. The study also lists uncertainties (95% CI) connected to the specific health impacts calculated, e.g. premature/attributable deaths, but the uncertainties are only due to one of the influencing factors, the applied concentration-response function (CRF) based on epidemiological studies, while in real life several other factors will influence the actual health impacts. In their study the health impacts of PM2.5 emissions from residential wood combustion (RWC) in four Nordic cities was assessed. The aim was to estimate the health effects on the population based on induced air pollution exposure, mortality data taken from the national health registers and a single all-cause mortality CRF. The latter was taken from a previous epidemiological study (Hvidtfeldt et al., 2019), believed to be representative for the Nordic countries, with a hazard ratio (HR) of 1.26 (95% CI: 1.10–1.42) per 1 μg/m3 increment in PM2.5 at 10 μg/m3 PM2.5 concentration for all-cause mortality based on a 15-year exposure to PM2.5 at the residential addresses. In the study the number of premature deaths, YLL, average YLL per premature death case and decrease in life expectancy were calculated using AirQ+. AirQ+, developed by the WHO, is a software tool for determining health risks of air pollution exposure. It has previously been used for the Nordic area, and it has also been compared and validated against other similar tools (Lethomäki et al., 2020). It enables users to apply CRFs for selected air pollutants, data regarding air quality, and data regarding the population in terms of population size, age distribution, and baseline mortality. With these data entered into AirQ+, it is possible to calculate the number of premature deaths, YLL, and decrease in life expectancy using different cut-offs and CRFs. No cut-off concentrations were used in the Orru et al. study based on the assumption that combustion particles are expected to be “equally” toxic at low concentrations as this principle had been applied in recent similar studies. However, this assumption greatly increases the number of attributable deaths, especially in areas with low PM2.5 concentrations. In the following, focus will be on attributable deaths. The population exposure to RWC induced air pollution from local sources was in the Orru et al. study based on both the modelled annual average PM2.5 concentration and the population density in different parts of the urban areas. For the air pollution modelling, wood usage, emissions factors and temporal (through the year) allocation of emissions were collected. In the modelling, a spatial resolution (size of grid-square cells) was e.g. 1 km × 1 km for Oslo. Only one year was modelled, 2013 for Oslo. Different dispersion models were used for all cities, e.g. using EPISODE (a 3D Eulerian-Lagrangian model) for Oslo. For each square km, 2013 official statistics was collected on the population, the population density and the age distribution of the population. Up to date total mortality data in the age group 30+ was applied, as no effects on premature mortality have been noticed among younger ages. However, people younger than 30 years, especially children, are also impacted by the air pollution.

The population-weighted PM2.5 concentration was calculated based on these data, i.e. in each grid-square cell the PM2.5 concentration was multiplied with its population. All products were then summed, and finally the sum was divided by the total population. Grids with a higher population density then contribute more to the population weighted mean concentration. However, using a population-weighted concentration introduce additional (and unnecessary) uncertainties. This is because the CRF is not a constant but a function where the health impacts per unit increase in concentration level continuously decrease with **increasing** concentration. The result is that using a population-weighted concentration will always give more attributable deaths. The choice of only focussing on one PM2.5 source (e.g. wood stoves), i.e. treating PM2.5 sources individually, and then summing up the results, will also always give more attributable deaths. Calculating an annual mean concentration based on temporal values will also always give more attributable deaths. The most correct way to use the CRF would be to limit the averaging approaches and use the CRF for each grid cell and with a temporal resolution. The average annual estimate of the number of premature deaths due to PM2.5 emissions from wood stoves was 232 for Oslo, with a 95% CI from 97 to 346 based solely on the CI of the CRF. In comparison the EEA calculated 390 attributable deaths due to all PM2.5 sources in Norway in 2023 (for 2021). I.e. a large discrepancy.

Mentioned uncertainties: 1) The authors pointed out that the concentration-response function choice has a crucial importance for the calculated health impacts. The selected CRF was based on exposure to PM2.5 in general, and not exclusively on RWC induced PM2.5, and it was based on the health impacts of secondary organic aerosols (SOA), which compared to secondary inorganic aerosols (SIA) and black carbon (BC)/soot has a significantly higher HR. **As already mentioned**, when using a population-weighted concentration in combination with the CRF, the shape of the CRF is disregarded, and is in practise regarded as a constant multiplied with the PM2.5 concentration. This introduces an unnecessary uncertainty, and results in more attributable deaths. 2) Another very relevant uncertainty mentioned is if wood-smoke particles, compared to other similar size ambient particles, pose different levels of risk. 3) The authors used home addresses air pollution concentrations as a human exposure proxy. However, pointing out the mobility of people, and they are therefore exposed to air pollution concentrations at different locations during a day (e.g. at work, at home, whilst commuting, during shopping). **In addition**, during a period of 15 years, many things will change, people will move to and from the area, the total population will change, technologies will develop and improve, the emission concentrations will change, the baseline mortality will change, etc. Hence, disregarding such influencing factors and making one year representative for a 15-year period becomes a serious weakness. 4) Their focus was only on local emissions and local impacts. However, pointing out that PM2.5 from wood burning is also transported long distances in the atmosphere, hence it can spread thousands of kilometres from where it was emitted. They pointed out that they only addressed ambient RWC concentrations, i.e. the RWC contribution to indoor air pollution was not assessed. **In addition**, people are also not exposed to the ambient conditions 24-7 but are in fact staying indoor more than outdoor, and this is also age related. Hence, people are then in many cases not exposed to such high concentrations and for so long duration as implied by the study assumptions.

Other considerations connected to uncertainties: **Particles - why particles are not particles:** Particles are the most important health impacting emission - a fact. However, different particle types and properties are not considered in main health impacts assessments (e.g. EEA), and the focus is on PM2.5, as an annual mean mass concentration. Health effects from particles differ due to different physicochemical properties, resulting all the way from the fuel, through the combustion process, to atmospheric conditions and reactions, to inhalation and fate in the human body. Primary carbonaceous particles are carriers for several other organic and inorganic pollutants/elements, with health impacts different than the carbonaceous structure itself. The extent to which particles reach the air that you are breathing depends on the emission sources and atmospheric conditions, controlling their airborne lifetime and dilution. For modern wood stoves the relative distribution of the different particles contributing to PM2.5 will be very different compared to old wood stoves, and hence treating all wood stove technologies in the same manner introduces also a significant uncertainty. The chemical composition of the particles change as the combustion process is improved, where for modern wood stoves it is mostly condensed tars and SOA, that has the highest HR, which is reduced. **According to IEA** (Nussbaumer, 2017), organic particles and condensables as found from manual combustion under non-ideal conditions exhibit a high cell toxicity, while inorganic particles as found in flue gases from properly operated automated biomass combustion systems reveal far lower or even undetectable cell toxicity under the investigated conditions. This is in line with Hvidtfeldt et al. (2019), where the SOA CRF has the highest HR. The particle formation processes are very complex and results in particles with very different characteristics, and potentially different health impacts, and using the same HR for all particles is a huge simplification. Using an all-cause CRF, which is commonly done, is also a simplification. **Particles - how are they dispersed?** Following possible reactions, they are diluted in the atmosphere. Dispersion is heavily dependent on atmospheric conditions, height of emission source, topography, weather conditions (e.g. rain) and particle properties. CFD modelling tools are increasingly used to model the dispersion and the final particle concentration at a certain location, however with limited grid resolution and many simplifications. Particles in such a modelling tool are treated as a black box. Hence, it is “impossible” to predict where specific particle sizes with specific physicochemical properties ends up, only where black box particles end up (with a certain accuracy) based on a particle size distribution with defined aerodynamical properties. Measurement stations can measure pollutants in the air, but with contributions from many sources and a wide geographical area. A particle size distribution can also be measured (optically or gravimetrically) and in principle it is possible to analyse the physicochemical properties of the different size fractions. Carbon-14 dating can say if particles originate from biomass or fossil fuels. Some health impacting compounds in particles very likely originates from biomass combustion. However, particles can also originate from far away. **Particles - which compounds and elements have health impacts?** The following elements when part of particles have guideline values: As, BaP, Cd, Hg, Ni and Pb. However, they are not included in the annual EEA health impacts assessment. In fact, the health impacts assessment does not distinguish between the source of the particles, nor the particle size distribution within one particle category, i.e. PM2.5. In fact, the health impacts of the particles are based on particles in general. The specifics of wood log combustion and the resulting particles are not caretaken at all. **Particles - how are particles treated in health impacts assessments?** Black box particles. PM2.5, with no particle size distribution in the PM2.5 range. CRF based on knowledge of the health impacts of particles in general, but SOA, SIA and BC/soot CRFs exist. **Particles - how are the health impacts results presented?** As specific values, e.g. attributable deaths. By EEA, without any uncertainty given in 2023, while recently also with CI (EEA, 2024). In some other assessments, e.g. Orru et al. (2022), with a 95% Cl based solely on the CRF, a CRF which is commonly an all-cause CRF, and based on particles in general. Hence, no other uncertainties are caretaken, underestimating the real CI. In conclusion, there is a great need to turn what is now more a calculation exercise providing qualitative results into a more comprehensive approach providing quantitative results. Presenting the calculation exercise results as truth is not appropriate. Presenting it with all major uncertainties caretaken is better. Still, knowledge and tools must be developed to make that possible.

* 1. Discussions

**Emission factors and real life:** Emission factors for wood stoves that are included in national emission inventories are solely derived based on testing according to a test standard, typically a type approval standard which can be far from the real-life use of the wood stove. Additionally, the accredited test institutes that are carrying out the type approval testing are striving to achieve the lowest emissions and are selecting the fuel and operating the stove, within the allowed flexibility, to achieve that. Hence, the emission factors are not useful in the quantification of health impacts. NS94 represent the type of test standard that comes closest to mimic real-life use of wood stoves of the established type approval standards, and especially when the testing according to the standard is carried out at a research institute (e.g. SINTEF), and not a type approval institution. Emission factors derived using NS94 used in atmospheric dispersion modelling provides relatively good fits with emission measurements carried out by emission monitoring stations, as mentioned earlier. **Health impacts assessment methods:** Large differences in health impacts can result from using different health impacts assessment methods and assumptions. Even if using the same assessment tool, as the established AirQ+ tool, still different choices and assumptions will heavily influence the results. E.g. the use of an emission threshold value or not makes a lot of difference, as well as the chosen threshold value itself. When the aim is to quantify the health impacts and distributing the responsibility for these health impacts on the different emission sources, this becomes serious. One should therefore be careful when making statements based on such assessments. In general, too specific statements are provided, given the large uncertainties involved. From a fact-based scientific viewpoint, more focus should be put on estimating and reporting the uncertainties connected to the assessment and the specific numbers reported. Stating specific health impacts numbers due to emissions of single emission compounds from single technologies when knowing the uncertainties connected to their establishment, should not be done without also assessing and presenting all relevant uncertainties. That said, drawing more general conclusions and pointing out the need to continuously focus on emission reduction, from any technology, is very appropriate. **Health impacts of single emission compounds and technologies:** While it would be very good to be able to quantify the health impacts of single emission compounds and technologies, this is a very challenging task with high levels of uncertainty connected to it. Major uncertainties are connected to the representativeness of measurements from a limited set of emission monitoring stations and their expansion to be valid for a larger area, i.e. a country. Emission factors for all relevant emission sources are needed to be able to source the contribution of single emission sources to the dispersed emission measured by the emission monitoring stations. Major uncertainties are connected to atmospheric chemistry and physics influencing the dispersion of emissions from single emission sources and the final state of the emissions. The health impacts of single emission compounds inhaled by individuals are also uncertain, and the emission compound (PM2.5) that influences health the most, due to its characteristics and concentration in the air, is commonly treated as a black box, where the physiochemical properties of the particles are not considered, nor is the particle size distribution in the PM2.5 range. The latter influence where the particles are ending up in the body. The health impacts are mainly a result of exposure to emissions over many years, with changing seasons, atmospheric conditions and discontinuous and seasonal use of the emission producing technologies, especially wood stoves. The influence of the emissions also differs between age groups, gender and the general health condition of individuals, and there might be several contributors to the health impacts, e.g. the cardiovascular and hearth related impacts. I.e., the issue of relating long-term health impacts to specific emission sources becomes very complex, with high levels of uncertainty connected to it. **On the making of specific statements based on the current knowledge:** Stating a specific number of people that dies each year in a country or city due to a single emission compound from an emission sector or a single technology, without quantifying the connected uncertainties, is not appropriate. The EEA today base their health impacts estimates mainly on measurements from emission monitoring stations but have also started to consider results from atmospheric dispersion modelling in the estimations. They report contributions to health impacts from different groups of emission sources, e.g. residential activities, which is based on estimations of relative emission contributions from the groups of emission sources. Large uncertainties are connected to these health impacts estimates. It is understandable that the EEA and national authorities want to provide specific numbers to showcase the status and point towards the need for reducing emissions further. However, this should not be done without also quantifying and reporting the connected uncertainties. EEA has now started to provide CI, which is good and appropriate. However, more work is needed to improve both data and methods used in the estimation of health impacts due to emissions to air. Attempts to make more detailed and potentially more accurate health impacts estimations for local areas, e.g. cities, are made, using atmospheric dispersion models in combination with measurements from emission monitoring stations. However, even at this scale significant uncertainties are connected to the estimations, and the results are heavily influenced by assumptions made. Hence, also at the city scale specific statements should be avoided, and uncertainties should be quantified and reported.

* 1. Conclusions

This review has targeted the current knowledge and key data and assumptions behind the health impacts numbers due to emissions to air presented by official institutions as the EEA and by scientists in scientific publications. Typically, health impacts estimations are presented as truth, without sufficiently pointing out the uncertainty connected to the specific numbers given. Then conclusions may be drawn based on a too weak foundation. There is a great need to increase the knowledge and data base and methods used, including uncertainties quantification. In the case of wood stoves, they represent an important contribution to the renewable energy system in many countries. Any estimations of health impacts from wood stoves, or other emission sources, must be fact-based and as accurate as possible. Drawing specific conclusions based on a weak foundation must be avoided, but this is not uncommonly done, especially by groups or individuals opposing the use of e.g. wood stoves on a general basis. Focus should rather be on replacing old technologies and developing new or improved technologies, and then one can for sure say that this contributes to less air pollution and less health impacts. But exactly how much the health impacts are reduced, that is still an open question.

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