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and Gender Equality**
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Clean Air Testzone MUDP-project

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1. Summary and conclusions

While new clean-burning woodstove technologies have been developed and tested in laboratories, their real-world emissions reduction effects under actual operating conditions by consumers remained undocumented. This project aimed to establish a Clean Air Testzone to evaluate the local environmental impacts when deploying advanced woodstove combustion technologies, emission filters, chimney optimizers, and user training on proper firing techniques.

The location of the Testzone was chosen based on two main selection criteria:

1. A high spatial density of woodstoves with frequent use.
2. A location distanced or shielded from other emitters or pollution sources.

The selected Testzone was a neighbourhood in a suburb of Aarhus, Denmark, and covered approximately 130 single-family homes, including 50 homes with woodstoves/fireplaces of varying ages and usage patterns based on chimney sweep reports, of these 25 households participated in the project in the period 2020-2023. This provided the needed diversity to assess the selected mitigation measures: new stoves, chimneys, filters, draft optimizers, and education. At each household, one or more interventions (new woodstoves, chimneys, addition of filters and/or draft optimizers, participation in training courses) were carried out. The interventions had to be allocated in a way that would allow to measure their effects against a noisy background. Distributing the interventions both in space and time was therefore a crucial part of the project.

The effect of the interventions was quantified both by ambient air quality measurements and measurements directly in the flue gas at selected participants. A monitoring network of sensors for indoor and outdoor air quality parameters was established in the *Testzone*. For outdoor air quality assessment, the sensor network consisted of four sensors measuring the concentrations of carbon monoxide (CO), nitrogen dioxide (NO₂), and particulates in three size classes (PM₁, PM_{2.5} and PM₁₀), as well as meteorological data in terms of temperature and relative humidity. These were supplemented by an additional sensor outside the *Testzone* to determine a background signal. A total of 20 indoor air quality sensors were installed to evaluate the effects of the interventions on the indoor air quality and monitoring the use of woodstoves in the participating households. Using the obtained data, advanced models were applied to correct for meteorological effects and seasonal variation in stove use. Ambient air quality measurements showed a clear seasonal variation of local particle emissions, suggesting woodstoves have a strong influence on local air quality. Furthermore, a decrease in the local emissions from the Testzone could be observed from season to season over the project period. This trend is particularly evident in PM₁ and PM_{2.5} while less evident for PM₁₀ (see section 5.1, FIGURE 24, FIGURE 25 and FIGURE 26).

Direct emission measurements were carried out at nine participating households, both before and after the respective intervention. These measurements were carried out using lab-grade equipment. Emissions of particles, CO, organic gaseous carbon (OGC), and nitrous oxides (NO_x) were measured, along with flue gas temperature, draft, and fuel consumption. Due to the size and complexity of the instruments, these measurements were carried out for a few hours at each location, typically spanning 4–5 charges. The results show that baseline measurements (i.e., before the interventions) vary significantly among participants, where the average concentration of particles over all charges range between 30 to 212 mg/m³, the concentration of CO between 2846 to 7871 mg/m³, and OGC concentrations between 158 to 2402 mg/m³. After the intervention, less variation was observed among participants. Globally, a decrease in emissions of particles, CO and OGC was seen for all participants. On average, particle emissions de-

creased by 40%, CO by 25%, and OGC by 43%. As a general observation, the largest improvements were achieved at locations with the highest baseline emissions. NO_x emissions were seen to increase by 15% (but remain within the limits acceptable under type testing), probably due to more efficient combustion at higher temperatures. In summary, measuring directly in the chimney showed that all interventions had the potential to reduce emissions from woodstove firing. No single intervention proved most effective – instead, the emission reduction depended highly on the state of the installation and the stove user's firing technique.

To address the challenges associated with woodstoves and their impact on indoor air quality and particle emissions, two complementary models were developed. The first model aims to assess the risk of indoor particle emissions from individual wood-stove installations, considering various factors related to the chimney, building, and stove characteristics. By identifying and scoring potential risk factors, this model can provide a simple tool to predict the likelihood of particle emissions and evaluate the indoor air quality hazards associated with specific setups. The development of the indoor climate model is based on several risk factors for increased pollution of the indoor climate, which are associated with errors and deficiencies in the individual parts of a woodstove installation. Risk factors associated with incorrect use and poor quality of firewood are considered as well. From the observations made in the field, it has become clear that the chimney construction, including its height and insulation condition, have the largest influence on particle contamination of the indoor climate. The second-most important factor is the tightness of the house and the possible presence of mechanical exhaust and ventilation. Together, these two conditions determine the buoyancy and thus the chimney draft that can be achieved. The second model focuses on simulating and estimating particle emissions from individual woodstove installations, combining knowledge of chimney buoyancy and particle release during combustion. The model was applied to the total of 59 woodstoves located in the *Testzone* area, i.e., including households with stoves that did not participate in the project. The total particulate emissions from the area were estimated at 95 kg for an average heating season. For individual installations, a high intensity of use combined with a low-quality installation (e.g., due to old technology or a poor chimney) leads to the largest particle emissions. For example, the installation that generates the most particles emits as much as the 25 average users of wood-burning stoves in the area.

DCE, Aarhus University has contributed to the project with emission estimates on national level and for the test-zone. Parameters from the national emission inventory prepared by DCE, Aarhus University were used to estimate emissions from woodstoves on national level and for the *Testzone*. Results from the chimney measurement carried out in the *Testzone* were used to estimate effects of the interventions, which were compared to the emission factors used in the national emission inventory. Scenarios was set up on national level to illustrate the potential effect of expanding the interventions to the national level. Five scenarios were considered; three focusing on technology and two focusing on installation of ESP filters.

In general, the emission factors estimated from the chimney measurements in the *Testzone* are a factor lower than the emission factors used in the national emission inventory for stoves of similar technologies. These differences may result from different methods used to measure particle concentrations for the national emission inventories and the measurements in this project, respectively. Uncertainties in the data and assumptions used for the emission inventories as well as the large statistical spread between measurements in the project may further complicate a comparison.

2. Clean Air Testzone

Use of woodstoves for residential heating is a relatively cheap source of energy with a low CO₂ footprint. However, the use of woodstoves is a significant contributor to the observed total air pollution: in Copenhagen, it is assessed that woodstoves is one of the two major local source of air pollution, besides traffic. Air pollution causes severe health problems and can contribute to early deaths. In this project, a *Clean Air Testzone* was established to demonstrate the effects of state-of-the-art woodstoves, flue gas cleaning technologies, and consumer education on air pollution attributed to residential woodstove use.

2.1 Overall description of the project

In recent years, there has been a large development within the design of woodstoves and emission reduction technologies for woodstoves. These technologies have all been developed and tested in laboratory settings – i.e., under ideal conditions to optimize the efficiency and reduce unwanted emissions. However, user behaviour and local conditions are known to have a large impact on the actual efficiency and emissions. Hence, the technologies' effect on reduction of emissions under real-life conditions remains undocumented.

This project aimed to demonstrate the effects on the local environment when implementing state-of-the-art technologies for combustion and reduction of emissions from woodstoves. Through this project, the effects of new low-emission woodstoves, filters, chimney and draft optimizers, and education in firing techniques were evaluated using sensor networks for particle and NO_x measurements to demonstrate the real-life effects of these emission reducing technologies. Sensor data for the indoor and ambient (outdoor) air quality were collected over the course of three years to assess the baseline levels (year 1), the effect of one set of interventions (year 2), and the effect of combined interventions (year 3). To enable comparison between different firing seasons with different weather conditions and changes in user behaviour, advanced modelling was performed to evaluate the air pollution attributed to woodstove use and the emission reduction effect per firing. Furthermore, models were established to estimate the emission from individual woodstoves and their influence on the indoor air quality. Finally, emission estimates from the *Clean Air Testzone* were compared to the national emission inventory to examine whether these estimates could contribute to improvements of the national emission factors.

Throughout the project, a high degree of user involvement was sought, as user behaviour was expected to have a large influence on the combustion efficiency, and thereby the emissions. Furthermore, user involvement was necessary to complete precise measurement campaigns over three firing seasons.

2.2 Selection of the *Clean Air Testzone*

In this project, a *Clean Air Testzone* was established to evaluate the local effects of implementing new low-emission woodstoves and emission reduction technologies. In this regard, a suitable location without significant influence from surrounding emitters were necessary.

Two main criteria for selection of the test location were defined:

1. A high spatial density of woodstoves with frequent use.

2. A location distanced or shielded from other emitters or pollution sources.

A large concentration of woodstoves in use is necessary to ensure a large effect of the initiatives implemented in the area. Potential areas in the municipality of Aarhus were identified by DCE - Aarhus University based on data available through BBR and their SPREAD model.^{1,2} Seven possible locations identified are located in suburbs and commuter towns, as seen in FIGURE 1. Frequency of stove use in these areas was assessed by the local chimney sweeper. The potential areas were subsequently examined relative to criterion 2, given that the test area should be relatively free from outside influences, so that observed changes in air quality could be more easily attributed to interventions in the project. This included e.g. distance from industrial areas, major traffic thoroughfares (road, rail), and agricultural combustion units (straw boilers), but also distance from other areas with a high density of woodstoves. For the latter, the predominant wind direction was also considered.

Overall, locations 5 (Mårslet), 6 (Beder), and 7 (Malling) matched these criteria best. The final choice of Mårslet was due to practical considerations, such as the availability of lampposts to install a sensor network. The area selected for the *Clean Air Testzone* project is a residential area with approximately 50 single-unit homes with a woodstove or open fireplace. The neighbourhood consists of a main road with several shorter branches and has no through traffic. Stoves installed differ by age and frequency of use, according to information from the local chimney sweeper. These conditions should provide a good opportunity to evaluate the effects of different measures, such as new woodstoves, new chimneys, filters, or draft optimizers. An overview of the selected location for the *Clean Air Testzone* can be seen in FIGURE 2, including the distribution of woodstoves/fireplaces in the area.

¹ Plejdrup, M.S., Nielsen, O.-K., Gyldenkerne, S. & Bruun, H.G. 2021. Spatial high-resolution distribution of emissions to air – SPREAD 3.0. Aarhus University, DCE – Danish Centre for Environment and Energy, 208 pp. Technical Report No. 215 <http://dce2.au.dk/pub/TR215.pdf>

² Plejdrup, M. S., Nielsen, O.-K. & Brandt, J., 2016: Spatial emission modelling for residential wood combustion in Denmark. *Atmospheric Environment*. 144, p. 389-396. <https://www.sciencedirect.com/science/article/pii/S1352231016307130?via%3Dihub>

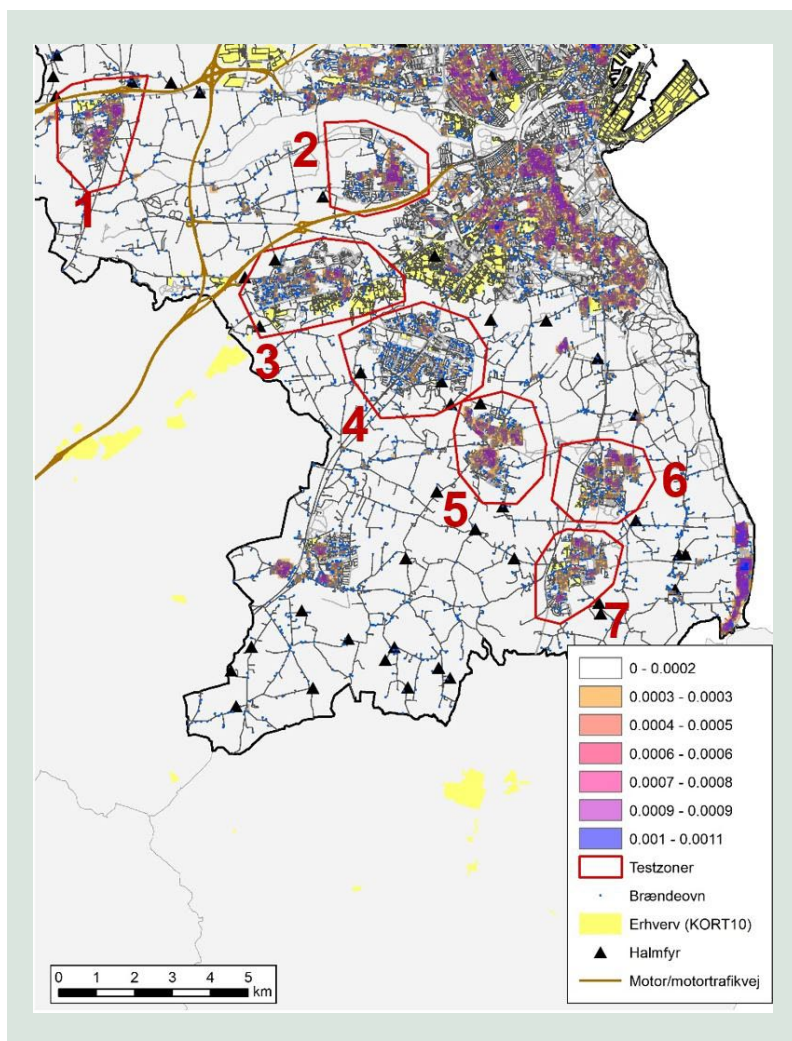


FIGURE 1. Map of woodstove concentration in the municipality of Aarhus. 7 possible locations for the *Clean Air Testzone* were identified, namely: 1. Harlev, 2. Stavtrup, 3. Hasselager, 4. Tranbjerg, 5. Mårslet, 6. Beder, and 7. Malling. Other emitters marked on the map: Industrial areas (yellow shade), agricultural straw combustors (black triangles) and major roads (brown).

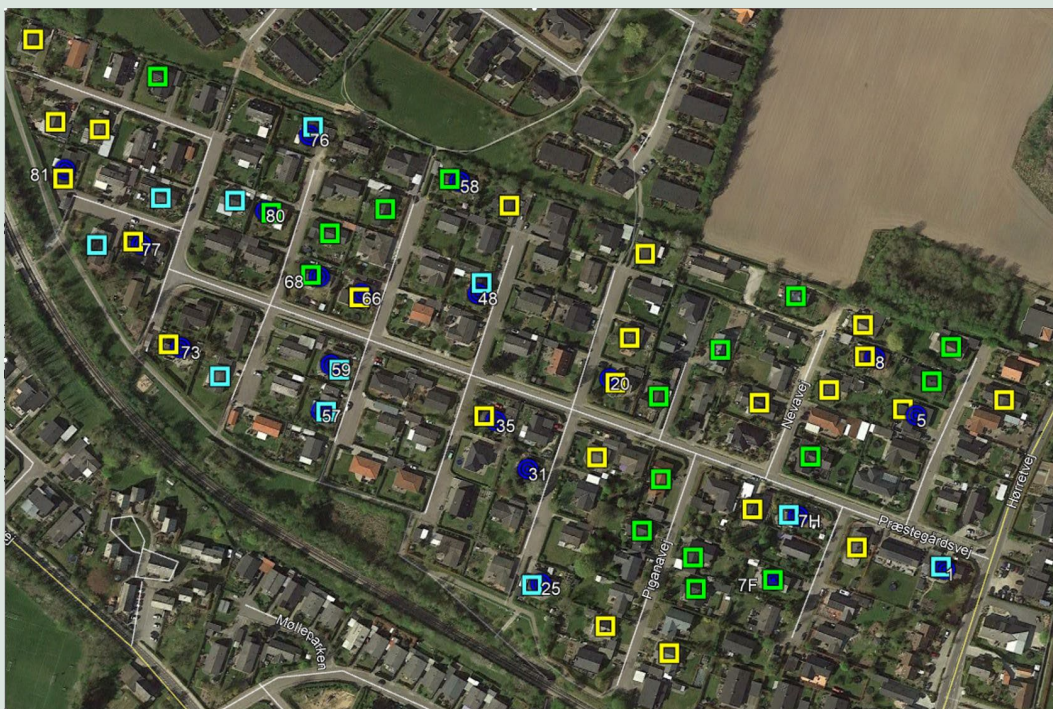


FIGURE 2. An overview of the location selected for the *Clean Air Testzone*. Coloured boxes represent the presence of a woodstove or a fireplace, the colours indicate the reported use from the local chimney sweeper. Green: Light use; Yellow: Moderate use, Turquoise: Heavy use.

2.3 Establishment of the *Clean Air Testzone*

The success of the project depended on a high number of active participants in the *Testzone*, as all interventions were carried out in private homes of volunteers. Involvement of the local citizens was therefore of very high importance. An information and recruitment campaign were initiated with information leaflets and a community information session highlighting the purpose of the project and the possibility to be a part of it. At the end of this campaign, 25 households had signed up for the project and were willing to have their current installations changed (new woodstoves, chimneys, addition of filters and/or draft optimizers) and participate in training courses.

To evaluate the effects of the interventions carried out in the *Testzone*, a monitoring network of sensors for indoor and outdoor air quality parameters was established. For outdoor air quality assessment, the sensor network consisted of four sensors measuring the concentrations of carbon monoxide (CO), nitrogen dioxide (NO₂), and particulates in three size classes (PM₁, PM_{2.5} and PM₁₀), as well as meteorological data in terms of temperature and relative humidity. Out of the emissions monitored, particulates are considered the most harmful pollutants from residential wood combustion and are therefore the focus of this project. The sensors were placed on lampposts with an approximate height of 4 meters. Power was supplied by the streetlights. Therefore, a built-in auxiliary battery was necessary to cover periods when the light was turned off. As the initial battery proved insufficient for this application, special external batteries were designed and installed by Danish Technological Institute.

To evaluate whether changes in the outdoor air quality in the area arise from local changes or from changes in long distance particle transport, a reference sensor was installed on the outskirts of Mårslet. The reference sensor is far away from local woodstoves or other major sources of particulate emissions. For further analysis, this sensor was supplemented with a local weather station measuring wind speed and wind direction.

A total of 20 indoor air quality sensors were installed to evaluate the effects of the interventions on the indoor air quality and monitoring the use of woodstoves in the participating households. Measured values included temperature, CO₂, relative humidity, PM₁₀, PM_{2.5}, light intensity, and sound.

3. Interventions in Mårslet

Several interventions have the potential to reduce woodstove emissions. A central aim of this project was to distinguish the effect of these interventions, both when applied alone and in combination. The interventions had to be allocated in a way that would allow to measure their effects against a noisy background. Distributing the interventions both in space and time was therefore a crucial part of the project.

3.1 Types of interventions

The emissions from woodstoves are influenced by several factors: the woodstove itself; possible auxiliary equipment such as filters and draft optimizers; the integration of woodstove and chimney/flue gas duct (by supplying draft); the building (influencing air supply and draft); quality of firewood; and the operating technique. This project focussed on stoves, filters, chimneys, and draft optimizers, as well as training in correct stove use.

3.1.1 Replacing woodstoves

Woodstove technology has advanced in recent years, aiming at reducing emissions (especially particulate matter) and improving fuel efficiency. Emissions and efficiency are mainly influenced by air flow and air distribution to the stove, combustion chamber design (dimensions, insulation), as well as heat transfer in the post-combustion chamber. Modern woodstoves have demonstrated lower emissions in mandatory type tests. However, these emission specifications can typically only be met within a narrowly defined interval of operating conditions. These conditions include draft (supplied by the chimney) and firing technique. Therefore, results from type tests, which take place in a laboratory setting, cannot fully predict behaviour in actual installations. The behaviour of modern, optimized stoves in the field is poorly documented.

Within this project, exchanging the existing stove for a new one was the most visible and also the most sought-after intervention. Existing stoves in the area were installed between approximately 1985 and 2019, with most stoves originally installed in the early 2000s. In 2008, newer and more stricter emission requirements for residential woodstoves were implemented in Denmark. For most of the participants, exchanging the stove would therefore be a significant upgrade. New stoves come with a short user's guide. Participants did not receive any guidance from the project whether to follow this guide or whether to continue their previous firing methods. It is however expected that several participants adapted their technique. Observed changes are therefore likely a compound effect of new equipment and change in use.

Woodstoves produced by Aduro, Heta, Hwam and Morsø were used in the project, with different models from each manufacturer.

3.1.2 Installation of filters

The common technology for filtering particles from woodstove flue gases is electrostatic precipitation. A static charge is induced in the particles as they pass through the top of the chimney. The potential difference between particles and chimney is used to precipitate the particles on a designated collector surface. Commercially electrostatic precipitators have an integrated flue gas fan to ensure proper draft and flow in the precipitator section. This will generally also improve

stove operation (similar to a standalone draft optimizer). Filters can be retrofitted to existing installations. In some cases, this may require adapting the chimney.

ESP-filters used in this project were supplied by Exodraft.

3.1.3 Installation of new chimney or draft fan

Woodstoves take the air necessary for combustion from the surrounding room. To maintain a constant flow, the pressure in the stove must be lower than in the surroundings. The low pressure is typically generated by the stove itself, as hot flue gases rise through the chimney, creating a vacuum that draws in fresh air (natural convection). Insufficient draft will result in poor combustion, creating a feedback loop as flue gasses become cooler. This problem is even more pronounced for new stoves due to their lower design flue gas temperature (lower flue gas temperatures mean a higher thermal efficiency, but less draft generation).

Older residential buildings often have over-dimensioned chimneys and flue gas ducts, especially when used in connection with a new stove. As a result, the chimney does not heat up sufficiently to provide natural draft. Additionally, older chimneys may have leaks and draw air from the surroundings, which limits draft. A possible solution is to install a chimney liner, which provides a leakage-free passage for flue gasses and limits the available flue gas cross section – resulting in higher gas velocities and less heat dissipation to the chimney. An alternative to this improved natural convection is to operate the stove with forced convection. In this case, a draft fan (often called “draft optimizer”) is installed at the chimney top. The draft fan maintains a constant, lower pressure in chimney and stove.

For this project, steel and “Isokern” (a light concrete) chimney liners were supplied by Schiedel, and draft fans were supplied by BlueChimney.

3.1.4 Training in better firing techniques

Modern woodstoves are optimized to perform well under standardized laboratory tests. Very specific firing procedures must be followed to achieve the same level of emissions in actual installations. However, the typical stove user is self-taught, and firing techniques are often based on trial-and-error experimentation with firewood and air supply or learned from other users. Hence, emissions from woodstoves in private homes frequently exceed those measured in laboratory settings.

As a non-technological intervention, participants were trained in correct firing technique at Danish Technological Institute’s woodstove laboratory (FIGURE 3). The training session was supported by the local chimney sweeper, who had a role of a trusted advisor and thereby acted as a link between Danish Technological Institute and the project participants.

Training and supporting material (leaflets, etc.) were designed to emphasize four key points:

1. Ignition: Ignite from the top (see FIGURE 4).
2. Firewood: Use pure, dry wood with a maximum moisture of 18%.
3. Air supply: Do not close stove door fully for the first 5–10 minutes, then reduce air flow when flames have spread to all logs.
4. Appearance: Check smoke from chimney (should be transparent) and flames (no soot).

These four recommendations were chosen to be easy to remember and implement by participants. Some supporting hints were given during the training session to more advanced stove users:

- Check that the combustion chamber door closes tight (paper test).
- Use the correct log size.
- Storage of firewood to achieve proper moisture content:
 - o Hard wood (oak, beech): +2 years.

- Other deciduous trees (e.g., pine): 1–2 years.
- Modern stoves use less primary, and more secondary and tertiary air.
- Gently reduce air flow when flames have spread (a few minutes after ignition or refueling).
- Flames should appear 'light' and 'lively'.
- Refuel in regular intervals: approximately 1.5 kg firewood every 45–60 minutes.
- Check if smoke from chimney is transparent.

Furthermore, training participants received a simple wood log moisture analyser to use at home. Participants were also asked to guess the correct amount of firewood, by selecting logs that corresponded to 1.5 kg from a pile. It was found that participants generally overestimated the amount of wood necessary. Untrained users will likely tend to overfill the combustion chamber (this was also seen in some of the field measurements, see chapter 5).



FIGURE 3. Training session at DTI's woodstove lab, 2021.



FIGURE 4. Correct positioning of firewood logs and ignition technique. Top: small and medium sized stoves, bottom: large stoves.

3.2 Allocation of interventions

The project aimed to examine the effects of the different interventions on particle emissions using sensor measurements, thus allowing a quantitative analysis. Over the course of three firing seasons, particle emissions were monitored in the *Clean Air Testzone*. Baseline measurements were performed in season 1, after which the effect of one intervention or combined interventions were examined in season 2 and 3, respectively.

3.2.1 Participating households in the *Clean Air Testzone*

At the start of the projects, 25 households originally volunteered to participate in the project. Five participants stopped after the baseline season: one household had their stove removed without replacement, two households were passive throughout the project and did not respond to e.g.,

invitation to training, and two households were not interested in the intervention chosen for them. Hence, the dataset consisted of 20 households that actively participated in the entire project.

All participants were interviewed individually at the start of the project, concerning:

- Stove usage (frequency, problems with draft, etc.)
- Using stoves in conjunction with ventilation
- Other possible sources of indoor air pollution (e.g., smoking, pets)

Furthermore, the current state of stove and chimney were visually examined, and participants were asked to prioritize the available interventions in the project. The above information was used for the subsequent planning of the project e.g., allocating interventions. Furthermore, observations from the local chimney sweeper on the state of the individual installations and their use were also considered.

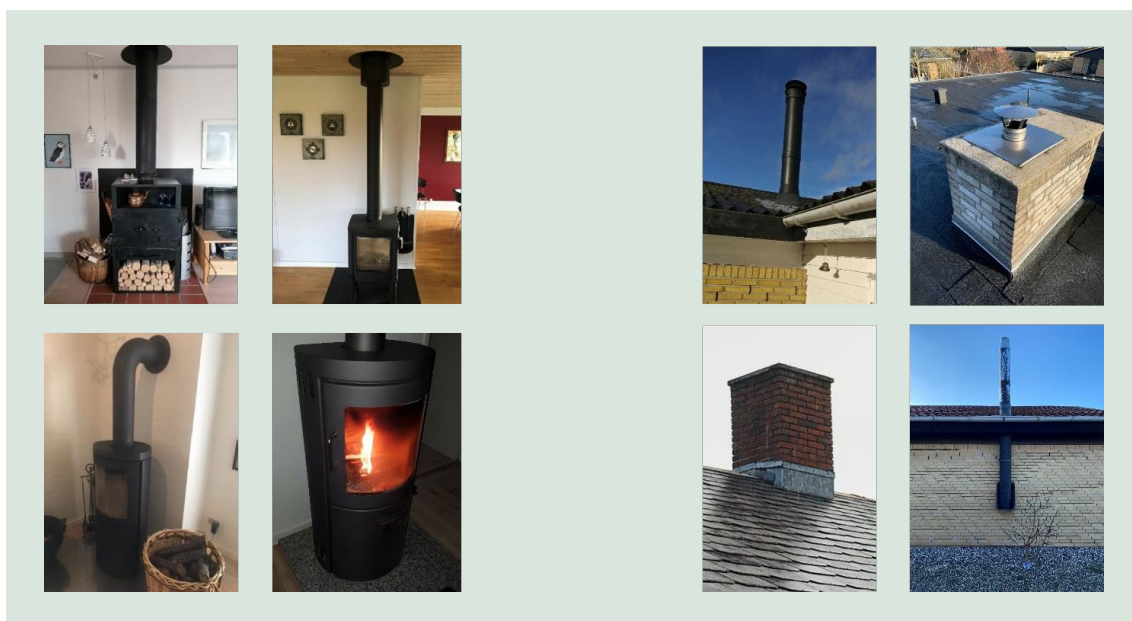


FIGURE 5. Examples of original installation of stoves and chimneys in the *Clean Air Testzone*.

3.2.2 Three clusters in the *Clean Air Testzone*

This project aimed to distinguish and directly evaluate the effect of different interventions using sensor measurements for evaluation of the ambient air quality. The *Clean Air Testzone* was divided in three clusters distributed around four air quality sensors. The *Testzone* was clustered with consideration to similar potential for upgrading/exchanging stoves (based on evaluation by DTI and the local chimney sweeper), the participants' own priorities and wishes, geographical location of participating households, and sensor positions. Sensor placements were limited to existing lamp posts due to the required height above ground and the availability of an electricity supply.

Clusters were formed with respect to the main wind direction, based on the assumption that wind would carry smoke plumes over the sensors – ideally allowing to distinguish plumes from individual clusters. Hence, all sensors were mounted slightly to the east of each cluster due to a main wind direction of west or southwest in southern Aarhus (Appendix 1.1, FIGURE 35). Based on location of participating households, grouping by planned intervention, and potential sensor positions, the test zone was divided into 3 clusters along the area's main road. FIGURE 6 shows the status at the start of the project, including recommendations and the participants' preferences. Other stoves in the area (households that did not participate in the project) are

shown for comparison. Participants that left the project after the first season are marked with dotted rings.

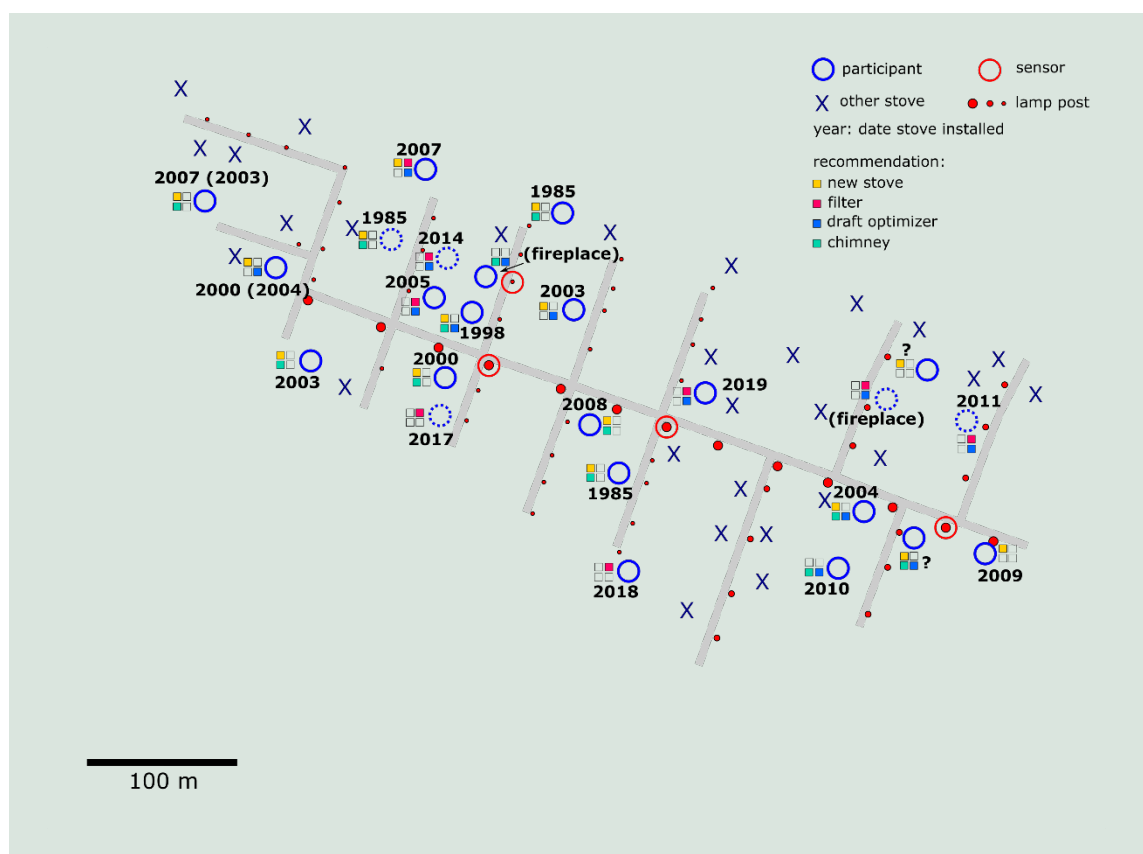


FIGURE 6. Schematic map of the *Clean Air Testzone* with status at start of the project. Two participants had an open fireplace instead of a woodstove. For two participants, there was conflicting information on the age of the stove. For participants marked ‘?’, the age of the stove could not be determined.

A secondary test zone in a nearby neighbourhood was included in the project to investigate whether an experimental, low-cost particle sensor mounted directly in the chimneys could be used for sampling in flue gas ducts and chimneys over longer periods. Midways in this campaign, draft optimizers were installed at the participants to investigate whether the effect of this intervention is detectable by low-cost particle sensors. Further information regarding the test setup, sensors, and results obtained from the secondary test zone can be found in Appendix 1.2.

3.2.3 Selection and allocation of interventions

The interventions were allocated according to the participants' priorities as far as possible. Exchanging an old stove for a new one was by far the most popular intervention (incidentally, one resident originally interested in the project quit after it could not be guaranteed their stove would be replaced). Equipment installation was carried out in the summer/autumn of 2021, and was completed at the start of the firing season 2021/22. In the largest cluster, cluster I, woodstoves were replaced by a new model. At two locations, a new chimney liner was installed at the same time. In cluster II, filters (ESP) were installed. Participants from cluster III received training in better stove use. The status at the start of the firing season 2021/22 is seen in FIGURE 7.

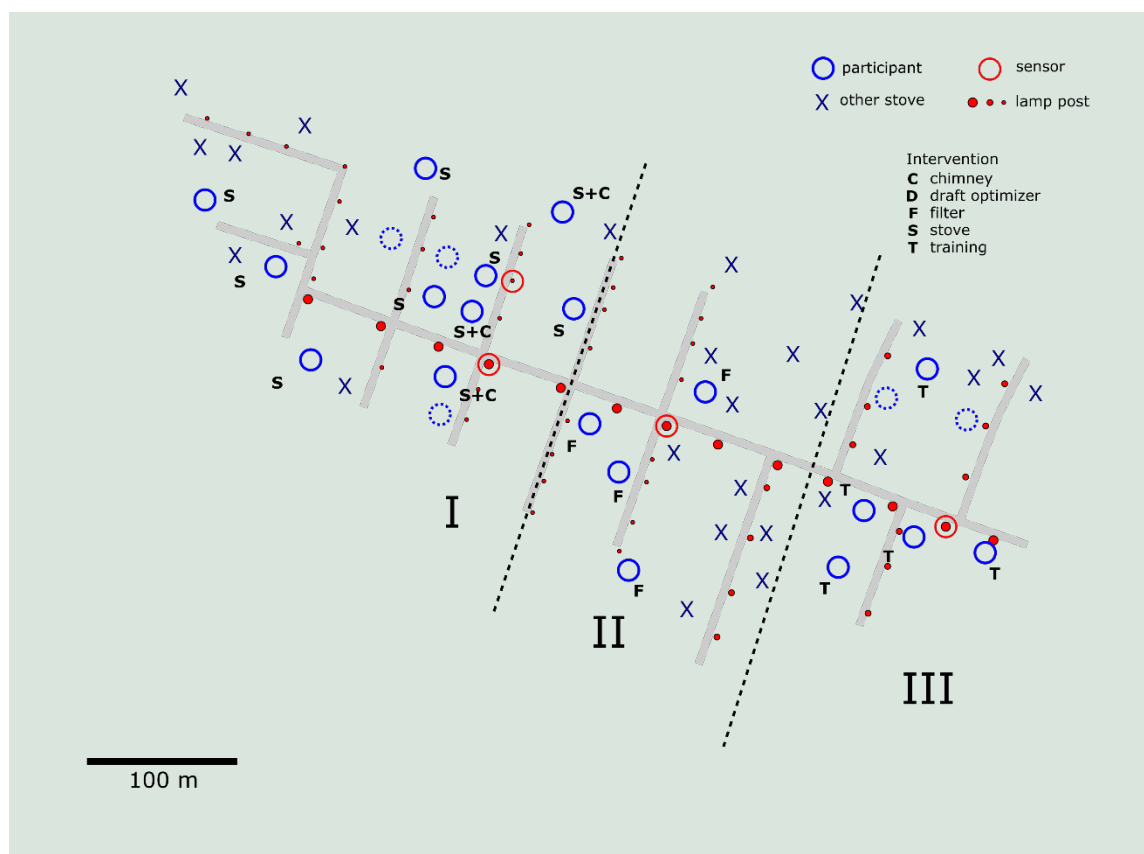


FIGURE 7. Status after intervention 2021/2022 (dotted rings: passive or withdrawn from project). Boundary lines between clusters I, II, and III are arbitrary and drawn as guide to the eye.

The second intervention was carried out from summer 2022 to winter 2022/23. While most installations were completed by the beginning of the firing season, installation of new chimneys was delayed due to long delivery times. The original division into clusters was loosened in this period. The first season had shown that the assignment of one sensor to one cluster each did not work well in practice. All in all, the interventions in the third season were: 7 new stoves (2 in cluster II, 5 in cluster III), 6 chimney/chimney liners (4 in cluster I, 2 in cluster III), 3 draft fans (2 in cluster I, 1 in cluster III), 2 filters (both in cluster III). All participants were invited to training, of which 7 participated (5 in cluster I, 2 in cluster III). The status during winter 2022/23 is seen in FIGURE 8.

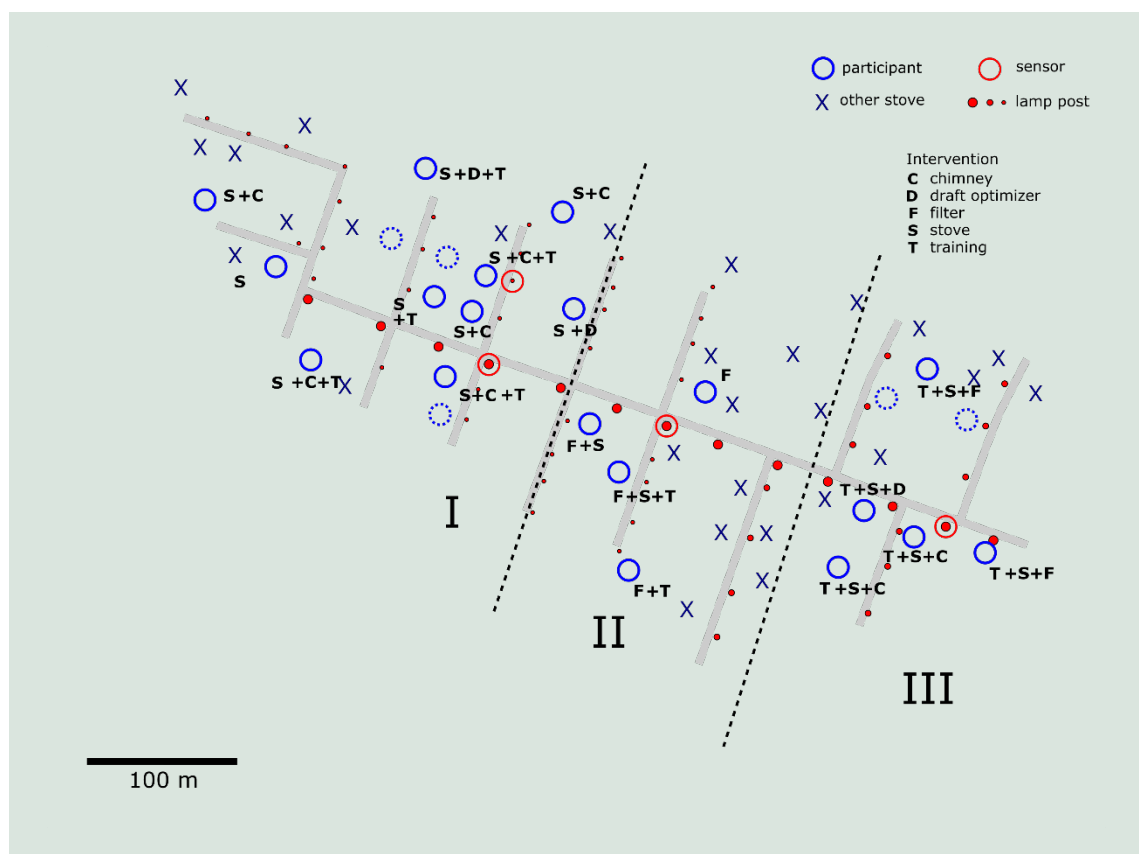


FIGURE 8. Status after intervention 2022/2023. Boundary lines between clusters I, II, and III are arbitrary and drawn as guide to the eye.

4. Methods for documentation of the effects

Point and continuous sensor measurements were used to document the reduction of woodstove emissions after the individual and combined interventions. Using the obtained data, advanced models were applied to correct for meteorological effects and seasonal variation in stove use.

4.1 Ambient air quality measurements

The use of so-called “low-cost” sensors allows the deployment of sensor networks for use in continuous measuring campaigns for ambient air quality. The sensors in this project were selected to measure the concentration of particulates present in the environment, since particulates are the most characteristic and concerning pollutant from woodstoves. The ambient air quality measurements were used to evaluate the effect of the interventions on the air pollution present in the *Clean Air Testzone*. Using advanced modelling, the data were corrected for meteorological effects and variation in stove use.

4.1.1 Establishment of ambient air quality sensor network

A total of five outdoor, low-cost sensors (Leapcraft *CPHSense*, see FIGURE 9) were placed in Mårslet, measuring temperature and relative humidity, the concentrations of carbon monoxide (CO), nitrogen dioxide (NO₂), and particulate subdivided into three different sizes (PM₁, PM_{2.5} and PM₁₀). The measurement of the gaseous pollutants was performed through solid state metal oxide sensors, while particulate was quantified through the principle of light scattering. The analysis of emissions will only focus on the above mentioned PM₁, PM_{2.5} and PM₁₀.



FIGURE 9. CPH sense ambient air quality sensors from Leapcraft.

Four sensors (labelled A1–A4) were installed in the end of November 2020 on streetlight posts located in the *Testzone* area with a height of around 4 meters apart from one, which was at a slightly lower height (around 2 meters). These sensors were powered directly from the electric

network at night (when the lamp was on), and by an internal battery during the daytime (when the lamp was off). The built-in battery was later replaced by special batteries designed and built by Danish Technological Institute (see FIGURE 10). The fifth sensor (A5) used for the quantification of the background pollution level was placed on a mast at Mårslet school. The background sensor was installed in January 2021 at a larger height and continuously powered from the electric network (see FIGURE 11).

All sensors were equipped with SIM cards and therefore able to continuously send the measured data to the Leapcraft cloud. Data were regularly and automatically downloaded through an API access from the Leapcraft cloud and stored in a dedicated database at DTI. The low-cost air quality sensor measurements were applied without the use of a calibration algorithm to correct for non-linearity in lower particulate concentrations, since the expected concentrations of particulates in the *Testzone* during firing seasons were within the linear response signals.

All four sensors in the *Testzone* showed a pronounced degradation in their performances over time (so-called “aging”) and a decrease in signals due to, among other factors, the harsh outdoor conditions, to which they were exposed to for a longer period. Thus, two sensors (A3 and A4) were replaced during the project in December 2022 (by A7 and A6, respectively). The background sensor located near Mårslet school was less affected by aging phenomena than the other units. An example of measurements suggesting sensor aging can be found in Appendix 2.1, FIGURE 38.



(a)



(b)

FIGURE 10. Ambient air quality sensor mounted on high (a) and low lamp posts (b). Figure (b) also shows the battery box on the post.



FIGURE 11. The sensor for qualification of background concentration (A5) was located on a mast in the area of Mårslet school.

4.1.2 Meteorological normalisation of ambient air quality measurements

In many cases, the effects of weather (or meteorology) on air quality are much more significant than the intervention put in place to reduce the emissions. Hence, meteorological normalisation^{3,4} was applied to the time series of the examined air quality parameters to account for the weather's influence on the observed reduction in emissions. Statistical modelling was employed in the meteorological normalisation to reduce the variability in the air quality time series. The reduction in variability was obtained by training a Random Forest model – a machine learning algorithm that employs multiple models to improve predictions, thereby creating a robust and accurate model – to explain a fraction of the variation of pollutant concentrations as a function of one or more independent variables. The statistical modelling was performed using R⁵ and the packages dweather⁶ and openair⁷, on a dedicated Linux cluster owned by Danish Technological Institute.

³ <https://doi.org/10.1016/j.scitotenv.2018.10.344> , Carslaw, David C., and Paul J. Taylor. "Analysis of air pollution data at a mixed source location using boosted regression trees." *Atmospheric Environment* 43.22-23 (2009): 3563-3570.

⁴ Carslaw, D.C., Williams, M.L. and B. Barratt A short-term intervention study — impact of airport closure on near-field air quality due to the eruption of Eyjafjallajökull. (2012) *Atmospheric Environment*, Vol. 54, 328–336.

⁵ <https://www.r-project.org/>

⁶ <https://github.com/davidcarslaw/dewweather/>

⁷ <https://davidcarslaw.github.io/openair/>

Initially, the model was optimized in relation to dependent variables to account for variability in the air quality time series attributed meteorological and time quantities. The used variables for general meteorological observations were temperature, relative humidity, wind speed and direction, in addition to time variables such as hour of the day, day of the week, or season. These variables functioned as proxies for the regular emission patterns connected to e.g., traffic, domestic heating habits or cyclic atmospheric chemistry processes (i.e., those connected with ozone levels). See Appendix 3.1, FIGURE 49 for the dependent's variables influence on measured PM_{2.5} concentrations.

Once the model was optimized to a level, where a sufficient amount of the dependent variable's variation could be explained, the influence of independent variables such as background pollutants caused by e.g., long-range transport phenomena, was accounted for by treating them as constant values. Using data collected from the background sensor, the background pollutant concentrations present in the *Clean Air Testzone* was subtracted in the model. By accounting for meteorological quantities, time quantities and background pollutants in the developed model, it was possible to obtain the emissions directly produced inside the *Testzone* using the final, thereby enabling a comparison of the effect of different interventions installed in the project (FIGURE 12).

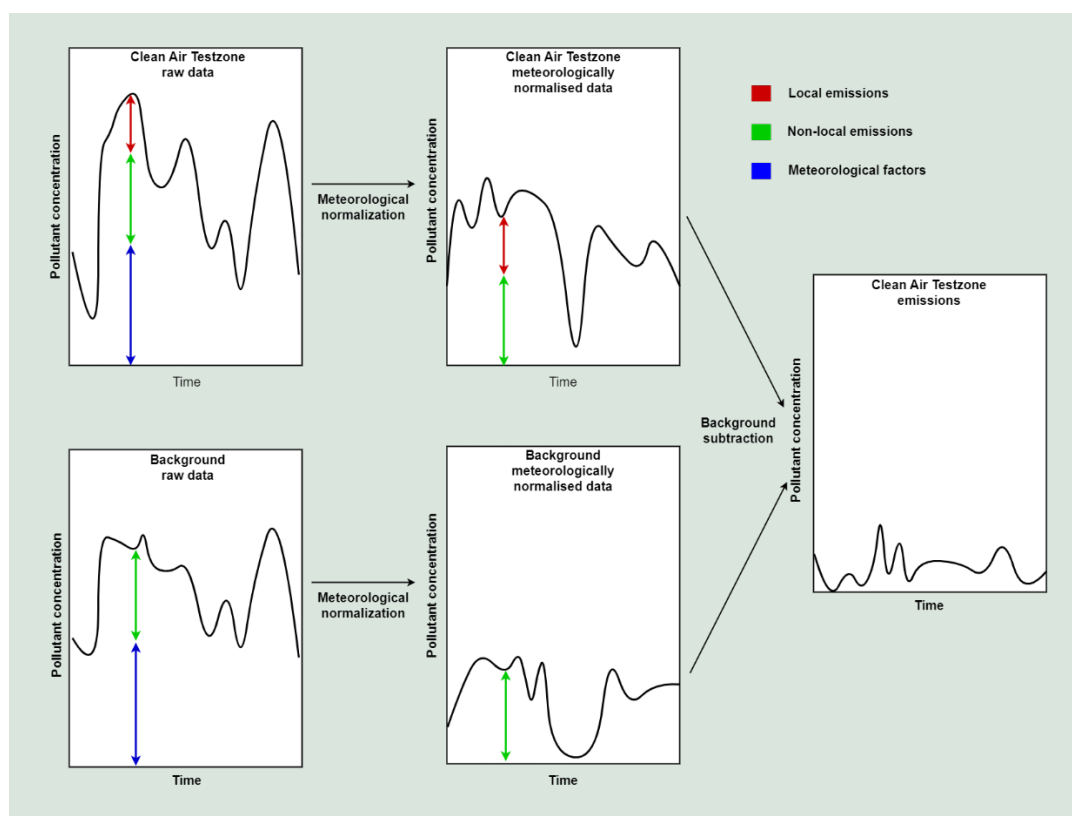


FIGURE 12. Determining local air pollution contribution from raw data, background data, and meteorological normalisation.

4.1.3 Data cleaning and de-aging of ambient sensor measurements

The ambient air quality in the *Clean Air Testzone* was assessed throughout the project using measurements obtained for PM₁, PM_{2.5}, and PM₁₀. As mentioned in section 4.1.1, the sensors were subject to aging during the project. Harsh weather conditions led to a degrading performance of the sensors. Reliable data could therefore only be obtained for parts of the project, and not necessarily for all locations simultaneously (See Appendix 4.2, FIGURE 50). To account for varying reliability in sensors, the local emissions were examined aggregated across the entire *Clean Air Testzone* (sensors A1–A4 and replacements A6/A7). The particulate measurements

were averaged over the active and reliable sensors. Hence, in some periods (e.g., winter 2020–2021, when all the sensors were brand-new and delivering reliable measurements) the reported value corresponds to the average over several sensor measurements. In other periods (e.g., winter 2022–2023, when only replacement sensor A6 was considered reliable) a single sensor had to act as a proxy for the measurements of the entire *Testzone*. Using this methodology, the overall impact of the interventions could be assessed. However, it was not possible to separate the impact of the interventions in the three individual clusters.

The background sensor A5 did not show any significant aging and was therefore used to numerically “de-age” the signal from sensor A2. Sensor A2 showed the least severe aging of the original four sensors installed in the *Testzone* (A1–A4). The de-aging was performed by using and comparing the sensor’s signal in global events. Global events were defined as episodes characterized by a significant, sudden, and persistent rise in the particulate concentration, considered to be the consequence of important meteorological changes and/or long-range pollutant transport phenomena. Hence, these episodes were assumed to be observable in a comparable intensity by all the sensors employed in the project. Global events identified in the background sensor data series were subsequently found in the timeseries for sensor A2. By determining the integral for the timeseries of global events and the ratios between the integrals for sensor A5 and A2 (See Appendix 4.2, FIGURE 51), a linear regression describing the deviation in signal intensity between sensor A2 and sensor A5 over time can be established (See Appendix 4.2, FIGURE 52).

The entire dataflow for the sensor measurements pre-processing outlined above is depicted in FIGURE 13 below. The data from this process were fed (together with the un-processed background sensor A5 data) to the meteorological normalization model described in section 4.1.2.

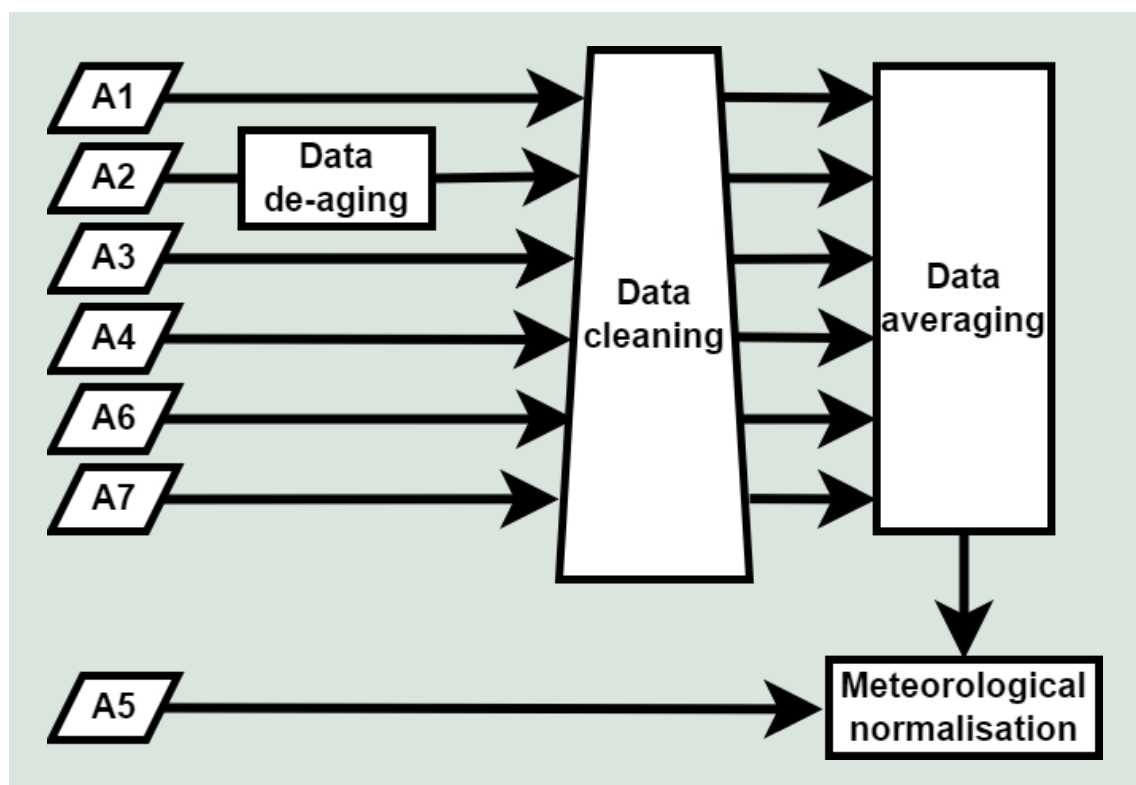


FIGURE 13. Dataflow for the sensor measurements pre-processing.

4.2 Direct flue gas measurements

To directly quantify the effects of the interventions, emissions were measured directly in the chimney of selected project participants. These flue gas measurements were carried out on site using gas analysis and particle concentration measurement equipment from DTI's woodstove lab (see section 4.1.2, below). Measurements were carried out before and after the intervention. Two participants per intervention were selected in the first season. The selection was based on scientific interest, suitability for measurements (e.g., place for analyser racks), as well as the participants' motivation. The selected households were a representative mix of the test zone concerning age and maintenance state of stoves, chimneys, frequency of use, etc. Parts of the measurement campaign had to be postponed due to Covid-19-concerns in winter 2020/21.

TABLE 1 below shows an overview containing a description of the houses/stoves included for direct flue gas measurements. Flue gas measurements at participants A–E were carried out before and after the first intervention, while the remaining F–I were carried out before and after the second intervention.

TABLE 1. Participants selected for flue gas measurements.

ID/Alias	Intervention	Year	Stove model, year installed
A	new stove + chimney	2021	Rais Mino, 2004 (1st measurement) Aduro Hybrid H1, 2021 (2nd measurement)
B	new stove	2021	Andersen 8, 2000 (1st measurement) Hwam 3120, 2021 (2nd measurement)
C	filter	2021	Aduro Hybrid H1, 2018
D	filter	2021	Contura 550, 2008
E	training	2021	Basic, 2002
F	training	2021	ABC Vivaldi, 2009
G	draft fan	2022	Hwam 3120, 2021
H	draft fan	2022	Aduro Hybrid H2, 2022
I	chimney	2023	Aduro 17, 2021

4.2.1 Experimental setup and procedure

Measurements were carried out using mobile equipment from DTI's woodstove lab (FIGURE 14) normally used for certifications, type testing, and research and development projects at DTI. Each measurement at participants A–I typically consisted of the ignition stage, as well as three to four refuelling charges. In a few cases, the first charge was missing as the participants had already started the stove before measurements could start. In other cases, measurements had to be stopped before three refuelling charges could be measured. Measured parameters included: Gaseous species CO, CO₂, NO and OGC (organic gaseous carbon), particles (mass) sampled on a filter over 30 minutes, flue gas temperature (for e.g., calculating woodstove efficiency), and pressure/draft.

Gases were measured in the dry flue gas. Measurements were normalized to 13% v/v O₂ and standard temperature and pressure in the flue gas. O₂ content was calculated from CO₂-measurements. Measurements were typically taken in the flue gas duct immediately above the stove (FIGURE 15). A special measuring section was installed at houses with filter interventions to measure particle concentrations after the filter installed at the end of the flue gas duct (FIGURE 16). Measurement of gaseous species, temperature, and pressure were continuous measurement, while particle measurements were carried out over a fixed time interval. Gas flow was recorded during the sampling duration to calculate particle concentrations. The obtained data are presented as integral or averaged values over one charge.

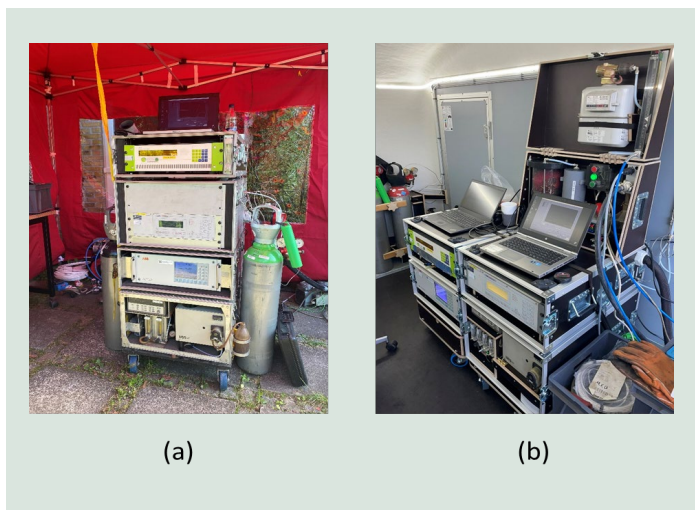


FIGURE 14. Analysis equipment for flue gas measurement. (a) as mobile rack, (b) built into a measurement trailer.

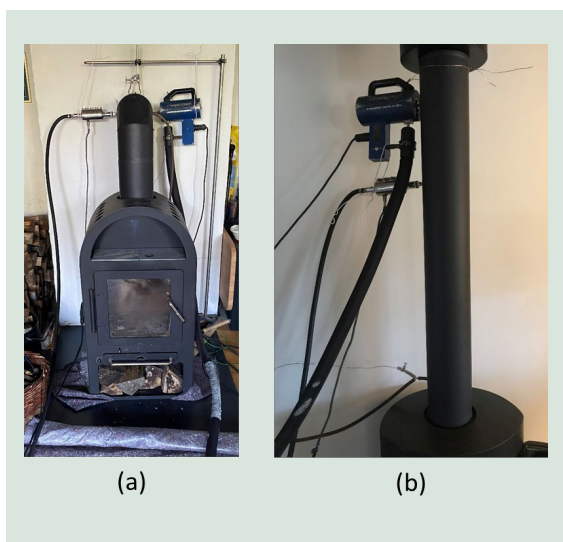


FIGURE 15. Normal measurement setup with sampling immediately above the stove. Blue: sampling probe for gas analysis, silver: particle probe, tube with “Y”-splitter (bottom right): temperature and pressure.

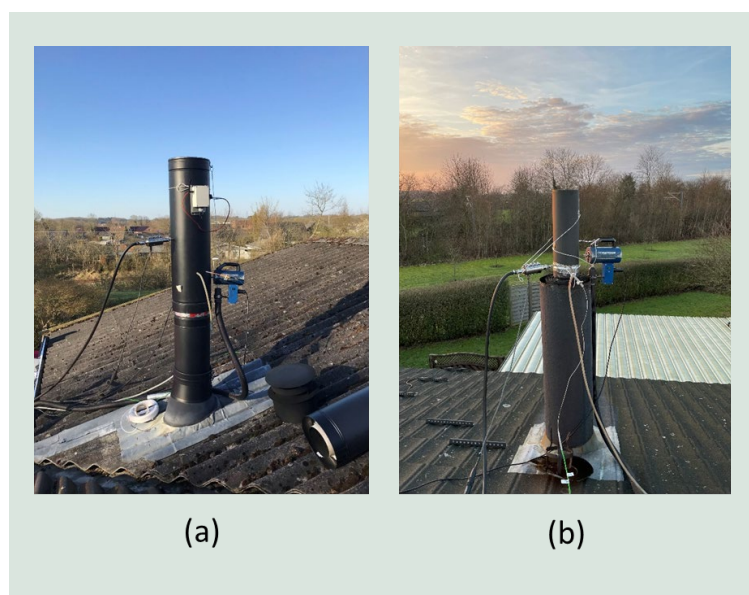


FIGURE 16. Measurement setup for interventions filter. Extra measurement section at the chimney top for interventions with filters, chimney liners, or draft fan. The grey box visible in the left image is the “OptiSmoke” sensor (see Appendix 1.2).

4.3 Correcting for changes in stove use frequency

Stove use frequency has a potentially large effect on the local emissions. To ensure that the changes observed throughout the project were attributable to the interventions and not due to a change in stove use frequency, this parameter was modelled and tracked. A model was developed to estimate the frequency of stove usage in the area, based on data from indoor air quality sensors (see Appendix 2.2). Although only half of the stove owners in the area participated in the project, it is expected that the modelled data gives a reasonable prediction of the entire *Testzone* (participants and non-participants).

4.3.1 Predicted stove use

Stove use varied widely among participants. In addition to the stove use frequency model (based on indoor temperature measurements and validated with firing logs, see Appendix 2.2), participants were asked to qualitatively assess how much they used their woodstove. Data for self-reported use frequency, indoor sensor response rate, and model-predicted stove use are summarized in TABLE 2.

As some participants had a low sensor response rate (i.e., long periods during which the indoor sensor was inactive), stove use was normalized by the number of active sensors. Normalized stove use was calculated as the ratio of number of firings per day, both start and refuelling, to the number of sensors active on that day. Results from this analysis can be seen in FIGURE 17. Further results are shown in Appendix 2.2.

TABLE 2. Self-reported use of woodstoves, sensor response rate, and predicted events.

ID	Cluster	Self-reported use (in season)	Sensor response rate	Events predicted	Events per active day
1	III	Infrequent/recreational use	44%	100	1.12
2	III	Daily	93%	1242	2.55
3	III	Daily	20%	526	3.20
4	II	Infrequent/recreational use	24%	245	2.06

ID	Cluster	Self-reported use (in season)	Sensor response rate	Events predicted	Events per active day
5	II	Daily	97%	1638	2.60
6	II	Several days per week	96%	521	2.07
7	II	Almost daily	50%	187	1.48
8	I	Daily/primary heating in living room	29%	96	1.43
9	I	Daily	84%	267	1.63
10	I	Daily/evenings	29%	352	2.06
11	I	Daily	67%	128	1.13
12	I	Daily	53%	263	1.26
13	I	Every other day	60%	286	1.64
14	I	Varies	67%	123	1.23
15	I	Almost daily when temperatures <10 °C	95%	509	1.57
16	I	As supplement to central heating	45%	234	1.46
17	I	Daily	79%	687	1.95
18	I	Daily	38%	202	1.40
19	I	4–5 days per week	67%	403	1.79
20	III	Daily	88%	884	2.28
21	I	1–2 days per week	20%	211	2.10
Average			60%	433	1.81
Sum			—	9104	—

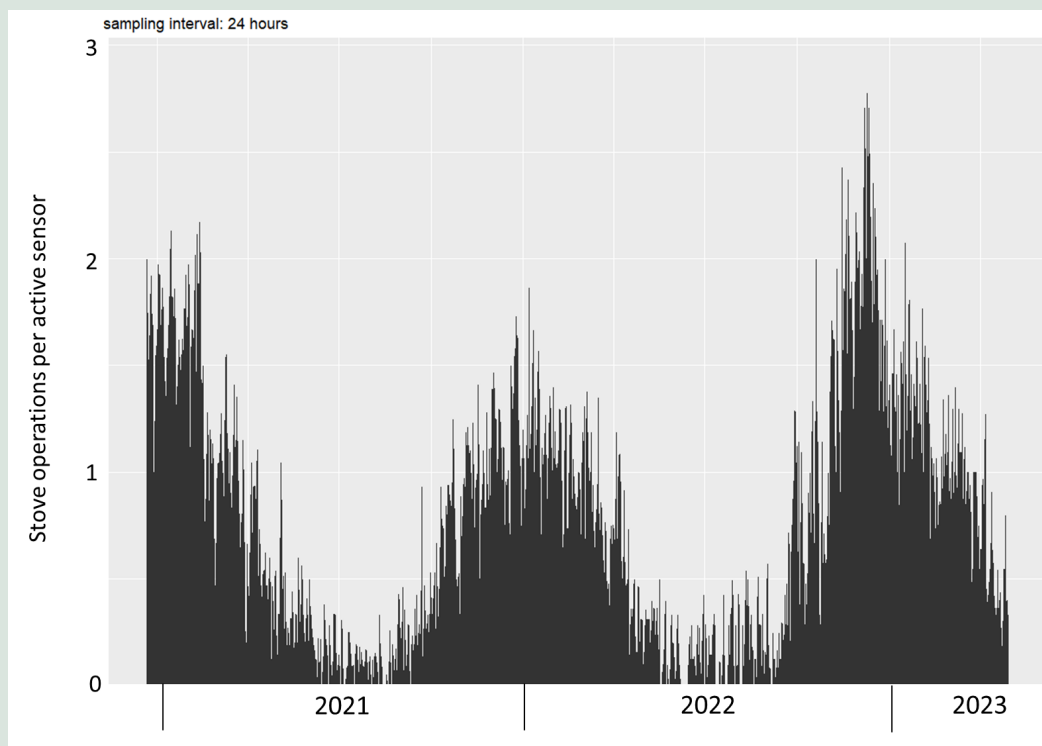


FIGURE 17. Number of stove operations per day, normalized with active sensors.

5. Measured effects of the interventions

The effect of the interventions was quantified both by ambient air quality measurements and measurements directly in the flue gas at selected participants. Ambient air quality measurements showed a clear seasonal variation of local particle emissions, suggesting woodstoves have a strong influence on local air quality. Local air quality appeared to improve throughout the project. Measuring directly in the chimney showed that all interventions had the potential to reduce emissions from woodstove firing. No single intervention proved most effective – instead, the emission reduction depended highly on the state of the installation and the stove user's firing technique.

5.1 Measured effects on the ambient air quality

Ambient air quality in the *Clean Air Testzone* was monitored throughout the project using a network of low-cost sensors. These sensors provided spatially resolved measurements of particulate matter (PM) in three size fractions: PM₁, PM_{2.5} and PM₁₀. The ambient data was analyzed to identify patterns and trends related to local emissions from residential wood combustion. To isolate the local contribution to PM levels from sources within the *Testzone*, a meteorological normalization was adopted and applied to the sensor data.

5.1.1 Measured ambient air quality in the *Clean Air Testzone*

The ambient air quality was examined using meteorologically normalized sensor measurements obtained for PM₁, PM_{2.5} and PM₁₀. The parameters were examined during the three firing seasons comprising a baseline season, a season with one intervention, and a season with one or several, combined interventions.

FIGURE 18, FIGURE 19, and FIGURE 20 show the (attributed) average weekly local contributions to PM₁, PM_{2.5} and PM₁₀, respectively, in red bars. Furthermore, the plots show the average ambient temperature (black line) and normalized number of stove firings (blue line). The ambient temperature was measured using either a meteorological station located together with sensor A5 or fetched from the NOAA observations through an API (available as a feature of the R package *deweather* cited in section 4.1.2). Stove usage was estimated from indoor temperature data sampled at the participants. The number of stove firings were normalized with the number of responding indoor sensors (see Appendix 2.2 for details).

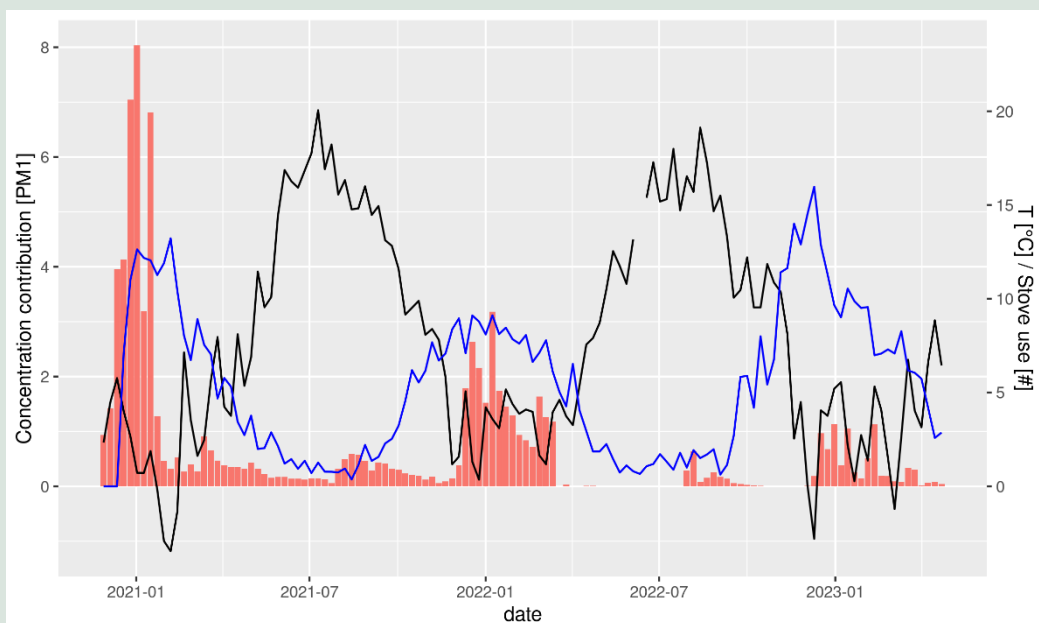


FIGURE 18. Local contribution of PM₁ (red bars) vs outside temperature (black) and stove use (blue).

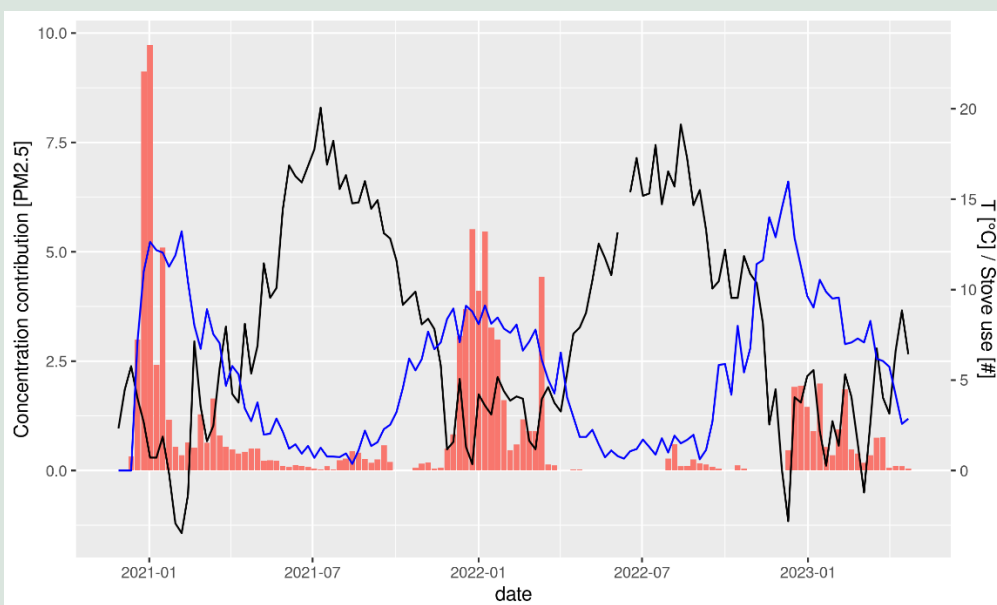


FIGURE 19. Local contribution of PM_{2.5} (red bars) vs outside temperature (black) and stove use (blue).

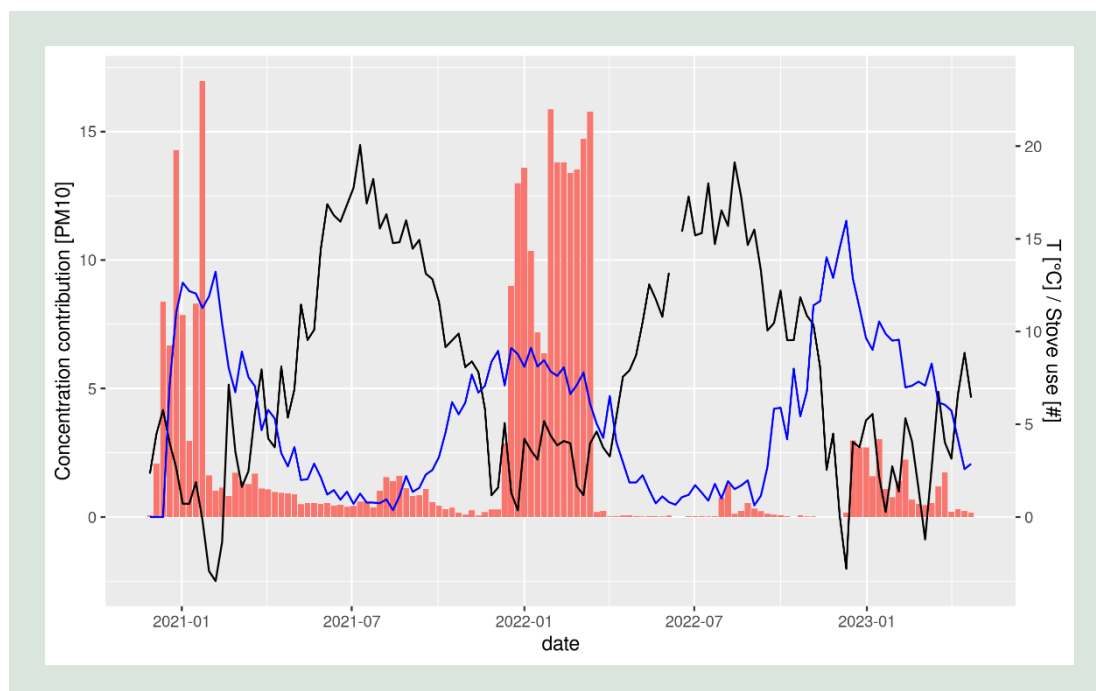


FIGURE 20. Local contribution of PM₁₀ (red bars) vs outside temperature (black) and stove use (blue).

The data summarized in FIGURE 18, FIGURE 19, and FIGURE 20 show a correlation between local emissions and stove usage, as well as an inverse correlation between local emissions/stove use and ambient temperatures. A decrease in temperature corresponds to an increase of stove use (as expected), and simultaneously an increase of the local contribution to PM₁, PM_{2.5} and PM₁₀. This suggests stove use as major contributor to local emissions. This interpretation is further supported by the weekly and hourly patterns presented in FIGURE 21, FIGURE 22, and FIGURE 23. FIGURE 21 shows the local contributions of PM₁ in the test zone presented as an average over the different days of the week. More local emissions occur during the weekends (Saturdays and Sundays). Furthermore, FIGURE 22 and FIGURE 23 display the local contribution of PM₁ detected in the test area as an average over different hours of the day during the summer and winter periods, respectively. These results show that the maximal local emission contributions are reached during the evening/nighttime in winter (FIGURE 23) and during the afternoon/evening in summer (FIGURE 22). These differences can likely be attributed to different human activities within the *Testzone*. Heating is typically used in winter mornings and evenings, i.e., outside work and school hours, and less during the middle of the day. (Demographically, the *Testzone* is a mix of families with children, adults at working age, as well as few pensioners).

Conversely, during summer higher emissions occur during daytime (albeit much lower in absolute value compared to winter emissions, as indicated by the y-axes). These may be attributed to other sources than woodstoves (but including other forms of combustion, e.g., bonfires and barbecues). During the night and early morning, when no activities are occurring in the test area and no woodstoves are in use, local emissions reach their minimum, nearly approaching zero.

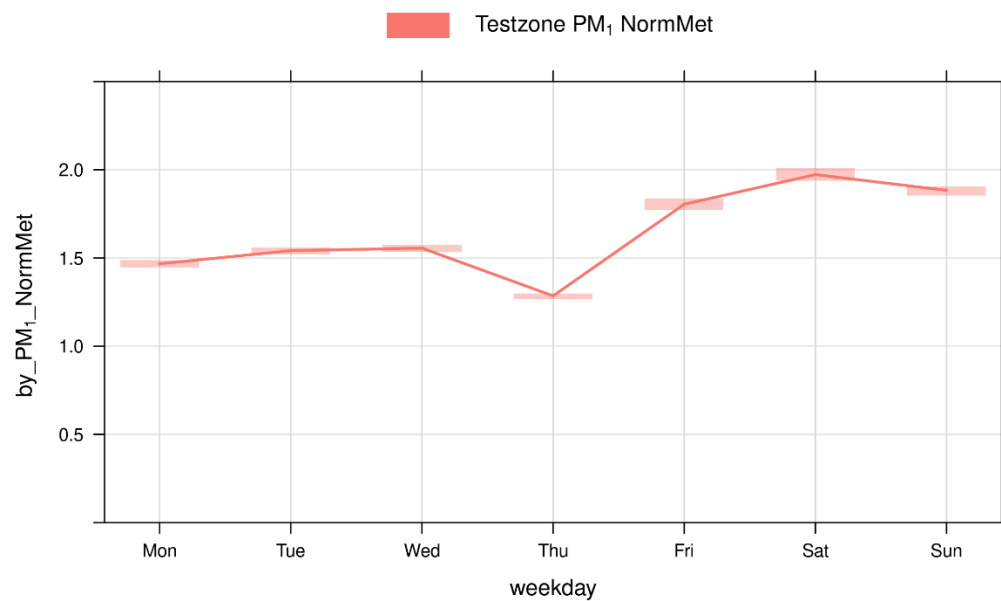


FIGURE 21. Average variation in PM₁ contributions over a week. The highest contributions are observed during the weekend period.

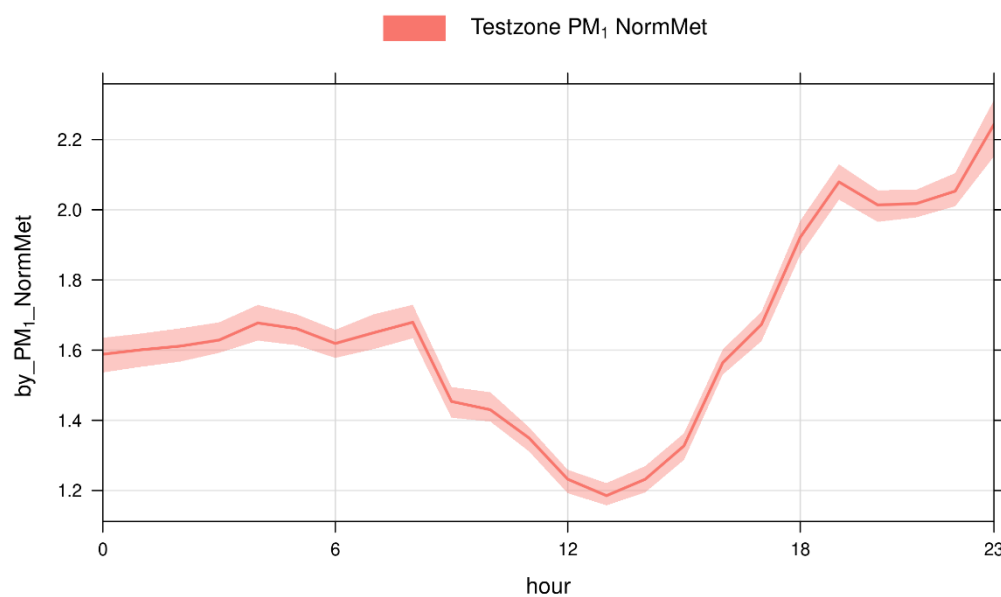


FIGURE 22. Average contribution of PM₁ in the wintertime during a day. Here, it is observed that the contribution is higher during evenings and mornings.

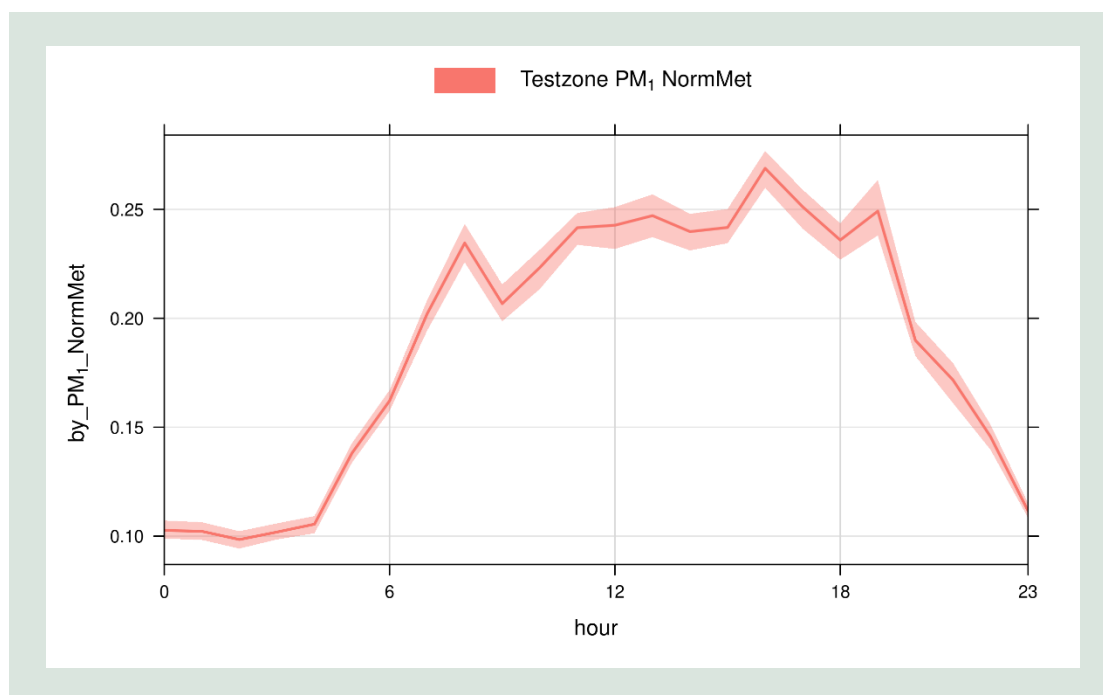


FIGURE 23. Average contribution of PM₁ in the summertime during a day.

Qualitatively, these results are in good agreement with the expected patterns in stove use and local pollutant contributions, lending credibility to the meteorological normalization algorithm.

Having thus established the validity of the employed methodology, the local emissions of the different firing seasons can be assessed. The obtained results show a decrease in the local emissions is obtained, when comparing season 1 (baseline, 2020-2021) with season 2 (first intervention, 2021-2022), despite the presence of some contrasting trends (especially when looking at the PM₁₀ levels in FIGURE 20, that appear to rise second winter). This observation aligns with the expectations, as the strongest decrease in local emissions were expected between the reference (no interventions) season and the first season with interventions in place. The variation from the second (2021-2022) to the third (2022-2023) firing seasons was expected to less pronounced, as both seasons already had the primary interventions in place, with only minor changes occurring (See section 3.2)

A potential criticism regarding the adopted approach is linked to the substantial and entirely unforeseeable global changes that occurred during the project. The first firing season (2020-2021) was notably marked by the COVID-19 crisis and the resulting significant restrictions in social and professional activities, leading to a considerable increase in domestic heating usage and, consequently, particulate emissions. Moreover, the winter of 2020-2021 was characterized by unusually low temperatures, especially in the month of February, as evident from the temperature plot in the previous figures. Subsequently, following a second firing season (2021-2022) with presumably more typical woodstove usage patterns but higher than usual temperatures, the third and final firing season (2022-2023) experienced an impetuous rise in fuel prices due to the war in Ukraine and the resulting international tensions. While the precise quantification of the effects of these events on domestic heating usage patterns is beyond the scope of the current report (especially considering the relatively limited sample population within the test zone), it is highly probable that they could have influenced, perhaps even unconsciously, the firing habits of some Mårslet residents, thereby introducing a source of uncertainty into the comparison between the different firing seasons.

5.1.2 Measured effects normalised to the number of stove firings per active sensor

Using the number of stove firings per active sensor as a normalization factor for the calculated local emissions, it was possible to derive a quantity that expressed the average emissions produced by each woodstove firing. The influence of the absolute woodstove usage extent during the concerned period was thereby removed.

$$\text{normalised local emission} = \frac{\text{local emission}}{\text{stove firings per active sensor}}$$

The stove use intensity was predicted to enable the correction of measured pollutant concentrations in the area for variations in stove usage over seasons, days, and initially, also geographically for the three clusters.

The average emissions produced by each woodstove firing is shown in FIGURE 24, FIGURE 25, and FIGURE 26 for PM₁, PM_{2.5} and PM₁₀, respectively. The results are depicted similarly as the original local emissions in FIGURE 18, FIGURE 19, and FIGURE 20. The normalized emissions during the summer periods have been omitted, as both emissions and stove use was low in this period. Data are not shown if the number of stove firings per active sensor was smaller than three per week (which led to numerical noise in the analysis).

A decrease in the woodstove-related emissions from the test zone as a consequence of the interventions can be observed. This is particularly evident when looking at the PM₁ particle size distribution shown in FIGURE 24, while less straightforward in the PM₁₀ particle size distribution shown in FIGURE 26, where also the normalized local emissions show an increase going from the first (2020-2021) to the second (2021-2022) firing season, eventually followed by a decrease to levels lower than at the project beginning during the third and last season (2022-2023).

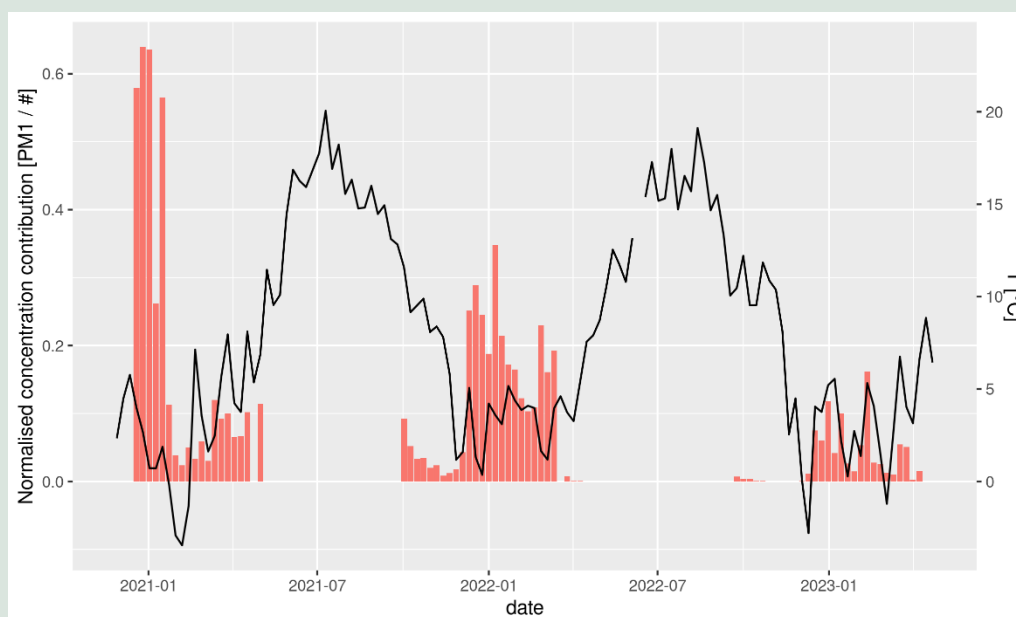


FIGURE 24. Normalised concentration contribution to the local particle concentration (PM₁) during the project period plotted against the daily temperature average.

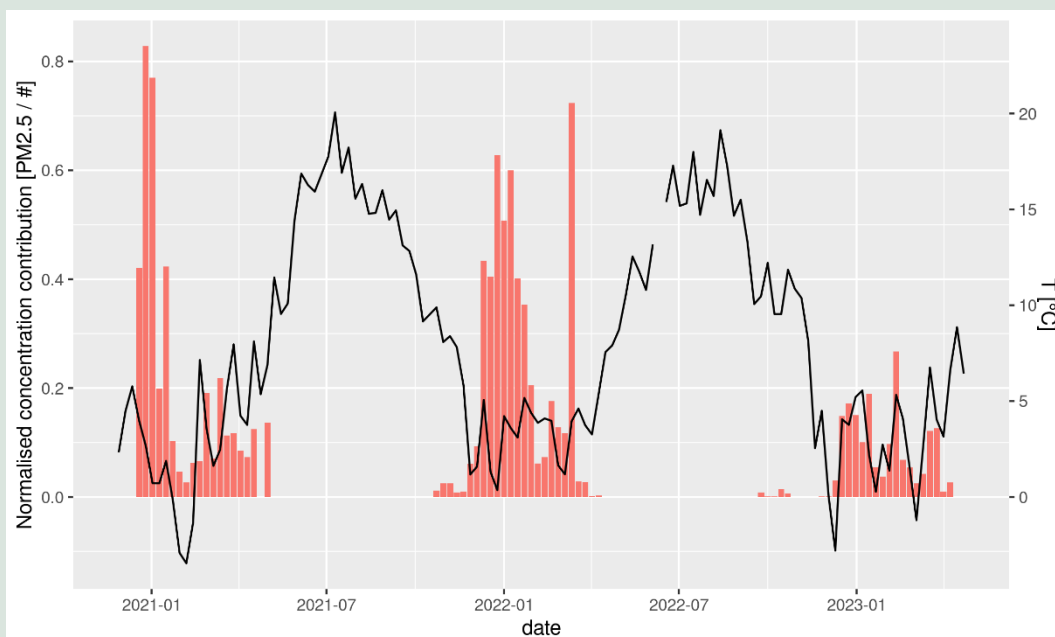


FIGURE 25. Normalised concentration contribution to the local particle concentration (PM_{2.5}) during the project period plotted against the daily temperature average.

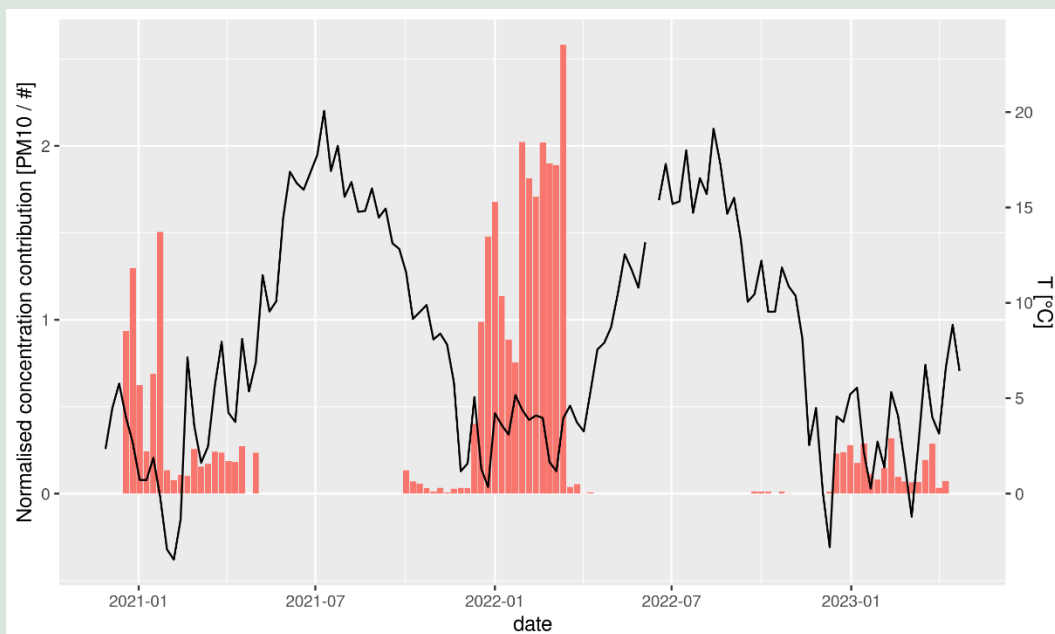


FIGURE 26. Normalised concentration contribution to the local particle concentration (PM₁₀) during the project period plotted against the daily temperature average.

5.2 Direct flue gas measurements

Direct flue gas measurements were used to assess whether the interventions in the project had an effect at the individual household of selected participants (see TABLE 1, section 4.2). Interventions considered were: new woodstove (participants A, B), filter (C, D), training (E, F), as well as draft fan (G, H) and chimney (A, I). Note that for participant A, the new stove and chimney were installed simultaneously. The selected households were a representative mix of the *Clean*

Air Testzone. Each 'before' and 'after' series required one day of measurements per participant, and results therefore show an image of that particular day. Nevertheless, some general conclusions can be drawn.

5.2.1 Results of the measurement campaign

Measured emissions of particle concentration, CO, OGC, and NO_x are shown in FIGURE 27 to FIGURE 30. To allow comparison between participants, all measured values are averaged over a single charge and normalized to standard temperature and pressure (STP) and 13% O₂ in the flue gas. The same type of normalization is also applied in type testing, which allows a direct comparison with these field tests. Emissions can vary drastically between charges (see e.g., the particle concentrations for participant A in FIGURE 27). This broad spread, as well as outlier measurements influence the average value over all charges, which are also shown in FIGURE 28 to FIGURE 31. The results show that baseline measurements (before the interventions) vary significantly among participants A–I, where the average concentration of particles over all charges range between 30 to 212 mg/m³, the concentration of CO between 2846 to 7871 mg/m³, and OGC concentrations between 158 to 2402 mg/m³ (See Appendix 4.1 for values averaged over all charges, including the ignition charge, and relative change following intervention for each household). After the intervention, less variation was observed among participants.

Globally, a decrease in emissions of particles (FIGURE 27), CO (FIGURE 28) and OGC (FIGURE 29) was seen for all participants A–I. As a general observation, the largest improvements were achieved at locations with the highest baseline emissions. Conversely, interventions at locations with relatively low baseline emissions can show a nominally negative effect, i.e., emissions after the intervention are higher than before (e.g., particle emissions at H: before 54 mg/m³, after 86 mg/m³; all participants: before 130 mg/m³, after 78 mg/m³). The largest relative improvements in particle emissions were seen for participants A (new stove and chimney) and I (new chimney), which both had a reduction of more than 70%. Participants C (filter) and E (training) had particle emissions reduced by almost 50% (FIGURE 27 and TABLE 20). The largest relative reduction in CO emissions was seen at household A (58% reduction), followed by household E (41% reduction – compare FIGURE 28 and TABLE 21). The largest relative improvements in OGC emissions were seen for A (83% reduction), E (64%) and B (new stove, 56% reduction – compare FIGURE 29 and TABLE 22).

In contrast, NO_x-emissions increased 5 out of 7 measured households as shown in FIGURE 30 and TABLE 23. The observed increase in NO_x emissions could be attributed a more efficient combustion chamber in modern woodstoves, leading to higher temperatures and more NO_x formation.

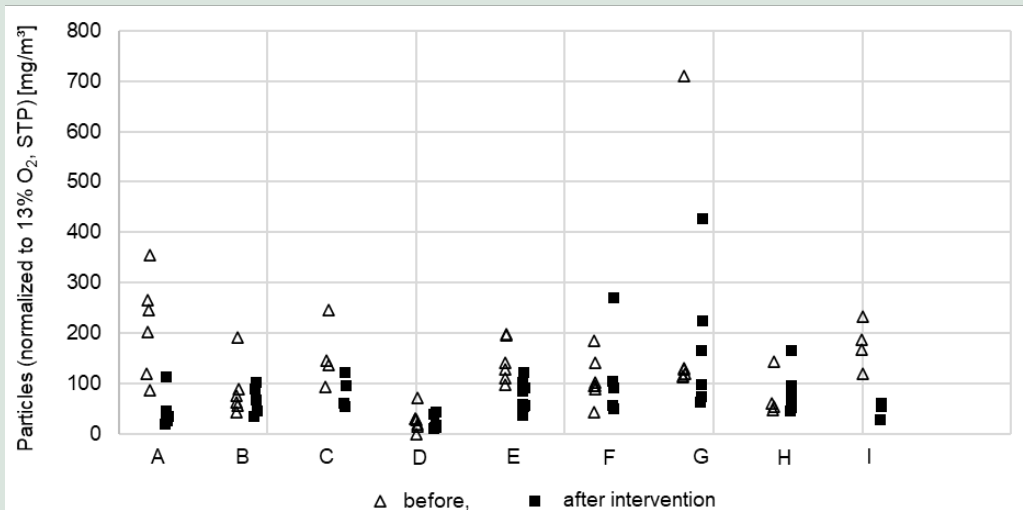


FIGURE 27. Normalized particle concentrations by charge measured before and after interventions. Particle concentrations measured prior interventions are depicted in white triangles, measurements after interventions in black squares, average measurements for each household before and after interventions is marked in blue lines and crosses, respectively.

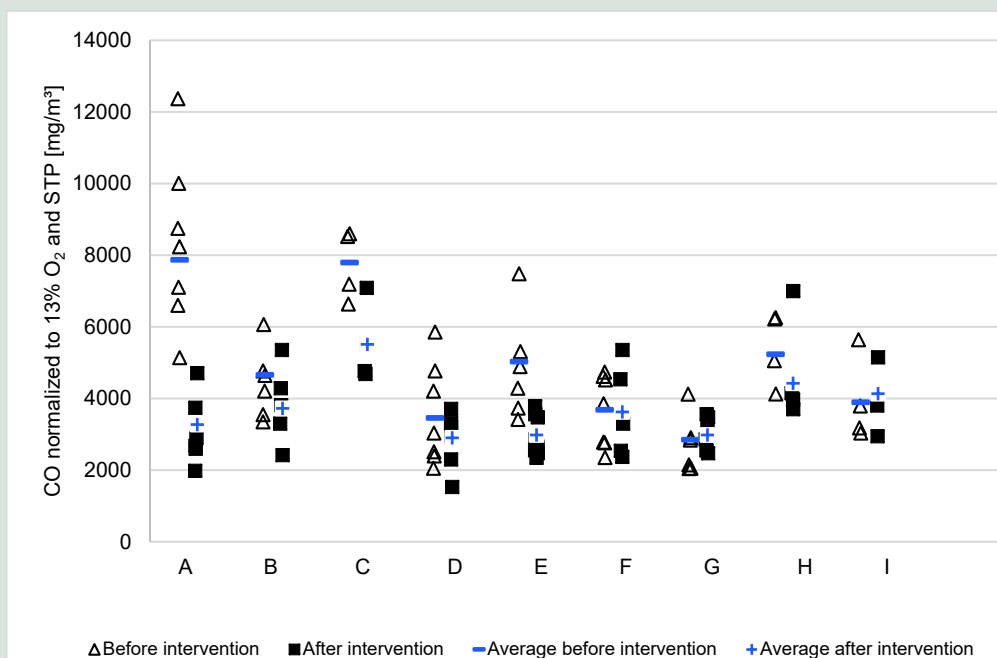


FIGURE 28. Normalized CO concentrations by charge measured before and after interventions. Particle concentrations measured prior interventions are depicted in white triangles, measurements after interventions in black squares, average measurements for each household before and after interventions is marked in blue lines and crosses, respectively.

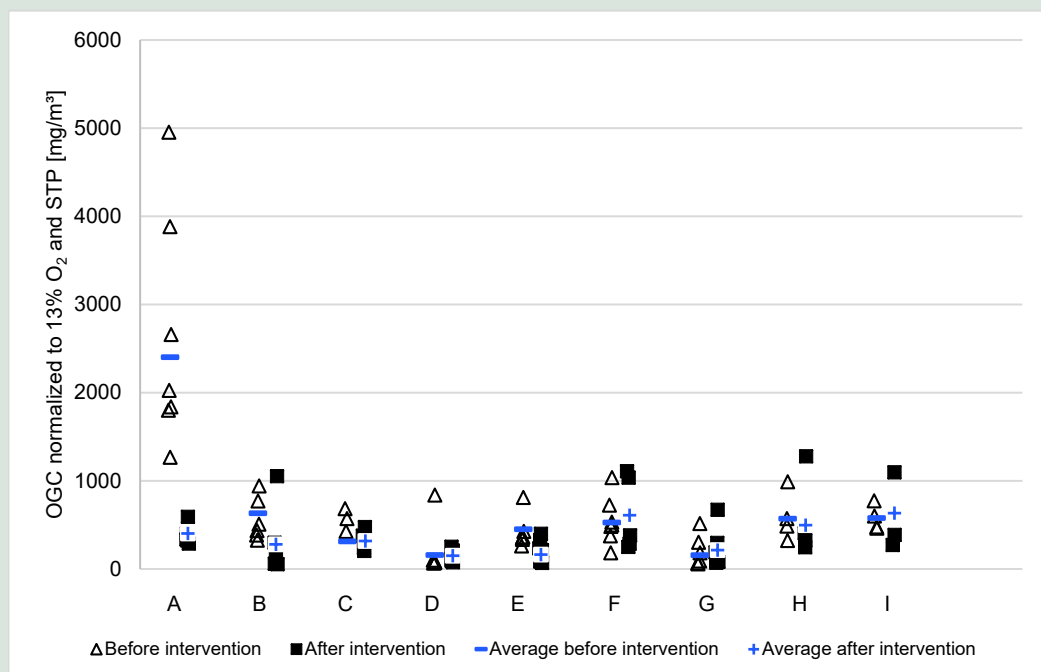


FIGURE 29. Normalized OGC concentrations by charge measured before and after interventions. Particle concentrations measured prior interventions are depicted in white triangles, measurements after interventions in black squares, average measurements for each household before and after interventions is marked in blue lines and crosses, respectively.

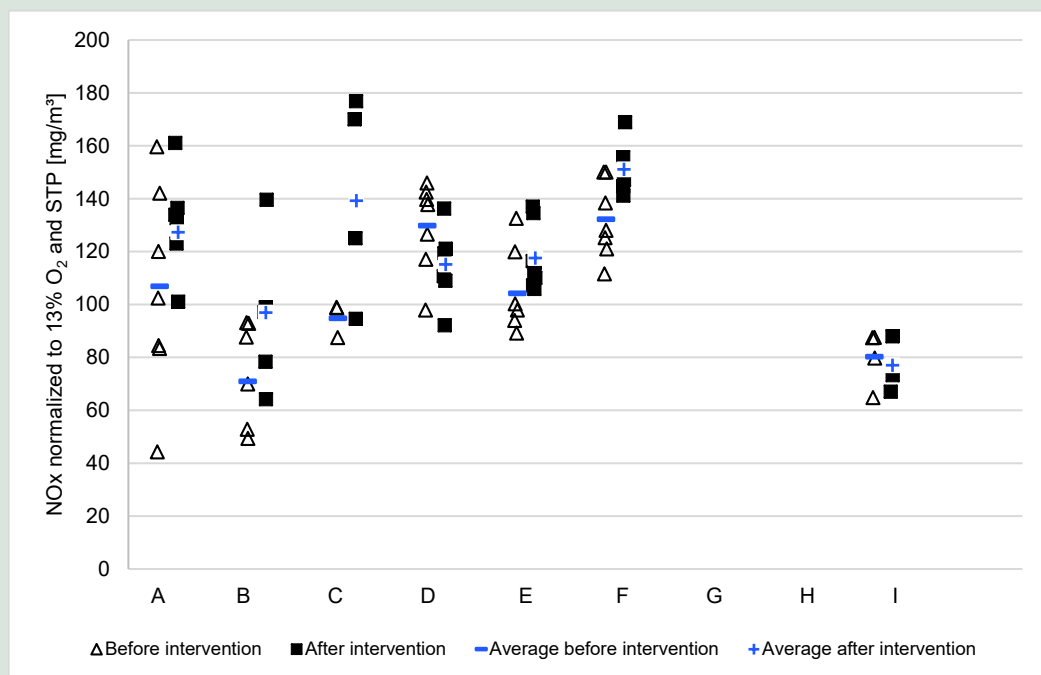


FIGURE 30. Normalized NOx concentration by charge measured before and after interventions. Particle concentrations measured prior interventions are depicted in white triangles, measurements after interventions in black squares, average measurements for each household before and after interventions is marked in blue lines and crosses, respectively. Data for G, H missing due to analyzer malfunction.

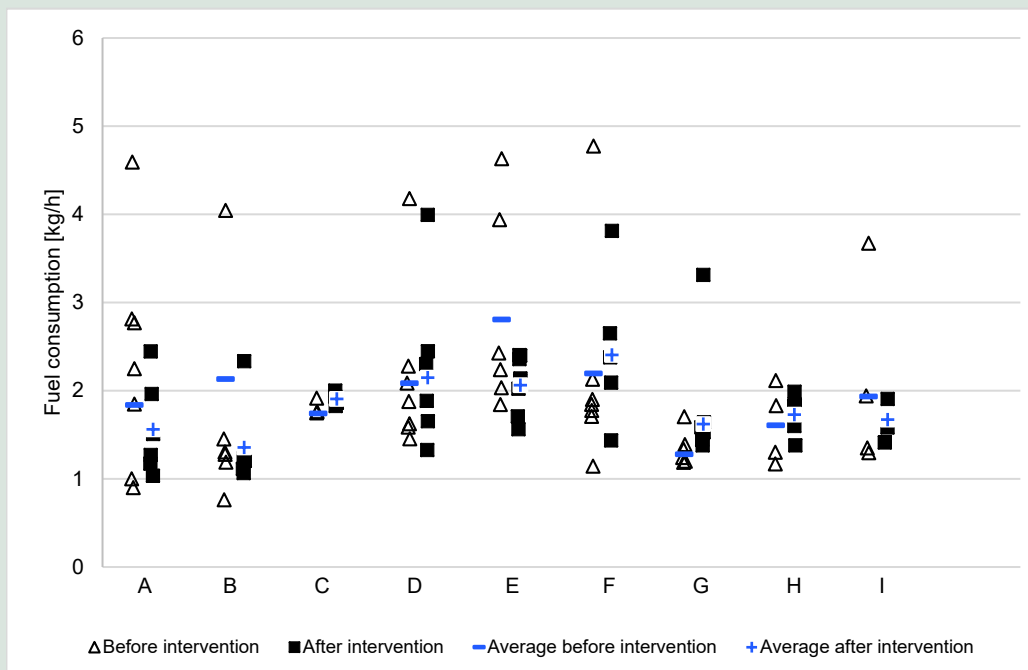


FIGURE 31. Fuel consumption measured before and after interventions. Particle concentrations measured prior interventions are depicted in white triangles, measurements after interventions in black squares, average measurements for each household before and after interventions is marked in blue lines and crosses, respectively.

TABLE 3. Global averages (all houses, average over charges). Emissions normalized to 13% O₂ and STP, in [mg/m³].

Parameter	Unit	Before	After	Δ	rel. change
Particles	[mg/m ³]	130	78	-52	-40%
CO	[mg/m ³]	4941	3728	-1213	-25%
OGC	[mg/m ³]	643	363	-279	-43%
NO _x (excl. G, H)	[mg/m ³]	103	118	15	15%
Fuel consumption	[kg/h]	2,0	1,8	-0,1	-7%

5.2.2 Evaluation of the interventions based on flue gas measurements

This project aimed to quantify the effects of different interventions by directly measuring the flue gas in chimneys. The obtained results showed that the interventions applied in the *Clean Air Testzone* could potentially reduce emissions of particles, CO, and OGC (FIGURE 27 to FIGURE 29). In particular, the potential in upgrading an installation can be seen at e.g., participant A, who were among the locations with the highest emissions before the installation of a new stove and chimney. Following the upgrade, emissions were drastically reduced and among the lowest measured. However, the reduction in emissions that could be achieved with any of the interventions depended highly on the state of the existing stove and chimney installation.

Another contributor to the reduction in emissions was operating behaviour. The influence of the participants' firing technique can be seen when comparing participants A, C, and H, who all had very similar stove models after the intervention (Aduro Hybrid H1 or H2 stoves that mainly differ in exterior design) but achieved different emission levels, especially for particles

and CO. However, the net effect of training and operator behaviour is difficult to distinguish from other interventions. Installation of new equipment, especially stoves, may have prompted users to reconsider correct firing techniques, and/or follow the manual of the new stove, where instructions are very similar to the guidelines from the training sessions in this project. For example, fuel consumption decreased slightly for participant A and B following the installation of a new stove (FIGURE 31). This could indicate a change in user behaviour and thus firing technique. It is also noteworthy that participant F reported that training had not influenced their operating behaviour markedly and that they had largely forgotten the content of the training. This corresponds with the results obtained for participant F, where little to no decrease in emissions was observed (TABLE 20 to TABLE 24).

Emissions measured in the field – both before and after interventions – exceed emission limits from type tests both including and excluding the first ignition charge (data not shown), except for NO_x (FIGURE 30) and particle emissions at participant D (compare TABLE 20, Appendix 4.1 and TABLE 4). Based on the observations in this project, it is unlikely that emissions in residential quarters can be reduced to values measured in the lab (and required for type certification).

Comparison of the results obtained for the different interventions show that no single intervention could be identified as the sole contributor for reducing emissions. Although the emissions in residential quarters are unlikely to be reduced to values obtained for type certification, training appeared the most efficient for reducing emissions, when compared to the cost of interventions.

TABLE 4. Measured values (before/after) as well as emission limits according to different regulations (NO_x: without G, H). Measured values are calculated by first averaging over the duration of each charge, then averaging over all charge-averages from participants A–I.

	PM	CO	OGC	NO _x
A–I, before intervention	130 mg/m ³	4941 mg/m ³	643 mg(C)/m ³	103 mg/m ³
A–I, after intervention	78 mg/m ³	3728 mg/m ³	363 mg(C)/m ³	118 mg/m ³
Ecodesign (EU 1185) – 2022	40 mg/m ³	1500 mg/m ³	120 mg(C)/m ³	200 mg/m ³
BEK nr 541 (DK)	30 mg/m ³	—	120 mg(C)/m ³	—

6. Models for emissions

To address the challenges associated with woodstoves and their impact on indoor air quality and particle emissions, two complementary models were developed. The first model aims to assess the risk of indoor particle emissions from individual woodstove installations, considering various factors related to the chimney, building, and stove characteristics. By identifying and scoring potential risk factors, this model could provide a simple tool to predict the likelihood of particle emissions and evaluate the indoor air quality hazards associated with specific setups. The second model focuses on simulating and estimating particle emissions from individual woodstove installations, combining knowledge of chimney buoyancy and particle release during combustion.

6.1 Model for indoor air quality effects of woodstove use

On one hand, particles from woodstoves normally find their way up through the chimney, where they are rapidly diluted. On the other hand, some particles diffuse indoors into living rooms, kitchens, and family rooms and might be harmful to health. Therefore, special attention must be paid to potential particulate emissions indoor when handling a wood-burning stove, e.g., in connection with kindling or loading new firewood.

The decisive factors for accidental releases in the space around the stove relate to chimney, stove, and house. The risk of indoor particulate emissions increases if the draft (buoyancy) in the chimney is insufficient, the stove is of an older model, and the house in which the stove is installed is too airtight (high air resistance). Draft depends on the construction of the chimney as well as the temperature difference between inside and outside, acting as a driving force. Draft is reduced in quiet weather and low air pressure. Ventilation systems, flue ducts, or hoods may also provide a back pressure that counteracts the chimney draft. Draft, however, may be improved with a flue gas fan. Particulate emissions directly from the combustion chamber via dampers or open doors will typically contain particles of all sizes, including soot particles, $PM_{2.5}$ (fine particles that can be weighed) and $PM_{0.1}$ (ultrafine particles that cannot be weighed). Especially the latter, which are neither seen nor smelled, are considered the most critical for health. On-site measurements of the pressure conditions as they may develop in wood-burning stoves, with and without cooker hoods and ventilation system in use, may reveal the potential danger of leakage; but require measuring equipment and measurements over a longer period to be registered. An alternative is to make a preliminary assessment of the overall wood-burning stove system, i.e., in the form of building, stove, and chimney (BSC). This is the purpose of the current particle model. In other words, the purpose of the indoor climate model has been to provide a simple tool that can easily predict the chances of particle emissions for each wood-burning stove installation.

6.1.1 Scoring system

Houses with woodstove installations are characterized by a point-score on a scale of 1 to 10. The model behind the point system established here is based on several hazard allowances linked to nine conditions at the entire wood-burning stove system, i.e., building, stove, and chimney. Each condition is evaluated qualitatively, and a "hazard penalty" is applied if the condition is met (TABLE 5). The nine conditions are divided into three conditions each related to chimney,

house, and wood stove. For the chimney, these are the height, height above the roof ridge, and the insulation and tightness of the chimney. For the house, these are the airtightness (age) of the house, the ventilation (air exchange) of the house, and possibly the use of an extractor hood. As outlined above, using a cooker hood can reduce draft. Finally, for the stove itself, the model focuses on the age and size of the stove as well as whether the stove is manually controlled or has some degree of automatic control. With automatic control, it is estimated that the danger of particle emissions is less than without and best when the control is electronic, e.g., by temperature and oxygen sensor (lambda probe). The latter ensures precise regulation of the CO/CO₂ ratio, in other words, the correct supply of oxygen.

The largest possible penalty for particulate hazard can be attributed to the chimney (up to 25%), followed by building-related conditions (up to 20%), and finally the stoves (up to 15%). The rationale behind this distribution is that the chimney design provides the buoyancy and thus the draft, which must ensure not only the supply of oxygen for combustion, but also the removal of particles from the firebox. The second largest hazard penalties are attributed to the conditions at the house that ensure that the air to be led to the stove does not meet unnecessary resistance, or even back pressure, as with the use of mechanical ventilation.

For the same reason, it is gaining increasing prevalence when installing wood-burning stoves in new airtight houses with mechanical ventilation to establish fresh air intake directly from the outside air. By short-circuiting the airflow and directing it unhindered to the wood stove, there is no impact on the indoor climate, and the house can be granted a hazard penalty of 0%.

TABLE 5. Hazard penalty of particulate emissions from wood-burning stoves related to chimney, house, and stove, expressed by points of attention, and the danger that may be associated with the individual installations.

	Danger of	Hazard penalty (maximum)
Chimney height	Low Chimney	25%
Height above roof ridge	Chimney pipe under roof ridge	25%
Chimney insulation/tightness	Medium/poor	25%
Density of the house	Dense houses	20%
House ventilation system	Mechanical ventilation	20%
When using Cooker hood	Powerful - medium – none	20%
Wood-burning stove age	Before 2000	15%
Size of stove	small og large stoves	15%
Wood-burning stove control	No automatics	15%

Hazard penalties were summarized and simplified to a 10-point scale (TABLE 6). For a penalty between 0 and 10%, only one penalty point is obtained (score of 1), for a total hazard penalty of 10-20%, the score 2 is given, etc. Any house with a total hazard of 90% or above receives a score of 10.

TABLE 6. Score of dangerous particulate emission.

Score	1	2	3	4	5	6	7	8	9	10
Hazard penalty	0-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	>90%

The allocation of hazard penalties must be made by on-site inspection and must be based on a mixture of measurement and objective assessment as well as rules in the wood-burning stove circular and requirements for the particulate emission of wood-burning stoves. Furthermore, the

allocation of hazard penalties can be supported by interviews of the homeowner, including assessment of the presence of particles when using and especially different uses of the stove. At this interview, it can also be determined whether a cooker hood and possibly ventilation system are bothering when lighting and filling new firewood.

6.1.2 Particulate hazard before intervention

To investigate to what extent, the indoor climate model can be used to assess in advance the particle hazard of a wood-burning stove installation, all houses included in the test zone in Mårslet have been examined and the total particle hazard has been calculated. This means that the entire wood-burning stove installation, including chimney and surrounding houses, has been reviewed to assess the risk of emissions from the stove. As the model indicates, both the chimney, the house, and the wood-burning stove have been subjected to a critical review, cf. the nine points of attention shown in TABLE 5.

To support the review of the individual houses, information from the Building and Housing Register (BBR), in the form of the building's construction date, age and size, has been collected. So is information regarding the Energy Labelling Scheme (EMO), to the extent that an energy label exists. Here, times for possible renovation, post-insulation and establishment of mechanical ventilation can help to support the assessment of the danger of particulate emissions. The on-site inspection has been carried out in such a way that a visit has been made to each house, and – if possible – questions have been asked to the owner and particularly, the user of the house's woodstove. Records have been made that systematically follow the table shown in TABLE 5. shows a sample of the records leading to the overall assessment of the particle hazard for each of the 25 houses, including a column with any comments. The table should simply show in abbreviated form some of the conditions at the chimney, house and wood-burning stove that count when assessing the particle hazard.

Many of the chimneys are lower than or at the same height as the roof ridge. This increases the danger of emitting particles indoors. All houses, with one exception, have natural ventilation. Most of the houses have a cooker hood in the kitchen. However, only a few of the users cite the hood in function as a nuisance when lightening their stove. Most stoves are of older date and in many cases of unknown make. The final statement in the last column of TABLE 8 shows that all houses contain a particle hazard, many with a large particle hazard and penalty points that trigger a grade above 5.

TABLE 7. State of chimney, building, and stove at the start of the project.

ID	Height	Chimney		Building		Stove		Notes from interview
		Height relative to roof ridge	Isolation	Erection year	Ventilation	Make	Year	
Installation	[m]							
1	7.0	above	above roof	1972	natural	ABC	2003	
2	5.0	same		1973	natural	unknown	old	
3	4.0	same	without	1973	natural	fireplace insert	old	Problems when lighting
4	3.5	same	without	1973 (rebuilt)	natural	Wiking	old	
5	5.0	same	above roof	1973 (rebuilt)	natural	Hwam	2005	
6	5.0	above	above roof	1973	natural	Aduro	ca. 2013	
7	5.0	above	above roof	1973	natural	unknown	ca. 2005	
8	4.5	under	Exterior at steel	1973	natural	unknown	1980s	Problems when lighting
9	4.0	under		1972	natural	Hwam	2017	
10	4.0	above	pass of ceiling	1973	mechanical	Andersen	old	
11	7.0	above	pass of ceiling	1973	natural	Hwam	2003	
12	4.5	same	isokern	1973	natural	Rais	old	
13	4.5	under	Under roof	1973	natural + extractor	unknown	old	
14	2.5	same	isokern	1972	natural	Wiking	ca. 2010	
15	6.0	above	internal	1972	natural + extractor	Rais	2019	
16	4.0	unknown	internal	1972	natural	Aduro	2018/19	Problems when lighting
17	4.5	under	unknown	1972	natural	Morsø	1990s	
18	4.5	above	unknown	1972	natural	Contura	old	Smoke when lighting
19	3.0	above	isokern	1968	natural	fireplace insert	2018	Smoke can go down
20	4.5	same	isokern	1970	natural	Basic	2002	
21	5.0	same	Unknown	1965	natural	ABC	2009	Problems when lighting
22	5.0	same	Masonry without	1965	natural	Morsø	2009	
23	5.0	same	unknown	1976	natural	Asgaard	ca. 2010	
24	5.0	same	unknown	1975	natural	Viking	ca. 2005	Difficult to regulate
25	3.0	same	Masonry without	1968 (rebuilt)	natural	fireplace insert	unknown	

TABLE 8. Values for particle hazard for a range of wood-burning stoves in Mårslet distributed by chimney, house, and wood-burning stove. The total hazard surcharge leads to grades of between 1 and 10, where 1 indicates that there is no particle hazard and 10 indicates that there is a high particle hazard when using the stove.

ID Installation	Chimney			Building			Woodstove			Hazard	
	Height	Height relative to roof ridge	Isolation tight- ness	Erection year	Ventilation	Extractor and Ventilation	Age	Size	Automatics	%	Score Total
	(max 25%)	(max 25%)	(max 25%)	(max 20%)	(max 20%)	(max 20%)	(max 15%)	(max 15%)	(max 15%)	(180%)	
1	0%	20%	25%	0%	0%	0%	15%	15%	15%	90%	9
2	10%	20%	10%	0%	0%	0%	15%	15%	15%	85%	9
3	15%	20%	25%	0%	0%	0%	15%	5%	15%	95%	10
4	25%	20%	20%	10%	0%	0%	15%	5%	15%	110%	10
5	10%	0%	0%	10%	0%	0%	0%	0%	0%	20%	2
6	10%	25%	25%	0%	0%	0%	5%	0%	15%	80%	7
7	10%	0%	10%	0%	0%	0%	10%	10%	15%	55%	6
8	10%	25%	25%	0%	0%	0%	15%	0%	15%	90%	9
9	10%	25%	0%	0%	0%	0%	0%	0%	0%	35%	4
10	10%	0%	10%	0%	0%	0%	15%	15%	15%	65%	7
11	0%	0%	10%	0%	0%	0%	10%	0%	10%	30%	3
12	10%	20%	10%	0%	0%	0%	15%	15%	15%	85%	9
13	10%	25%	10%	0%	0%	0%	15%	15%	15%	90%	9
14	10%	20%	0%	0%	0%	0%	10%	0%	15%	55%	6
15	10%	0%	10%	0%	0%	0%	10%	5%	15%	50%	6
16	15%	20%	10%	0%	0%	0%	10%	5%	15%	75%	8
17	10%	25%	0%	0%	0%	0%	15%	5%	15%	70%	8
18	10%	5%	20%	0%	0%	0%	15%	5%	15%	70%	8
19	20%	5%	20%	0%	0%	0%	5%	10%	15%	75%	8
20	10%	20%	10%	0%	0%	0%	15%	5%	15%	75%	8
21	5%	20%	25%	0%	0%	0%	15%	5%	15%	85%	9
22	5%	0%	10%	0%	0%	0%	15%	15%	15%	60%	7
23	5%	20%	10%	0%	0%	0%	15%	15%	15%	80%	9
24	5%	20%	15%	0%	0%	0%	15%	15%	15%	85%	9
25	25%	5%	25%	0%	0%	0%	15%	15%	15%	100%	10

TABLE 9. In eight buildings (ID1–4, 6–9) a new wood-burning stove was installed during the project. At ID5, the installation occurred ahead of the project. In all cases, however, we see that new wood-burning stoves can significantly reduce the danger of particulate emissions. Especially large effects arise if at the same time renovation or replacement of the chimney has taken place. Compare TABLE 8 for original values.

ID	Height	Chimney		Building			Wood-burning stove			Hazard	
		Height relative to roof ridge	Isolation tightness	Erection year	Ventilation	Extractor and ventilation	Age	Size	Automatics	%	New score
Installation	(max 25%)	(max 25%)	(max 25%)	(max 20%)	(max 20%)	(max 20%)	(max 15%)	(max 15%)	(max 15%)	(180%)	(change)
1	0%	20%	25%	0%	0%	0%	0%	0%	0%	45%	5 (-4)
2	10%	20%	10%	0%	0%	0%	0%	0%	0%	40%	4 (-5)
3	15%	0%	0%	0%	0%	0%	0%	0%	0%	15%	6 (-4)
4	25%	20%	20%	10%	0%	0%	0%	0%	0%	75%	8 (-2)
5	10%	0%	0%	10%	0%	0%	0%	0%	0%	20%	2 (-)
6	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1 (-6)
7	10%	0%	10%	0%	0%	0%	0%	0%	0%	20%	2 (-4)
8	10%	25%	25%	0%	0%	0%	0%	0%	0%	60%	6 (-3)
9	10%	25%	0%	0%	0%	0%	0%	0%	0%	35%	4 (-)

6.1.3 Particulate hazard after intervention

In the project, nine houses have had a new woodstove installed and, in some cases, had their chimneys renovated or replaced. For one house (ID5), the owner has chosen in advance to replace the stove and renovate the chimney. The example is nevertheless included in the overview, which tells how much the risk of particulate emissions has been reduced because of the completed upgrades (see TABLE 9).

The consequences of the interventions taken are shown by the total hazard surcharge, especially when comparing the scores before and after the intervention. In one case, ID6, the particle hazard has been reduced from 80% to 0%, which has meant that the score has changed significantly from 7 to 1. This has been achieved by replacing the chimney together with the woodstove. In another case, ID7, the particle hazard has been reduced from 6 to 2. Here, the good score is linked to the combination of a modern woodstove and a well-functioning chimney. This is at the level of ID5, where nothing has been altered. A modern wood-burning stove and a well-functioning chimney had already ensured a low particle hazard of just 20%. The rest of the houses that have had a new wood-burning stove installed, the gain is limited, as in all cases scores between 4 and 8 have been achieved, corresponding to a particle hazard of 40% and 75%. The model reflects that a new woodstove is not sufficient by itself. At least as important is a well-functioning chimney, i.e., a chimney where the height is sufficient and where the chimney insulation is optimal.

6.2 Model for emissions from individual wood stove installations

As part of the project, Build developed a particle model to simulate particle emissions from individual woodstove installations. This model was used to estimate the annual particle emission from the *Clean Air Testzone*. The particle model is based on the knowledge that Build has developed during the CAT project on characterizing and thus predicting particle emissions from the individual wood-burning stove installations. The aim was to complement the experimental data with a particle model based on information about the individual stoves calibrated within the framework of the CAT project. Build's particle model combines knowledge of chimney buoyancy with knowledge of the release of particles during combustion in woodstoves. This means that the model can provide an estimate of how the buoyancy in the chimney grows from the moment of lightening to reach a maximum and then decreases again as the temperature drops. At the same time, the model estimates the particle concentration at different times in a combustion cycle and thus the number of particles distributed over each cycle. The generation of the model is elaborated in . The model is based on the theory of buoyancy. This means that average temperature at specific time steps in a combustion process was combined with knowledge about everything related to the airflow, for instance the airtightness of house, the quality of chimney, and the power of stove. As a final output, the model is able to estimate the flue gases generated for each specific installation, and consequently the amount of particles.

6.2.1 Particulate emissions from a single wood-burning stove

By use of particulate model, it was possible to simulate a given wood-burning stove installation. The better the installation can be described with respect to building, stove, and chimney, the more accurate the simulation. If necessary, the model can be fine-tuned using factors additional to those listed in TABLE 25. As an option, by comparing installations with tests of new stoves, the model can be calibrated with the test certificates available for each type of woodstove. In the same way, a more detailed specification of the size of the woodstove can be made, just as test certificates for a given model can further ensure a satisfactory simulation of a given woodstove. Similarly, with new airtight and well-insulated chimneys, higher precision can be achieved by observing the specific quality of the chimney.

6.2.2 Particulate emissions from *Testzone* Mårslet

In principle, the model can be used for any selection of wood-burning stoves, e.g., a selection of local stoves. In this case it was used to estimate the total emission of particles of all wood-burning stove installations in the test zone. This means that the model has been used to estimate the emission of particles from the total of 59 wood-burning stoves located in the area. Since the area is part of the *Testzone*, knowledge about the installations in the area was already established. This includes knowledge about the age of the houses and the age of the individual wood-burning stoves, i.e., the technology on which it is based. Concerning technology, a distinction was made between woodstoves based on the latest technology (factor 0.8), modern technology (factor 1) or old technology (factor 1.2).

Furthermore, knowledge about the use of the individual installations was utilised. The knowledge was gained from a series of interviews conducted in the area. The users were asked whether the house's stove is "used a lot", "used", "used a little", or "not used". The first three categories were translated as (on average) daily use for 4 hours each, 2 days a week for 4 hours each, and once every four weeks for 4 hours, respectively. Interviewees answering "no use" were neglected.

Lack of knowledge about chimney, air resistance in the house and the presence of automatic control means that the default value of 1 was applied. For each wood-burning stove, this gives a total weighting of particle emissions of a charge of between 0.8 and 2.4. Multiplied by the number of operating hours and charges that the individual stove was estimated to be used; the total particle emissions were calculated. For the entire area, the result is that a total of 95 kg of particles was produced during a heating season of 35 weeks (see TABLE 10).

TABLE 10. Estimate of the total emission of particles for each of the 59 wood-burning stove installations in the *Testzone* in Mårslet over a period of 35 weeks, corresponding to an average heating season. A total of 95 kg particles (PM) was found.

ID Installation	Time of use (hours)	Number of charges	Size of stove	Quality of chimney	Air resistance	Mechanical ventilation	Stove Technology	Automatics	Quality of wood	Total Weighting	PM single charge	PM all charges
1	980	1,180	1.0	1.1	1	1	1.2	1.2	1	1.6	5.2	6,090
2	280	340	1.5	1.1	1	1	1.2	1.2	1	2.4	7.8	2,610
3	35	40	1.0	1.1	1	1	1.0	1.2	1	1.3	4.3	180
4	980	1,180	0.6	1.1	1	1	1.2	1.0	1	0.8	2.6	3,050
5	280	340	1.0	1.1	1	1	1.0	1.2	1	1.3	4.3	1,450
6	35	40	1.5	1.1	1	1	1.2	1.2	1	2.4	7.8	330
7	280	340	1.0	1.1	1	1	1.2	1.2	1	1.6	5.2	1,740
8	35	40	1.5	1.1	1	1	1.2	1.2	1	2.4	7.8	330
9	280	340	1.0	1.1	1	1	1.0	1.2	1	1.3	4.3	150
10	280	340	1.0	1.1	1	1	1.0	1.2	1	1.3	4.3	1,450
11	280	340	1.5	1.1	1	1	1.2	1.2	1	2.4	7.8	210
12	35	40	1.0	1.1	1	1	1.0	1.2	1	1.3	4.3	180
13	0	0	0.6	1.1	1	1	1.2	1.0	1	0.8	2.6	0
14	280	340	1.0	1.1	1	1	1.0	1.2	1	1.3	4.3	1,450
15	980	1,180	1.0	1.1	1	1	1.0	1.2	1	1.3	4.3	5,080
16	0	0	0.6	1.1	1	1	1.2	1.0	1	0.8	2.6	0
17	280	340	1.0	1.1	1	1	1.2	1.2	1	1.6	5.2	1,740
18	280	340	1.0	1.1	1	1	1.2	1.2	1	1.6	5.2	1,740
19	980	1,180	0.6	1.1	1	1	1.2	1.0	1	0.8	2.6	3,050
20	35	40	1.5	1.1	1	1	1.2	1.2	1	2.4	7.8	330
21	35	40	1.5	1.1	1	1	1.2	1.2	1	2.4	7.8	330
22	0	0	0.6	1.1	1	1	1.2	1.0	1	0.8	2.6	0
23	280	340	0.6	1.1	1	1	1.2	1.0	1	0.8	2.6	870
24	980	1,180	1.0	1.1	1	1	1.0	1.2	1	1.3	4.3	5,080
25	980	1,180	0.6	1.1	1	1	1.2	1.0	1	0.8	2.6	3,050
26	35	40	0.6	1.1	1	1	1.2	1.0	1	0.8	2.6	110
27	35	40	1.0	1.1	1	1	1.2	1.2	1	1.6	5.2	220

ID Installation	Time of use (hours)	Number of charges	Size of stove	Quality of chimney	Air resistance	Mechanical ventilation	Stove Technology	Automatics	Quality of wood	Total Weighting	PM single charge	PM all charges
28	980	1,180	1.0	1.1	1	1	1.2	1.2	1	1.6	5.2	6,090
29	980	1,180	0.6	1.1	1	1	1.2	1.0	1	0.8	2.6	3,050
30	35	40	1.5	1.1	1	1	1.2	1.2	1	2.4	7.8	330
31	280	340	0.6	1.1	1	1	1.2	1.0	1	0.8	2.6	870
32	280	340	0.6	1.1	1	1	1.2	1.0	1	0.8	2.6	870
33	980	1,180	1.5	1.1	1	1	1.2	1.2	1	2.4	7.8	9,140
34	280	340	0.6	1.1	1	1	1.2	1.0	1	0.8	2.6	870
35	980	1,180	1.0	1.1	1	1	1.0	1.2	1	1.3	4.3	5,076
36	980	1,180	1.0	1.1	1	1	1.2	1.2	1	1.6	5.2	6,090
37	35	40	0.6	1.1	1	1	1.2	1.0	1	0.8	2.6	110
38	280	340	1.0	1.1	1	1	1.0	1.2	1	1.3	4.3	1,450
39	280	340	1.5	1.1	1	1	1.2	1.2	1	2.4	7.8	2,610
40	280	340	0.6	1.1	1	1	1.2	1.0	1	0.8	2.6	870
41	0	0	1.5	1.1	1	1	1.2	1.2	1	2.4	7.8	0
42	35	40	0.6	1.1	1	1	1.2	1.0	1	0.8	2.6	110
43	35	40	0.6	1.1	1	1	1.2	1.0	1	0.8	2.6	110
44	35	40	1.0	1.1	1	1	1.0	1.2	1	1.3	4.3	180
45	0	0	1.5	1.1	1	1	1.2	1.2	1	2.4	7.8	0
46	0	0	1.5	1.1	1	1	1.2	1.2	1	2.4	7.8	0
47	280	340	1.5	1.1	1	1	1.2	1.2	1	2.4	7.8	2,610
48	280	340	0.6	1.1	1	1	1.2	1.0	1	0.8	2.6	870
49	0	0	1.5	1.1	1	1	1.2	1.2	1	2.4	7.8	0
50	280	340	1.0	1.1	1	1	1.2	1.2	1	1.6	5.2	1,740
51	35	40	1.0	1.1	1	1	1.0	1.2	1	1.3	4.3	181
52	280	340	1.0	1.1	1	1	1.0	1.2	1	1.3	4.3	1,450
53	280	340	0.6	1.1	1	1	1.2	1.0	1	0.8	2.6	870
54	280	340	1.0	1.1	1	1	1.0	1.2	1	1.3	4.3	1,450
55	35	40	1.0	1.1	1	1	1.2	1.2	1	1.6	5.2	220
56	280	340	1.0	1.1	1	1	1.2	1.2	1	1.6	5.2	140
57	35	40	0.6	1.1	1	1	1.2	1.0	1	0.8	2.6	110

ID Installation	Time of use (hours)	Number of charges	Size of stove	Quality of chimney	Air re- sistance	Mechanical ventilation	Stove Tech- nology	Automatics	Quality of wood	Total Weighting	PM single charge	PM all charges
58	35	40	1.0	1.1	1	1	1.0	1.2	1	1.3	4.3	180
59	280	340	1.0	1.1	1	1	1.0	1.2	1	1.3	4.3	1,450
											total	95,000

6.2.3 Summary and conclusion

For the *Clean Air Testzone* (CAT), Build has contributed with two results: A tool for screening wood-burning stove installations for indoor particle hazards and a tool for simulating particles from wood-burning stove installations. The results take the form of an indoor climate model and a model for particle emissions from wood-burning stoves in general.

The indoor climate model can be used to assess the danger of particle emissions in the individual house, and thus the danger of deteriorating the indoor climate with particles. The particle model can be used to simulate the particle development from a wood-burning stove, given detailed specifications of the stove, and given specifications of the chimney and the house of the stove installation.

The development of the indoor climate model is based on several risk factors for increased pollution of the indoor climate, which are associated with errors and deficiencies in the individual parts of a wood-burning stove installation. The risk factors associated with incorrect use and poor quality of firewood are considered as well.

From the observations made in the field, it has become clear that the chimney construction, including its height and insulation condition, have the largest influence on particle contamination of the indoor climate. The second-most important factor is the tightness of the house and the possible presence of mechanical exhaust and ventilation. Together, these two conditions determine the buoyancy and thus the chimney draft that can be achieved.

Thus, if negative pressure and hence an optimal air supply to the combustion chamber can be established throughout the whole combustion process, particles will not be able to leave the chamber and contaminate the room.

To take a closer look at the extent to which the interventions made during the CAT project, all replacements of wood-burning stoves and refurbishment of the chimneys etc. have been included in the indoor climate model. This way, it turns out that installation of a new wood-burning stove only led to significant improvements in combination with a well-functioning chimney.

The development of the particle model was based on existing theory of buoyancy. Thus, to reach a particle model, the buoyancy function was paired with a typical particle release intensity for a combustion cycle of 50 minutes (kg/s). Both buoyancy and combustion closely follow temperature developments. Additionally, the model builds on the assumption that a wood-burning stove of 1.5 kW is able to incinerate 1 kg of standard wood while emitting 3.27 g particles.

Like the indoor particle model, a number of additional factors must be observed, so that wood-burning stoves and wood-burning stove installations of different construction can be compared in terms of particle emissions.

To test the model on a collection of wood-burning stoves, an attempt has been made to apply the model to the total of the 59 wood-burning stoves located in the test zone area in Mårslet. Here, the aggregated model utilizes knowledge about the individual wood-burning stove installations, including knowledge of the age of the stoves and houses. The age of the stove is further used to determine the technology of the individual installations, which is used to determine a weighting factor. Perhaps most importantly, knowledge about the frequency of stove use must be established. This was achieved through a survey conducted in the area.

For each wood-burning stove, this gives a total weighting of particle emissions of a charge of between 0.8 and 2.4. Multiplied by the number of hours and charge that each stove was used, the total particulate emissions from the area were estimated at 95 kg for an average heating season.

A comparison of emissions from the individual stoves shows, as expected, that a high intensity of use combined with a low-quality installation (e.g., due to old technology or a poor chimney) leads to the largest particle emissions. For example, the installation in Mårslet that generates the most particles emits as much as the 25 average users of wood-burning stove in the area.

7. Local and national evaluation of effects

DCE, Aarhus University has contributed to the project with emission estimates on national level and for the test-zone. Parameters from the national emission inventory prepared by DCE, Aarhus University were used to estimate emissions from woodstoves on national level and for the *Testzone* in Mårslet. Results from the chimney measurements carried out in the *Testzone* were used to estimate effects of the interventions, which was used in scenarios on national level to illustrate the potential effect of expanding the interventions in Mårslet to the national level. Five scenarios were considered: three focusing on technology and two focusing on installation of ESP filters.

7.1 The national emission inventory

The model calculating emissions from residential wood combustion uses many parameters. The most important parameters are: number of wood burning appliances grouped by type (e.g., new/old woodstove, open fireplace), replacement rates of appliances, unit wood consumption, and emission factors for each pollutant and appliance type. The emission is calculated using the equation:

$$\sum_i ADs_i \times EF_i$$

Where ADs is the scaled activity data, EF is the emission factor, and i is the appliance type. ADs is calculated using the following equation:

$$ADs_i = N_i \times UC_i \times \frac{AD_{stat}}{\sum_i N_i \times UC_i},$$

where AD_{stat} is the statistical wood consumption from the energy statistics, N is the number of appliances, UC is the unit consumption and i is the appliance type.

The parameters relevant for the emission calculation for woodstoves are described in the following, and a comprehensive description of the parameters in the national emission model is available in Nielsen et al., 2021.⁸ An extended description of the emission calculations for the present project supplemented with further details about the national emission inventory model is available in Plejdrup & Nielsen (2023)⁹.

7.1.1 Woodstoves in Denmark

The number of woodstoves in Denmark is based on information from the Danish chimney sweeper association (SFL) for 2017, supplemented with data from the national building and dwelling register (BBR). The total number of woodstoves is around 670 000 and further 48 000 other appliances (open fireplaces, masonry stoves, etc.).

⁸ Nielsen, O.-K., Nielsen, M. & Plejdrup, M.S., 2021. Updating the emission model for residential wood combustion. Aarhus University, DCE – Danish Centre for Environment and Energy, 85 pp. Scientific Report No. 442. <http://dce2.au.dk/pub/SR442.pdf>

⁹ Plejdrup, M.S. & Nielsen, O.-K. 2024. Partikelemissioner fra brændeovne – med fokus på testzone of målinger i Mårslet. Aarhus Universitet, DCE – Nationalt Center for Miljø og Energi. Videnskabelig rapport nr. 611. <http://dce2.au.dk/pub/SR611.pdf>

Woodstoves are divided into technologies based on the regulation with which they comply. In 2020 most woodstoves are in the categories “Stove (1990-2007)” and “Eco labelled stove / new advanced stove (2014)”. The distribution of woodstoves per technology is shown in TABLE 11.

TABLE 11. Number of woodstoves in 2020 per technology.

Technology	Description	Number in 2020
Stove (-1989)		29 486
Stove (1990-2007)	Stove with Danish Standard mark	272 377
Stove (2008-2014)	Stove conforming with Danish legislation (2008)	14 920
Stove (2015-2016)	Stove conforming with Danish legislation (2015)	4 100
Stove (2017-)	Stove conforming with Danish legislation (2017)	8 200
Eco labelled stove / new advanced stove (-2014)	Stove conforming to the ecolabel (Svanemærket) until 2014	229 563
Eco labelled stove / new advanced stove (2015-2016)	Stove conforming to the ecolabel (Svanemærket) 2015-2016	36 900
Eco labelled stove / new advanced stove (2017-)	Stove conforming to the ecolabel (Svanemærket) from 2017	73 800
Open fireplaces and similar		45 186
Masonry stoves and similar		3 000
SUM, stoves		669 346
SUM, stoves+other appliances		717 532

7.1.2 Unit consumption

The total wood consumption for woodstoves is estimated from the unit consumption. The same unit consumption is used for all woodstove technologies while separate unit consumptions are used for other stoves (see TABLE 12). Data is based on Ea Energianalyse (2016).¹⁰

TABLE 12. Unit consumption per technology (Ea Energianalyse, 2016).

Technology	Unit consumption [GJ/appliance/year]
Woodstove	23.4
Open fireplaces and similar	11.8
Masonry stoves and similar	42.1

The total wood consumption estimated from the number of appliances and the unit consumptions deviate from the wood consumption reported in the national energy statistics published by the Danish Energy Agency. The guidelines prescribe that the national emission inventory shall be based on the official energy statistics, and following the estimated wood consumption is scaled to be consistent with the numbers in the energy statistics. The scaling is made evenly over all technologies. The wood consumption per technology for 2020 is listed in TABLE 13.

¹⁰ Ea Energianalyse, 2016: Brændeforbrug i Danmark 2015. November 2016. Available at: https://ens.dk/sites/ens.dk/files/Statistik/braende_2015.pdf

TABLE 13. Wood consumption per technology for 2020.

Technology	Scaled wood consumption in 2020 [GJ]
Stove (-1989)	429 932
Stove (1990-2007)	3 971 497
Stove (2008-2014)	217 547
Stove (2015-2016)	59 782
Stove (2017-)	119 563
Eco labelled stove / new advanced stove (-2014)	3 347 231
Eco labelled stove / new advanced stove (2015-2016)	538 035
Eco labelled stove / new advanced stove (2017-)	1 076 069
Open fireplaces and similar	331 398
Masonry stoves and similar	78 610

7.1.3 National emission factors

The emission factors used in the national emission inventories are based on a large number of sources, including limit values in regulations and approvals for different technologies, and information from measurement campaigns.

The emission factors must reflect average real-world conditions, which may differ greatly from optimal conditions in a laboratory. Measurements that are taken into account are, to the greatest extent possible, made in a dilution tunnel, whereby they include condensable particles. Furthermore, measurements preferably cover the full cycle including ignition and burn-out, and are in-situ measurements that include both full and partial load, moist and dry wood, different types of wood and normal firing practices including commonly occurring inappropriate firing practices.

The emission factors for particles, as for most other substances, are lower for newer technologies compared to older technologies (TABLE 14). This does not apply, for example, to NO_x, where the emission factors are higher for the newer technologies, as they have a higher combustion temperature, which means that more NO_x is formed (also compare section 5.2).

TABLE 14. Emission factors for particles (TSP, PM₁₀ and PM_{2.5}) per technology.¹¹

Technology	EF _{TSP} [g/GJ]	EF _{PM10} [g/GJ]	EF _{PM2.5} [g/GJ]
Stove (-1989)	1 000	950	930
Stove (1990-2007)	500	475	465
Stove (2008-2014)	389	370	362
Stove (2015-2016)	317	301	295
Stove (2017-)	253	240	235
Eco labelled stove / new advanced stove (-2014)	253	240	235
Eco labelled stove / new advanced stove (2015-2016)	190	181	177
Eco labelled stove / new advanced stove (2017-)	127	121	118
Open fireplaces and similar	882	838	820
Masonry stoves and similar	63	60	59

¹¹ Nielsen, O.-K., Plejdrup, M.S., Winther, M., Mikkelsen, M.H., Nielsen, M., Gyldenkerne, S., Fauser, P., Albrechtsen, R., Hjelgaard, K.H. & Bruun, H.G. 2023. Annual Danish Informative Inventory Report to UNECE. Emission inventories from the base year of the protocols to year 2021. Aarhus University, DCE – Danish Centre for Environment and Energy, 603 pp. Scientific Report No. 540. <http://dce2.au.dk/pub/SR540.pdf>

Technology	EF _{TSP} [g/GJ]	EF _{PM10} [g/GJ]	EF _{PM2.5} [g/GJ]
Stove (-1989)	1 000	950	930
Pellet stove	51	48	47

7.1.4 Emissions from woodstoves in Denmark

The total national particle emissions from woodstoves (including open fireplaces, masonry stoves etc.) in 2020 is 3 932 t for total suspended particles (TSP) and 3 656 t for PM_{2.5} (FIGURE 32). The trend since 1990 follows the trend in the total wood consumption, which show a large increase 2002–2007. Replacement of older stoves with newer technologies contributes to reduce the particle emissions, which means that the particle emissions do not increase to the same degree as the wood consumption.

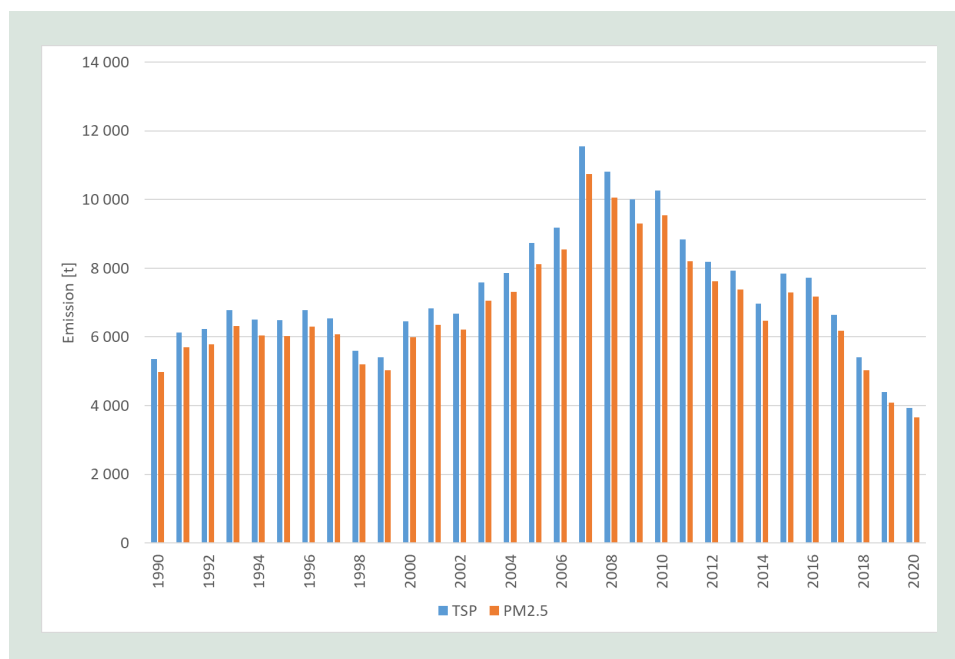


FIGURE 32. Particle emissions from woodstoves.

7.2 Emission estimates for the test zone

Emission estimates were calculated for those participants in the *Testzone*, where direct measurements in the chimney had been carried out by 2022 (see section 5.2). These were later used to calculate emission scenarios on a national level.

7.2.1 Estimated effects of the interventions

In the following sections, the effect of the interventions is described based on measurement results from Mårslet (see section 5.2), and a comparison is presented with estimates based on the national emission inventories. It must be kept in mind that the measurements before and after the interventions were made on different days and will therefore be influenced by factors other than the interventions alone. In contrast to laboratory measurements, where uniform firing conditions are aimed for, the measurements in Mårslet can be influenced by variation in both weather, fuel type and quantity, and firing practices.

7.2.1.1 New stove

Two participants (A, B) have had their stoves from 2004 and 2000 replaced with new stoves and in both cases, lower concentrations were measured after replacement. The original stoves are both relatively old and are assumed conventional stoves that do not meet special environmental requirements such as the Nordic Ecolabel *Svanemærket*. The new stoves both have the label

Svanemærket and thus meet the requirement for a maximum emission of 2 g of particles per kg of wood.

Estimates based on the measurements at the two addresses before and after replacement show a reduction in the emission of particles (TSP) of 72% and 29% (TABLE 15). For comparison, a reduction of 75% is estimated from the replacement based on emission factors from the national emission inventory.

In general, the emission factors estimated from the measurements in Mårslet are lower than the emission factors used in the national emission inventory for stoves of similar technologies.

Both the measurements and the emission factors used in the national inventories are subject to large uncertainties. For address A and B both before and after the replacement of stoves, emission factors based on measurements are significantly lower than for the national inventory. A possible reason is the use of different methods, where the first three minutes after ignition or refuelling are not included in the measurements, which are periods of high emissions compared to the rest of the combustion cycle. Furthermore, condensed particles are included in the factors in the national inventories but not in the field measurements in Mårslet. Emission factors based on measurements are between a factor of three and nine lower than the factors used in the national inventories.

TABLE 15. Emission factors based on measurements, emission factors used in the national emission inventories and reduction shares when replacing with a new woodstove.

Address	Measurement			National emission inventory		
	EF before [g/GJ]	EF after [g/GJ]	Reduction [%]	EF before [g/GJ]	EF after [g/GJ]	Reduction [%]
A	122	34	72	500	127	75
B	59	42	29	500	127	75
Average			51			75

7.2.1.2 ESP filter

Particle filters have been retrofitted at two addresses (C, D). The woodstoves at these addresses are from 2018 and 2008, and both are assumed to meet the requirements for the Nordic Ecolabel. In 2008, the requirement for the Nordic Ecolabel was 4 g/kg, while in 2018 it was tightened to 2 g/kg.

Electrostatic particle (ESP) filters from Exodraft have been used. The efficiency of the filters is stated by the manufacturer (Exodraft, 2022)¹² to be 70-75% for reduction of the particle mass when measured according to the Norwegian standard NS3058 (measurement in dilution tunnel whereby condensable particles are included). The filters have an integrated smoke extractor (draft fan). Corresponding filter efficiency (70%) has been found through a comprehensive literature study (Plejdur et al., 2021a)¹³, but the study shows that there is great variation between the measured efficiency levels.

¹² Exodraft, 2022: Wood Stove Filter - exodraft chimney fans & heat recovery. <https://exodraft.co.uk/product/particlefilter/esp-particle-filter/> (08-11-2022)

¹³ Plejdur, M.S., Nielsen, O.-K., Christensen, J.H. 2021a. Emission scenarios and air quality modelling for residential wood combustion. Impact analysis of measures for small wood burning appliances in Denmark and effect on transport of black carbon to the Arctic. Aarhus University, DCE – Danish Centre for Environment and Energy, 54 p. – Scientific report no. 426 <http://dce2.au.dk/pub/SR426.pdf>

The measurements in Mårslet show a reduction in particle emissions of 48% and 18% after fitting a particle filter (TABLE 16), which is significantly lower than the 70-75% stated by the manufacturer. The measurements in Mårslet were carried out directly in the chimney in the hot flue gas, while the filter manufacturer refers to measurements of cooled flue gas in the dilution tunnel, whereby condensable particles are included. It is not known whether the filter has the same efficiency throughout a full combustion cycle, or whether the degree of efficiency is affected by the fact that the ignition phase, where there are high particle concentrations and lower flue gas temperature, and the burnout phase are not included in the measurements. No detailed information has been collected about fuel type and quantity, firing practices, etc., which is why it is not possible to assess to what extent measurements before and after filter installation are influenced by possible variations in these parameters.

When compared with the national statistics, the measurements show emission factors at the same level as the national statistics for house C, but significantly lower for house D, where the estimate based on measurements or before and after fitting the particle filter is a factor of 14 and 3 lower.

TABLE 16. Emission factors based on measurements and default emission factors, and reduction shares when retrofitting ESP filters.

Address	Measurement			Default		
	EF before [g/GJ]	EF after [g/GJ]	Reduction [%]	EF before [g/GJ]	EF after [g/GJ]	Reduction* [%]
C	104	54	48	127	38	70
D	19	15	18	253	76	70
Average			33			70

* The filter efficiency is assumed 70% according to the manufacturer (Exodraft, 2022) and in agreement with a literature study by Plejdrup et al. (2021a).

7.2.1.3 Training

User behaviour is a significant factor in relation to particulate emissions from woodstoves, and both the choice of fuel and firing practices can have a major influence. Optimal firing requires that clean, dry wood is used, that the amount of firewood is suitable for the stove, and that there is adequate air supply to the combustion chamber during both the ignition phase and the rest of the firing cycle.

The participants at the relevant addresses received training in better firing practice, with a focus on e.g., ignition, amount of firewood, and air supply. There is a tendency to use too large amounts of wood. The participants at address E have stated that, after the training, they have been aware of reducing the amount of wood, as they previously used too large amounts. For address E, lower emissions were measured after the training, which may be an indication of a change in user behaviour towards a better firing practice.

Address F is the only location where the measurements showed higher concentrations after the intervention than before (TABLE 17). The participants keep a log of fires, and it is stated that for one of the refuelling phases after the intervention, a larger piece of wood was ignited, and that the fire took longer than usual to catch. Poor combustion results in increased particulate emissions, and it is plausible that this is the cause of an increased emission factor following the intervention at address F.

As mentioned, the emission factors used in the national emission inventories must describe average conditions, and they are therefore based on both combustion under optimal conditions

with low emissions and conditions that stand out in the case of, for example, high emissions. Together, the factors must reflect an average firing practice, including the extent of correct firing. The emission factors are often based on a small number of measurements and are therefore associated with great uncertainty, e.g. in relation to whether the number of extreme observations is representative in relation to the occurrence for the total population of woodstoves in Denmark. Since the factors describe average conditions, it is not possible on that basis to assess the effect of improved firing practices.

TABLE 17. Emission factors based on measurements and default emission factors, and reduction shares after training in better firing conditions.

Address	Measurement			Default		
	EF before [g/GJ]	EF after [g/GJ]	Reduction [%]	EF before [g/GJ]	EF after [g/GJ]	Reduction* [%]
E	96	51	47	500	500	—
F	72	85	-18	253	253	—
Average			15			—

**Not relevant as the emission factors used in the national emission inventories reflect average conditions, including firing practice.*

7.2.2 Emission estimates on national level

To give an impression of the effect of transferring the interventions in Mårslet to the national level, scenario calculations have been carried out based on the national emissions inventories for 2020. The estimates must be taken with great caution due to the significant uncertainties of the national emission inventories and the estimated effects of the interventions. The scenarios that illustrate a change in technology through the replacement of stoves, and assuming a proportion of stoves that meets environmental requirements, must be seen in the light of the fact that there is no national statistics on the technology distribution of woodstoves in Denmark. The technology distribution in the national emission reports is based on replacement rates, sales figures and the proportion that meets environmental requirements, which are parameters that are based to varying extents on assumptions. Therefore, the scenario estimates must be seen as an assessment of the order of magnitude of a given intervention rather than an exact estimate of the effect of the intervention.

The national total particle emissions in 2020, cf. the national emissions inventories, are listed in TABLE 18, and the emissions from wood-burning stoves separately. Woodstoves only include emissions from woodstoves and thus do not include pellet stoves, open fireplaces, masonry stoves etc.

TABLE 18. National total emission in 2020 cf. the national emission inventories.

	TSP [ton]	PM ₁₀ [ton]	PM _{2.5} [ton]
NATIONAL TOTAL	84 274	22 412	11 983
Woodstoves (excl. open fireplaces etc.)	3 635	3 453	3 380
Woodstoves per national total emission	4%	15%	28%

Woodstoves, which are included in the sector Other stationary combustion, make up a relatively small proportion of the national total emissions for particles because there are many other significant sources. Agriculture constitutes a major source for TSP in particular and to a lesser extent for PM₁₀. For PM_{2.5}, there is a significant contribution from small stationary combustion

plants that are fired with fuels other than wood, just as several other sectors contribute significantly to the national total PM_{2.5} emissions.

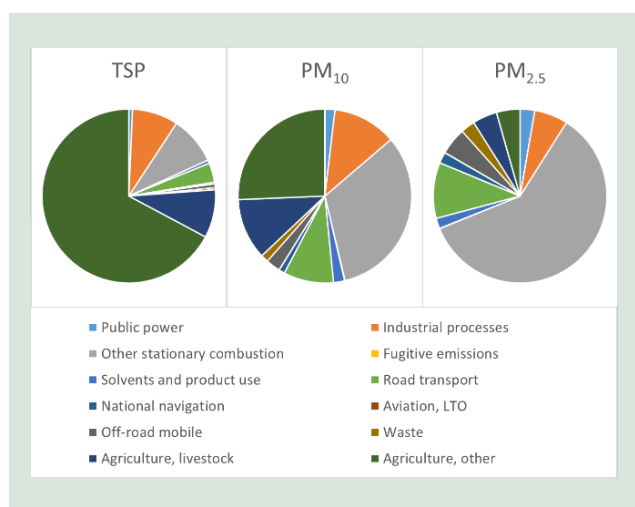


FIGURE 33. National total emissions of TSP, PM₁₀, and PM_{2.5} in 2020 per sector.

Five scenarios have been set at national level; three focusing on technology change and two illustrating the effect of installing filters (TABLE 19). The technology scenarios are based on the assumptions that

- 1) all stoves in each technology category comply with the corresponding environmental requirements,
- 2) all pre-2008 stoves are replaced with the latest technology and comply with the corresponding environmental requirements,
- 3) all stoves are replaced with the latest technology and comply with the corresponding environmental requirements.

For installation of ESP filters, two scenarios have been set up with the assumption that all stoves are retrofitted with filters with

- 4) an efficiency of 33%, corresponding to average effect based on measurements in Mårslet and
- 5) 70%, corresponding to average effect found through literature study and corresponding to the manufacturer's information on efficiency.

TABLE 19. National level emission scenarios.

Scenario	Description
Base	The national emission inventory
1	All stoves comply with environmental requirements
2	All pre-2008 stoves replaced by the latest technology
3	All stoves replaced by the latest technology
4	All stoves retrofitted with filters with an efficiency of 33 %
5	All stoves retrofitted with filters with an efficiency of 70 %

The scenarios are focusing on the conditions examined in the *Testzone*. The estimates assume that the interventions are fully implemented, in order to illustrate the maximum effect. Generally, measures will not be introduced immediately but will be notified and implemented over years.

However, the scenario calculations compare the year 2020, as it appears in the national emissions inventory, with 2020 with fully implemented measures for each scenario. No decision has been taken on which measures could be most plausible. At present, it is required to replace pre-2003 stoves in connection with change of ownership. Requirement for replacement with new technology or installation of filters at national level will require a national register, including information on technology and filter for all appliances. Registration could be done in connection with statutory chimney sweeping carried out by authorized chimney sweeps. The measures can be imposed nationally or in selected areas, e.g. district heating areas or urban areas, just as the measures can apply to all stoves or certain technologies.

Scenario 3 in TABLE 19 should be considered a sensitivity analysis to assess the influence of the proportion of wood-burning stoves that meet environmental requirements, rather than a potential initiative. In the national emissions statements, it is assumed that 90% of the stoves from 2008 and later meet the environmental requirements for the Nordic Ecolabel.

The results of the scenario calculations at national level are shown in FIGURE 34. Replacement of pre-2008 stoves shows a reduction of emissions of approx. 50%, while the effect of replacing all woodstoves with the latest technology is approx. 65%. The largest effect is achieved through replacement of the oldest stoves, which have the highest emission factors. It must be kept in mind that all stoves are assumed to have the same fuel consumption, and therefore it is not possible to take into account whether older stoves are used more or less than average. The scenarios for retrofitting of filters depend solely on the filter efficiency. It is not possible to assess the extent to which filters have maximum effect or whether the effectiveness depends on the type of stove, fuel, user behaviour and age of the filter. The measurements in Mårslet indicate a filter efficiency of 48% for a combined pellet and woodstove and 18% for a woodstove. As the measurements were carried out on two different days, other conditions than the filter alone can have an influence on the measurements.

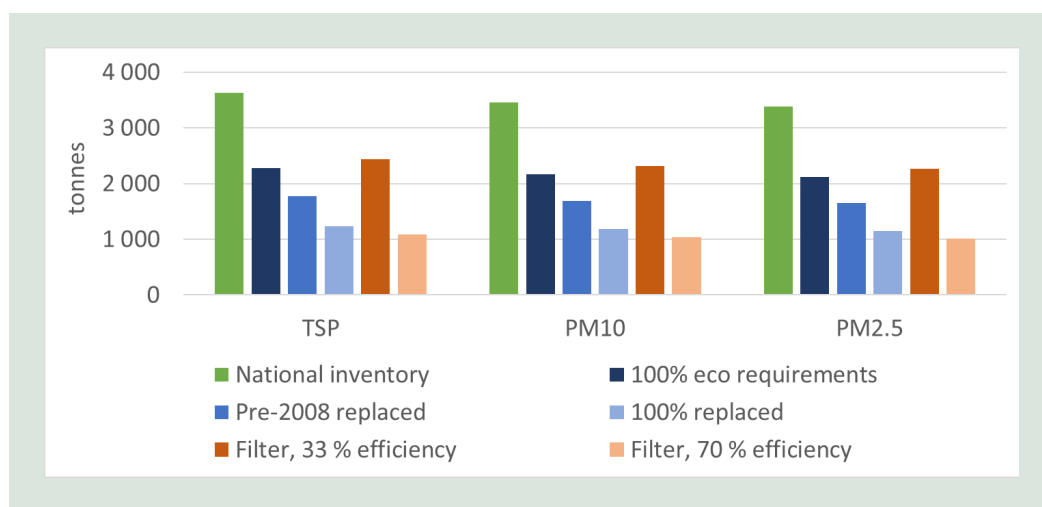


FIGURE 34. Emissions from wood-burning stoves based on the national emission inventory for 2020 and for the technology and filter scenarios listed in TABLE 19.

Appendix 1. Interventions in Mårslet

Appendix 1.1 Dominating wind direction in southern Aarhus

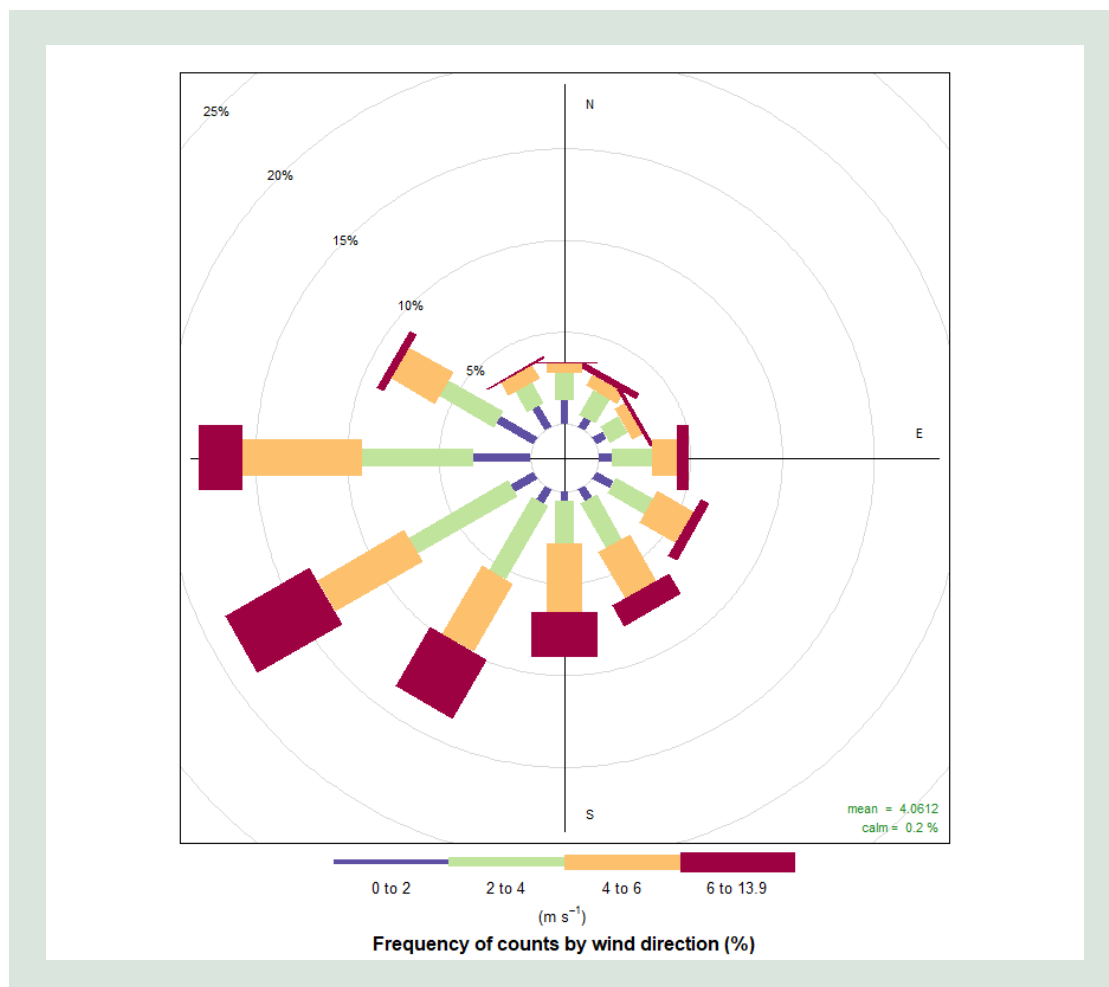


FIGURE 35. Dominating wind direction in southern Aarhus.

Appendix 1.2 Secondary test zone

Residents of a second, nearby neighborhood were originally invited to participate in the project. Potential participants in this area were few and spread out, i.e., no obvious clusters emerged. Instead, long-term measurements with an experimental, low-cost particle sensor (OptiSmoke) mounted directly in the chimneys were carried out in four participating houses. Midways in this campaign, draft optimizers were installed at the participants. Participants in the trials were asked to continue using their stove as they were used to (both in terms of frequency and firing technique).

“OptiSmoke” was installed outdoors, directly on the chimney from early January 2023 to late March 2023. Draft fans were installed on January 30. The centrepiece of the device was a low-cost optical sensor for particle concentrations, type Nova SDS198, for $\text{PM}_{2.5}$ and PM_{100} , with a

nominal range of 0–20 mg/m³. With this measuring range, flue gases need to be diluted to give a reasonable output, and measurements were of a more qualitative nature. The sensor had a small integrated fan to ensure flow past the actual measuring unit. The particle sensor was installed together with a temperature probe. A simple gas conditioning was integrated in the unit, comprised of dilutor and condenser/water separation.

A few versions were built and tested in DTI's woodstove lab, and selected prototypes were tested in conjunction with on-site measurements (FIGURE 36). The final version had both gas intake and exhaust to the chimney, to avoid pressure fluctuations influencing the measurements. Measurements were not directly verified with state-of-the-art laboratory equipment. Soot, particles, and condensate were found inside the sensor after use. One of the earlier prototypes was completely disassembled. Here, it was found that soot and dust had deposited inside the sensor unit (FIGURE 37).



FIGURE 36. Prototype of the OptiSmoke sensor installed on a brick chimney. The red cable connects to a temperature probe. Not visible in the image is the short segment of steel pipe used as a nozzle to access the flue gas channel inside the chimney.

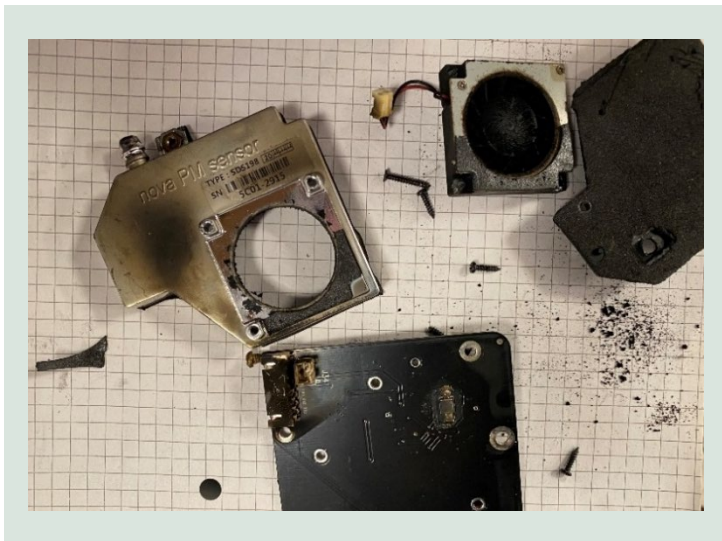


FIGURE 37. A disassembled particle sensor with dust and soot deposition.

Appendix 2. Methods for documentation of the effects

Appendix 2.1 Sensor aging

Sensor Aarhus-4, which started to show unreliable measurements during the summer 2021, was returned to Leapcraft for maintenance and finally replaced with sensor Aarhus-6 (reconditioned device) in December 2022. The remaining sensors in the Testzone all showed a pronounced degradation in their performances over time (the so-called “aging”) and a decrease in their signals, though not as dramatically as sensor Aarhus-4. This prompted us to replace sensor Aarhus-3 (Præstegårdsvej 49) with sensor Aarhus-7 (brand new device) in December 2022.

An example of the sensor aging can be seen by comparison of the measurements acquired during the 2021, 2022 and 2023 New Year's Eve's (see in FIGURE 38). New years eve can be characterized as a very strong particulate producing episode, which could be considered a relatively constant entity across the years. However, a large difference is observed from year to year and across the installed sensors. The dramatic decrease in the measured particulate levels (here numerically represented, for comprehension, by the integral of the $PM_{2.5}$ signal) from one year to the other therefore provides an undeniable hint for significant sensor aging phenomena.

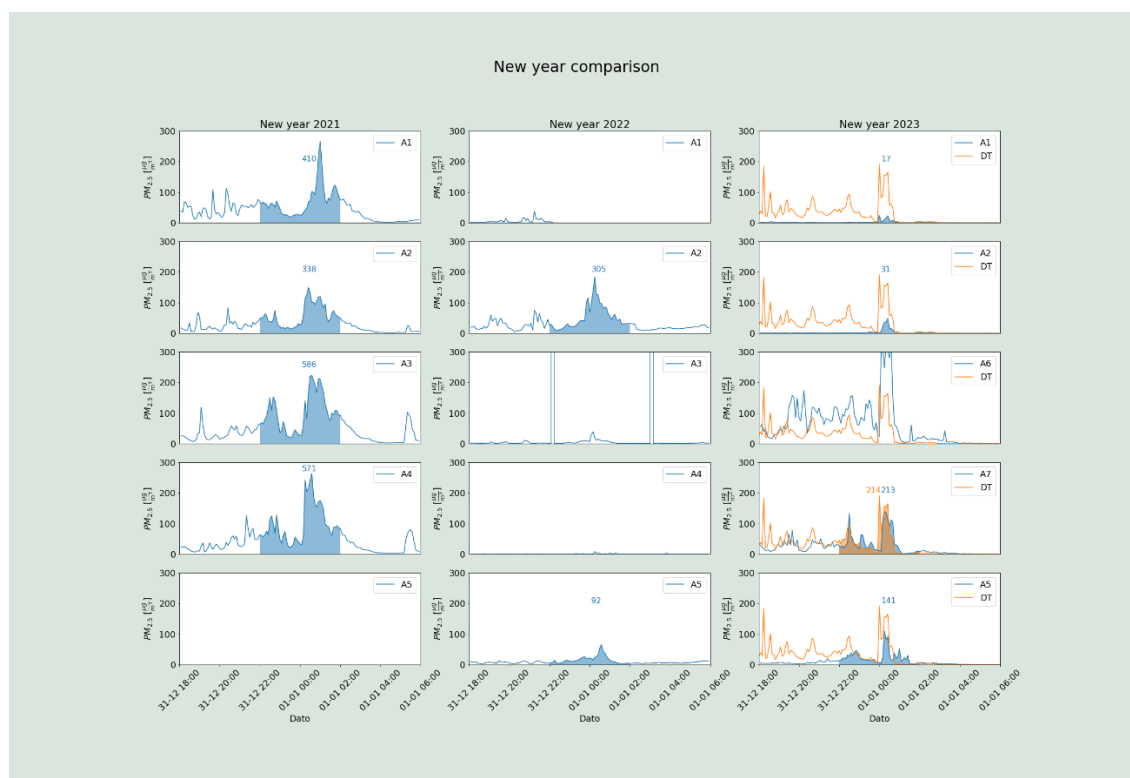


FIGURE 38. Measured particle concentrations during New Years Eve of 2021, 2022 and 2023.

Appendix 2.2 Estimating stove use frequency

Stove use was estimated based on data from indoor climate sensors. For a few weeks at the start of the project, participants were asked to write manual logs whenever they used the stove (ideally with both ignition and refueling). It was observed that the temperature signal from the sensors was a relatively reliable predictor of stove use: The indoor temperature typically shows a sharp increase several minutes after the time participants registered a “stove operation”, i.e., igniting or refueling the stove. This was found to be independent of the absolute temperature values.

In the measured data, a maximum in the temperature gradient dT/dt , followed by an increase in temperature was used as a marker for stove usage. Threshold values for dT/dt and time intervals for stove use were adjusted based on data from firing logs and indoor sensors (i.e., known stove operations). These values were then used in an automated model, scanning the temperature signal for likely stove operation.

The model parameters (see FIGURE 39) were tuned to catch as many of the recorded stove operations as possible, while at the same time avoiding false positives (i.e., the model predicted a stove was in use, but no usage was recorded in the log). Double peaks i.e., predicted firing events unrealistically close to each other, were removed from the model. Buffer time was included in the model between the timestamp recorded in the log and the temperature increase in the indoor sensor signal due to a delay occurring between charging the stove and a noticeable increase in room temperature. Model parameters were the same for all sensor data, i.e., no attempt was made to fit modelling parameters individually due to variation in the quality of manual firing logs and indoor sensor data.

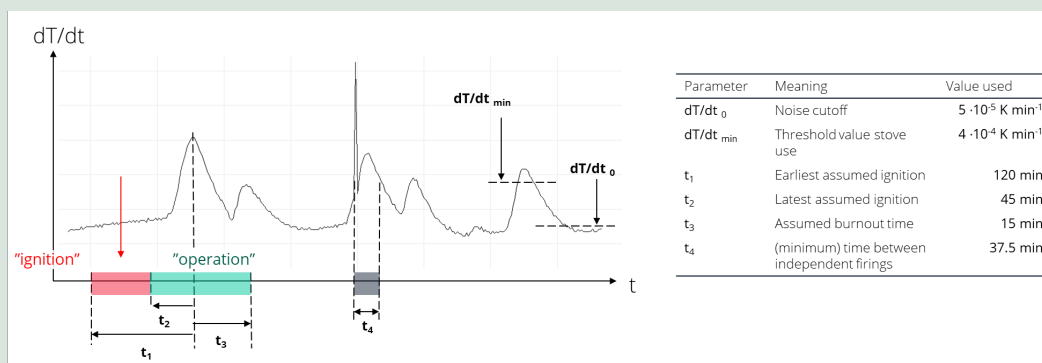


FIGURE 39. Model to detect ignition and stove use from increase in indoor temperature (spike in indoor temperature increase): example and model parameters.

The obtained model predicted 60-70% of the recorded stove operations correctly across participating households, in addition to predicting some false positives. Typically, the number of false positives was in the same order of magnitude as the recorded events the model did not predict. The model parameters were therefore considered an optimum between “tight” and “loose” modelling. Sources of deviation between recorded stove use and stove use predicted by the model were: incomplete logs, incomplete sensor data, poor signal to noise ratio, and lumping separate refuelling events into one. FIGURE 42 shows a comparison of reported and model-predicted stove use for a project participant, where 71% of reported stove use events were identified by the model.

The response rate of sensors varied over the duration of the project as illustrated in FIGURE 40. Approximately 15 indoor sensors were active (i.e., recording and sending data) on any given day in the firing seasons 2020/2021 and 2021/2022. Sensor activity was lower in season

2022/23, with around 10–13 sensors active on any given day. During the summer periods, sensor response rate dropped. The main reason was that project participants disconnected/dis-mounted their sensor. Additionally, if sensors stopped sending data due to technical issues, this was typically first fixed at the start of the firing season.

Sensor response rate was checked against the number of predicted stove use events to see whether there was any bias in sensor response rate – e.g., whether participants who used their stove more often were more interested in having a functioning sensor (and thus reporting any outages promptly). No correlation between sensor response rate and (predicted) stove use events was found. Additionally, to avoid any bias in the sensor response rate, some of the analyses were repeated with the subset of participants that had a response rate of >75 % throughout the project.

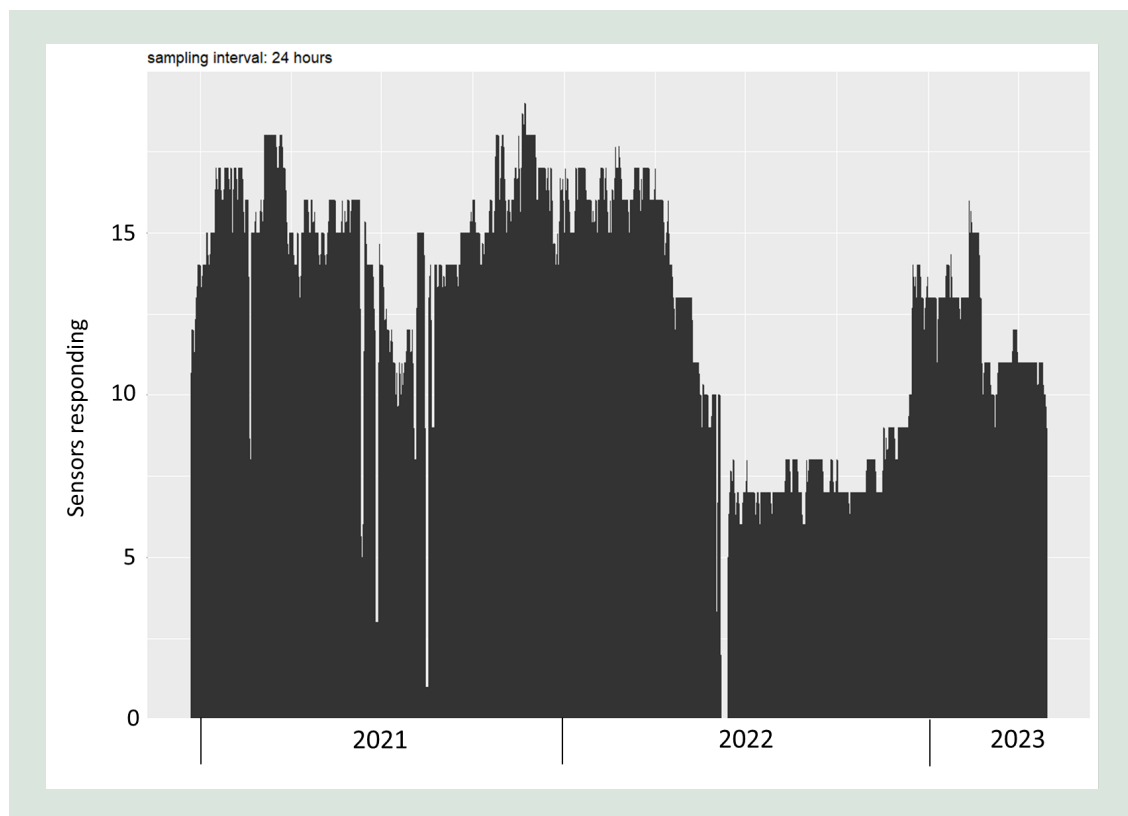


FIGURE 40. Sensor response rate varied over the duration of the project.

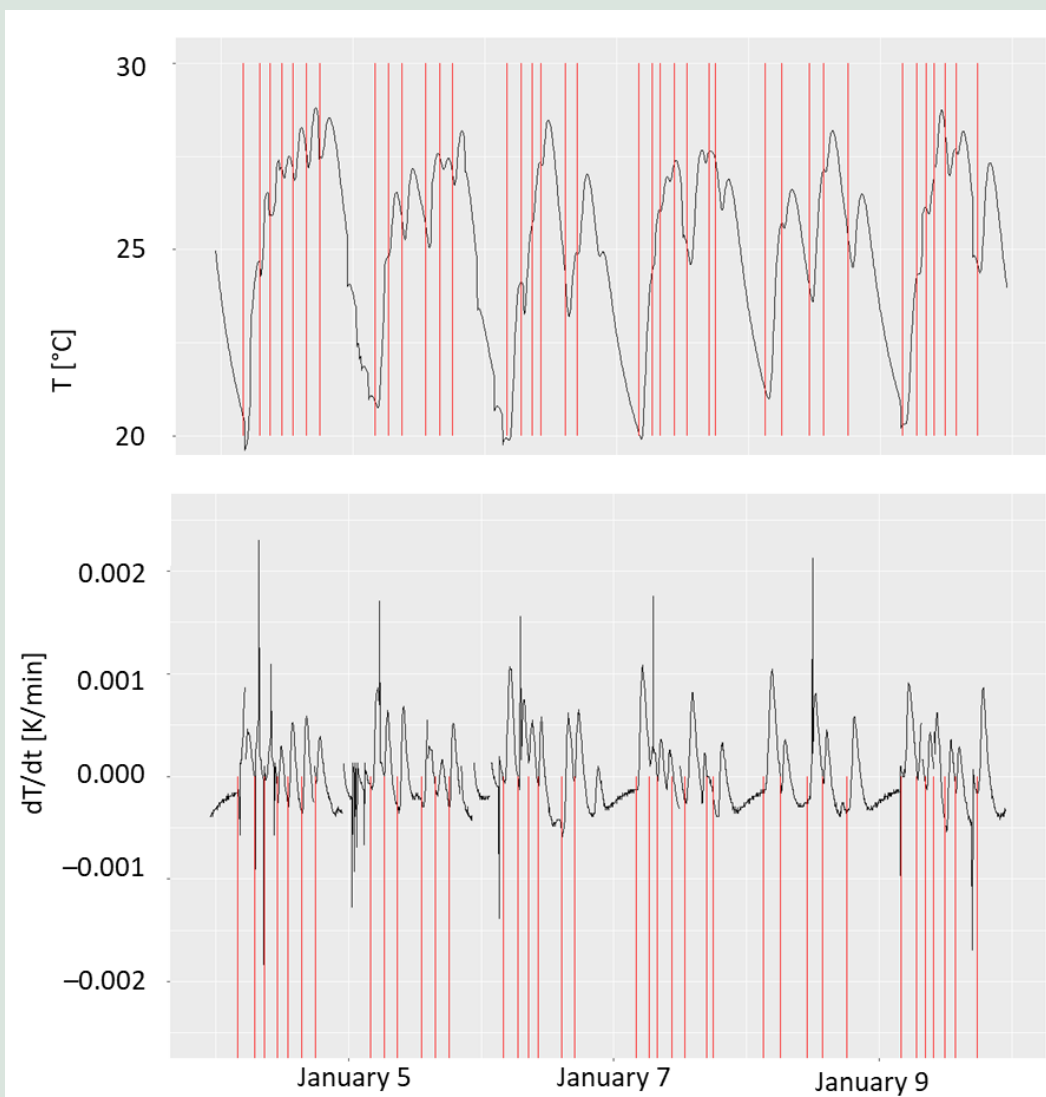


FIGURE 41. Example of indoor temperature measurements (top), temperature gradient (bottom), and self-reported firing and refueling operations (red lines).

A (significant) delay between igniting/refueling and the observed temperature increase could be observed. This was attributed to thermal inertia: the stove must heat up itself before it starts heating its environment, and heat transfer from the stove surface to the sensor (by convection and/or radiation) was not immediate (FIGURE 41).

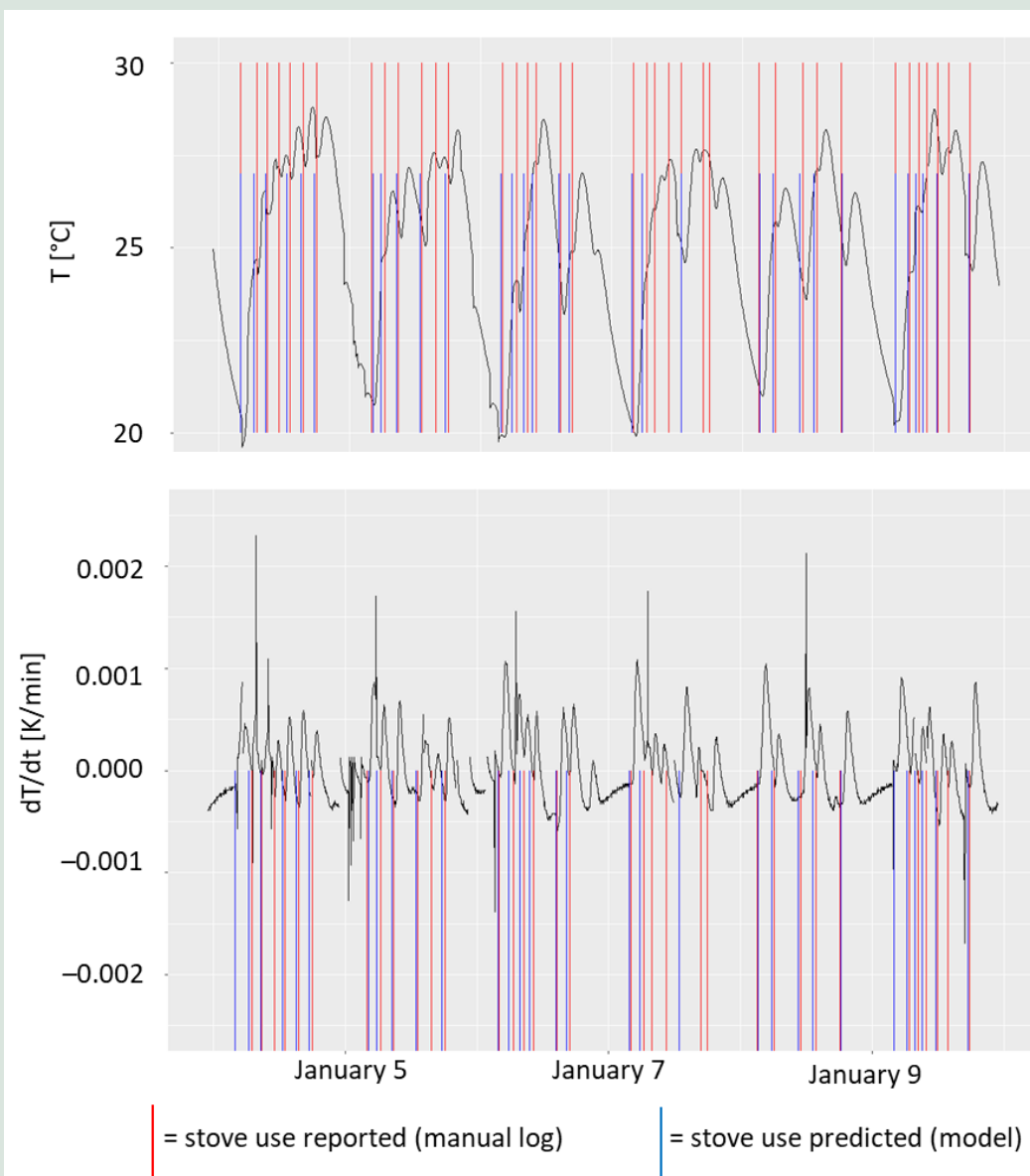


FIGURE 42. Example of self-reported stove use vs. model prediction.

It was also found that for individual participants, predicted total number of events did not fully reflect the reported use, with some participants reporting “almost daily” or “daily” stove use, but below average number of events was predicted (compare TABLE 2 in section 4.3). Some of the discrepancies can be attributed to low sensor response rate, compare e.g., participants 3 and 8. Another effect is that the model possibly did not catch refueling events very well. The rightmost column in TABLE 2 in section 4.3 shows the average number of use events (i.e., start and refueling), on days where the stove was active (i.e., average events per days, where at least one event was predicted). Here, two events would correspond to starting the stove and refueling once. Nearly all participants have an average of below 3, and most are under 2 – which suggests that the number of refueling events may be underestimated.

Comparison of unnormalized (FIGURE 43) and normalized data (FIGURE 17, see section 4.3) shows the effect of normalizing by the number of active sensors. While both datasets show a decrease in activity from season 2020/21 to season 2021/22, the normalized data (FIGURE 17)

suggest an increase in stove use in winter 2022/23. This increase is not apparent in the unnormalized data. Differences between the unnormalized and normalized data are due to the loss of sensors reporting data in 2022.

It was also seen that predicted stove use correlated inversely with the average outdoor temperature in Aarhus municipality, FIGURE 44. In the absence of other data, outdoor temperature is a reasonably good predictor of stove use, although there is some considerable scatter (FIGURE 45).

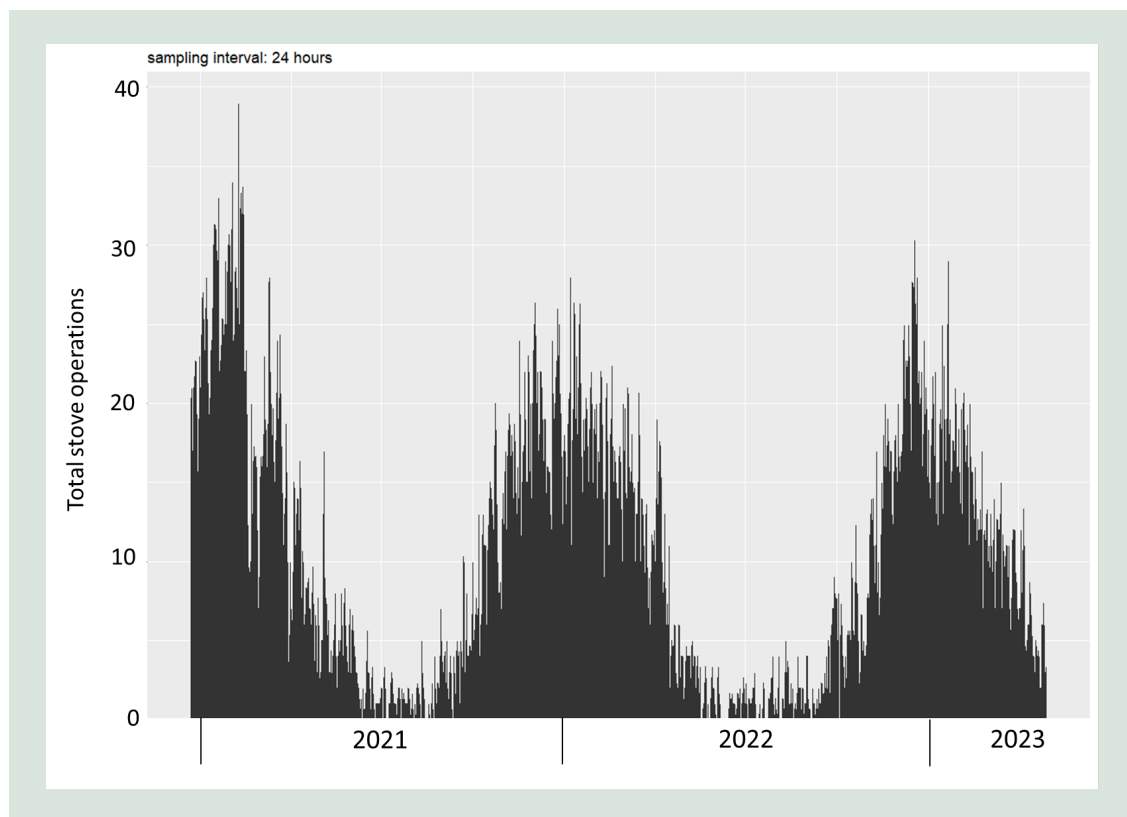


FIGURE 43. Total woodstove operations per day (start and refueling).

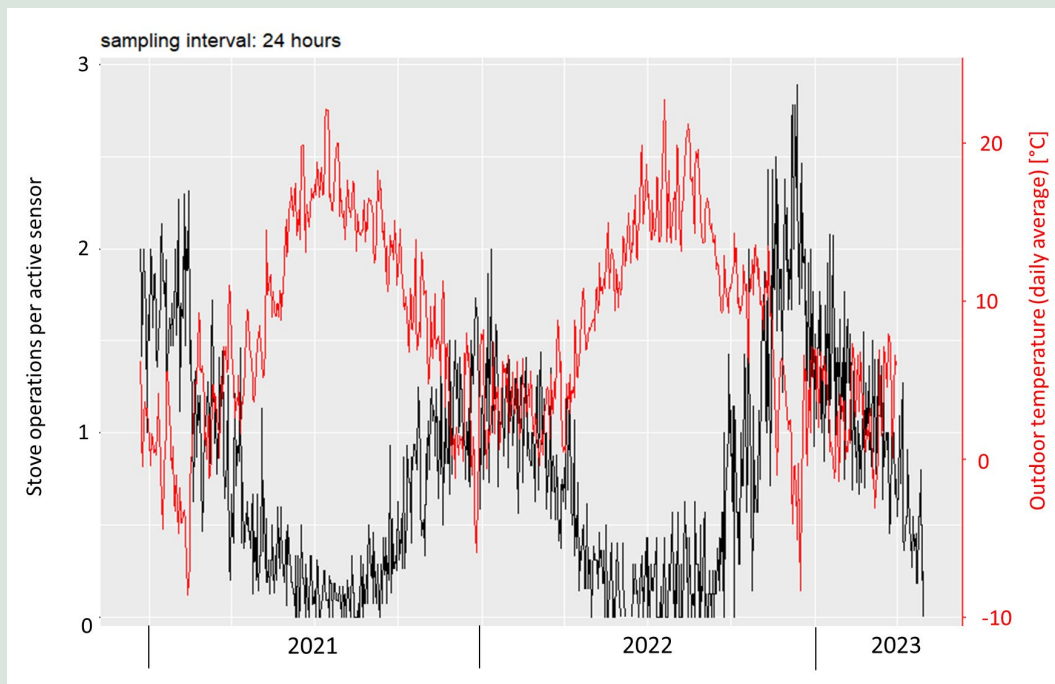


FIGURE 44. Stove use agrees qualitatively with outdoor temperature in Aarhus Municipality (source for weather data: *Danmarks Meteorologiske Institut*, dmi.dk).

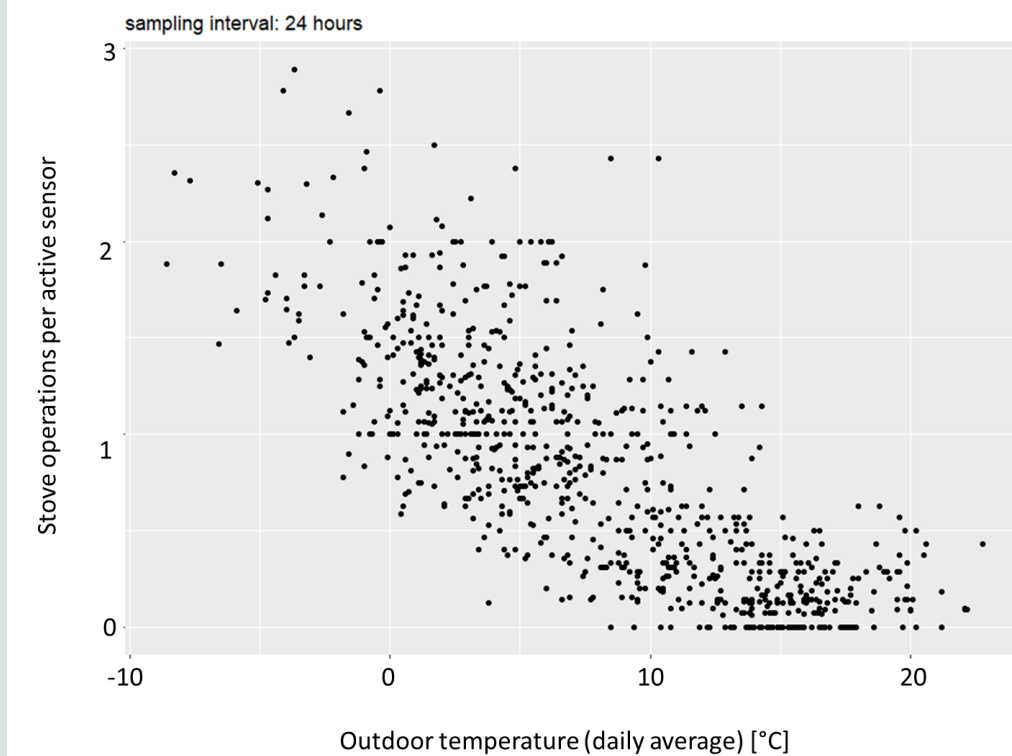


FIGURE 45. Stove operations vs. outdoor temperature (compare FIGURE 44).

Appendix 2.3 Further analysis on stove use data

Model data of stove use were further analysed for temporal variations, using the *timeVariation* function from the R package *openair*. The results show some characteristic usage patterns (FIGURE 46, FIGURE 47, and FIGURE 48). Distribution of stove use by months (bottom center in all figures) shows the same pattern as previously seen in FIGURE 17, but in a more condensed form: stove usage is much more frequent in winter months (roughly, October to March), and highest in December, when the entire project duration is considered (FIGURE 46 and FIGURE 47). This is likely explained by the holiday season, i.e., more people at home lead to a more frequent use of woodstoves (although January and February tend to have colder weather). The top row of plots in each figure shows the diurnal distribution by weekdays. Here, it is apparent that stove use is most frequent around 6 p.m. Mondays through Fridays, and more evenly spread on weekends. Stove use appears largely outside of normal working hours. This appears plausible, given the demographics of the participants – mainly people active in the workforce, with few retired among them. The magnitude of increased stove use is however interesting. As the signal is quite pronounced, it should be possible to attribute any possible increase in local pollutants during the evening hours to stove use. The diurnal distribution aggregated over all weekdays (bottom left plot) does not add much extra information, as the stove use patterns are dominated by activities Monday through Friday. Similarly, weekly variations show a slight increase in stove use on Fridays, which would agree with (some) participants using their stove for recreational purposes. Patterns for all participants (FIGURE 46) do not differ significantly from those for the participants with high (>75%) sensor response rate (FIGURE 47). Therefore, for the purpose of this project, these two datasets can be used interchangeably to demonstrate the effect of interventions on the reduction of emissions.

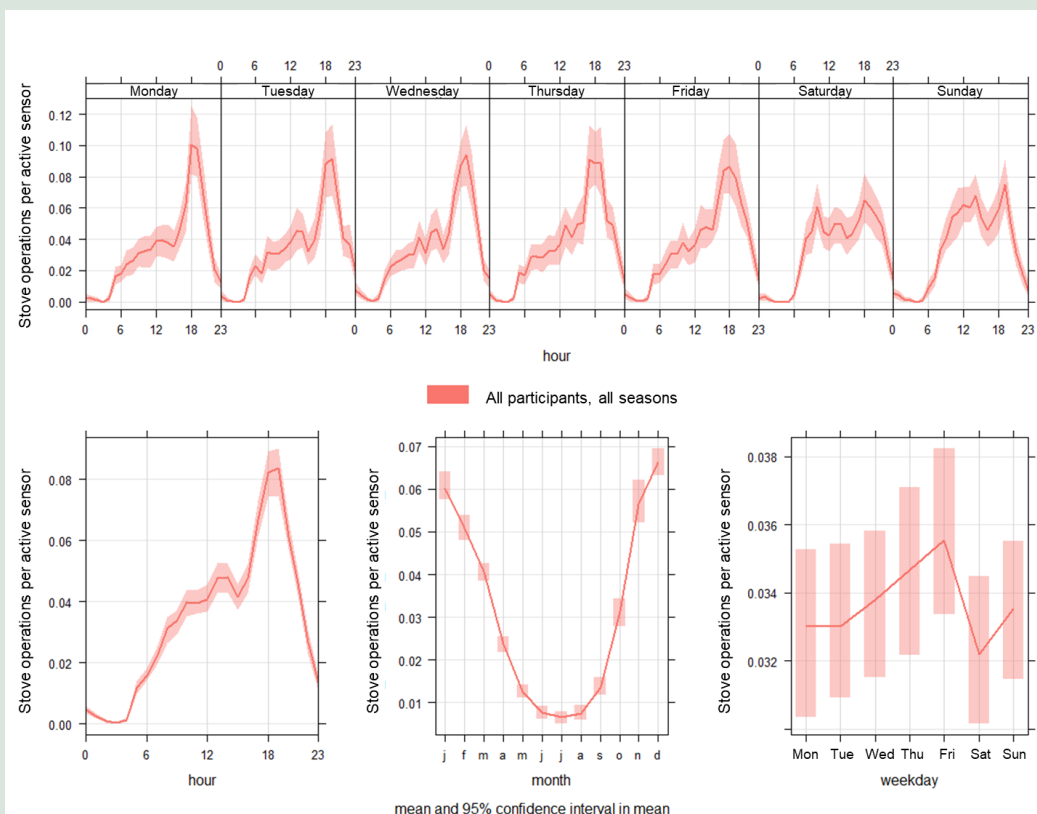


FIGURE 46. Distribution of normalized stove use over hours, weekdays, and months – all participants, all seasons.

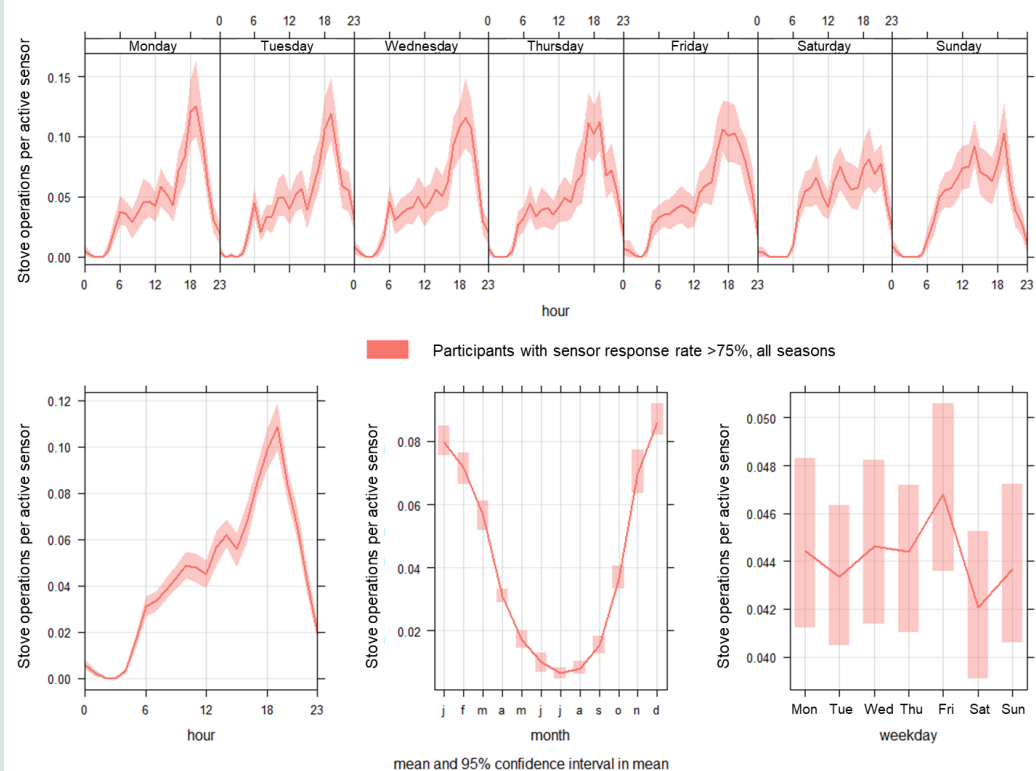


FIGURE 47. Distribution of normalized stove use over hours, weekdays, and months – participants with sensor response rate above 75% throughout the project, all seasons.

Some more variations can be seen when the data is divided into seasons, FIGURE 48. Here, the three firing seasons (“winter”) were considered individually, as well as the project’s two off-season periods (“summer”). For simplicity, winter was defined as the half year from October 15 to April 15 of the following year, and summer as the remaining time. Here, the baseline season, winter 2020/21, stands out with a more even diurnal distribution of stove use, including a second peak in stove use between 8 a.m. and 10 p.m. (bottom left plot). This can most likely be attributed to the Covid-19-related closure of offices and other workplaces. Unfortunately, this means the baseline season was an unusual year – so the three seasons must be compared with care. Comparing the two seasons with interventions (winter 21/22 and winter 22/23), it appears that stoves were used significantly more often in 22/23 than in 21/22 (compare e.g., bottom row of FIGURE 48). Most of this appears to be due to more stove use in November and December 2022, which would agree with the slightly colder outdoor temperatures compared to the previous year (see also FIGURE 44).

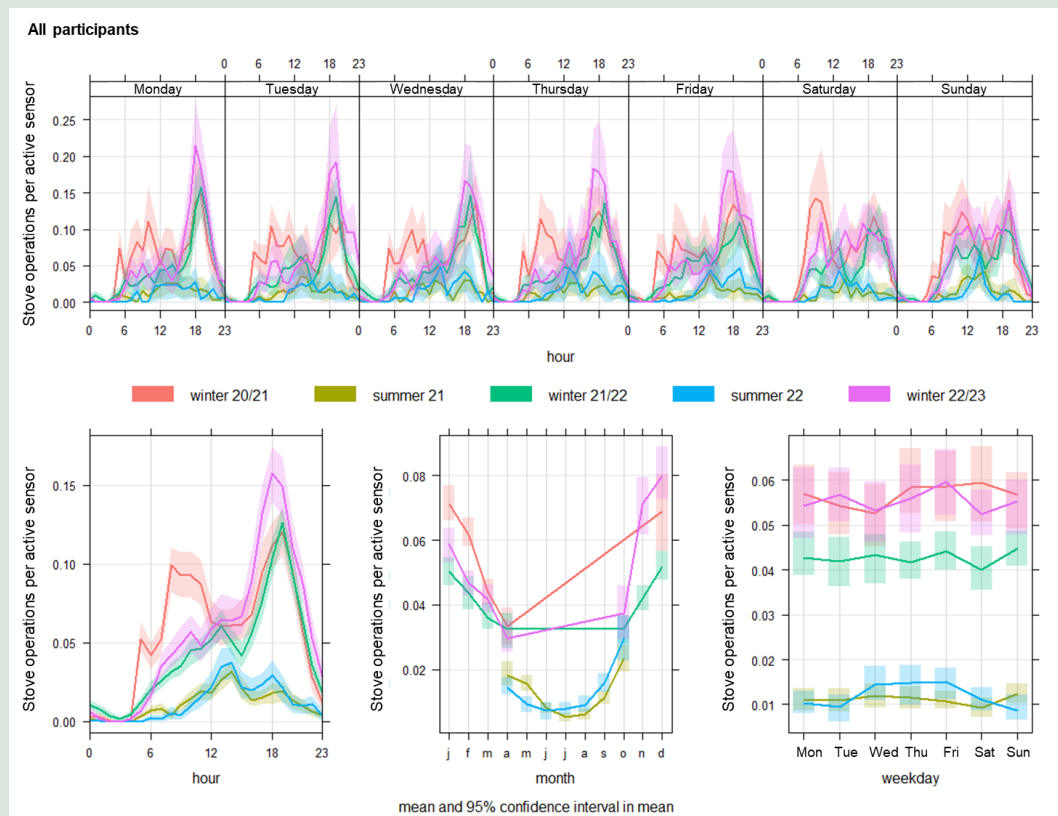


FIGURE 48. Distribution of normalized stove use over hours, weekdays, months, and seasons – all participants (same data base as FIGURE 46).

Appendix 3. Measured effects

Appendix 3.1 Meteorological normalization

FIGURE 49 shows the influence of several meteorological and time quantities on the PM_{2.5} levels measured by an ambient air quality sensor during the first months of the project. The influence of the meteorological and time quantities was quantified and expressed as a percentage.

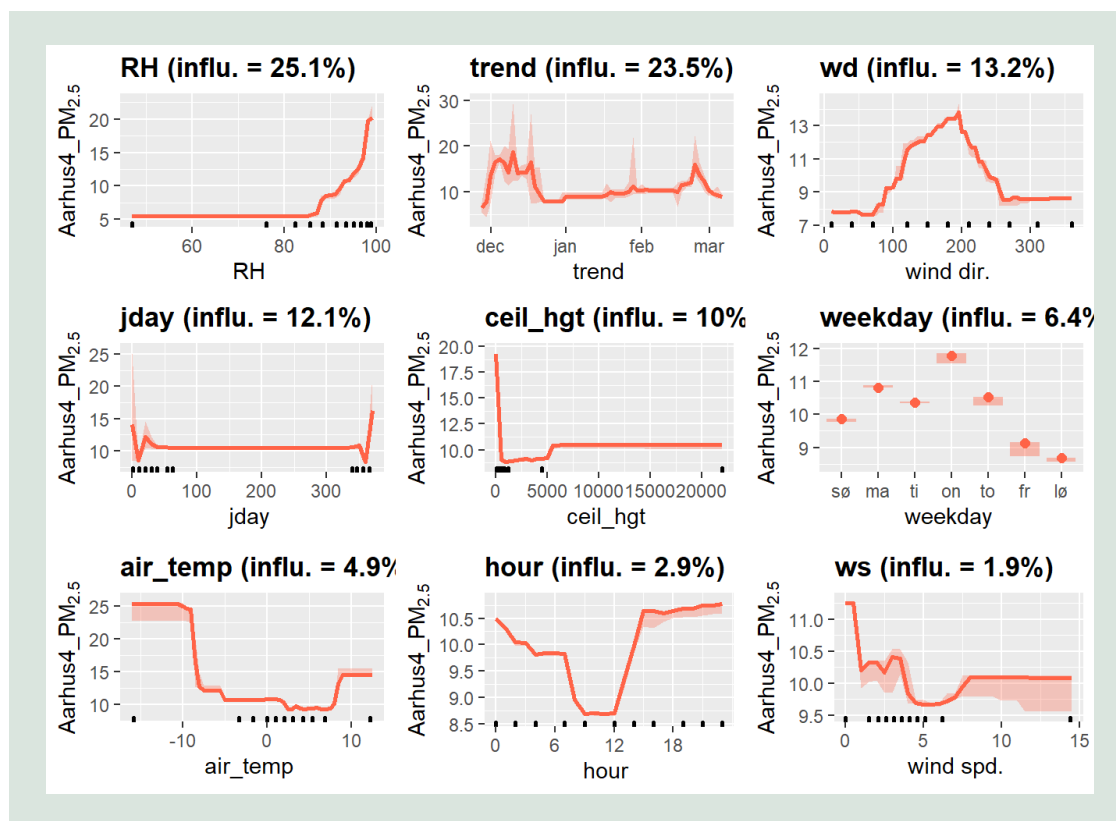


FIGURE 49. Example of partial dependencies between the pollutant of interest and different influencing phenomena.

Appendix 4. Measured effects of interventions

Appendix 4.1 Raw data for direct flue gas measurements

In the following, data are normalized to 13% O₂ in the flue gas and standard temperature and pressure (STP). The data shown in TABLE 20 through TABLE 24 are values averaged over all charges, including the ignition charge. Note that the number of charges may differ among measurement series.

From the condition of the chimney in houses G and H, it was unclear whether a draft fan was likely to lead to improvements. While the installation of a fan was recommended by the chimney sweep, the draft fan manufacturer did not expect any effect for these locations, as the height and types of chimneys selected are already estimated to support the required draft in the chimney.

TABLE 20. Particle concentrations, normalized to 13% O₂ and STP, in [mg/m³].

ID/Alias	Intervention	Before	after	Δ	rel. change
A	new stove + chimney	212	45	-167	-79%
B	new stove	86	67	-19	-22%
C	filter	155	83	-72	-47%
D	filter	30	22	-7	-25%
E	training	145	76	-70	-48%
F	training	107	114	7	+6%
G	draft fan	207	164	-43	-21%
H	draft fan	54	86	32	+60%
I	chimney	176	47	-129	-73%

TABLE 21. CO concentrations normalized to 13% O₂ and STP, in [mg/m³].

ID/Alias	Intervention	before	after	Δ	rel. change
A	new stove + chimney	7871	3274	-4597	-58%
B	new stove	4658	3721	-936	-20%
C	filter	7796	5509	-2287	-29%
D	filter	3457	2901	-556	-16%
E	training	5027	2981	-2046	-41%
F	training	3684	3627	-57	-2%
G	draft fan	2846	2981	135	+5%
H	draft fan	5235	4423	-812	-16%
I	chimney	3894	4136	242	+6%

TABLE 22. OGC concentrations normalized to 13% O₂ and STP, in [mg/m³].

ID/Alias	Intervention	before	after	Δ	rel. change
A	new stove + chimney	2402	404	-1998	-83%
B	new stove	632	279	-353	-56%
C	filter	312	318	6	2%
D	filter	158	151	-7	-5%
E	training	451	164	-287	-64%
F	training	526	611	84	+16%
G	draft fan	156	214	59	+38%
H	draft fan	571	497	-74	-13%
I	chimney	578	633	55	+10%

TABLE 23. NO_x concentrations normalized to 13% O₂ and STP, in [mg/m³]. No data for participants G, H due to analyzer malfunction.

ID/Alias	Intervention	before	after	Δ	rel. change
A	new stove + chimney	107	127	20	+19%
B	new stove	71	97	26	+37%
C	filter	95	139	45	+47%
D	filter	130	115	-15	-11%
E	training	104	118	13	+13%
F	training	132	151	19	+14%
G	draft fan	—	—	—	—
H	draft fan	—	—	—	—
I	chimney	80	77	-3	-4%

TABLE 24. Fuel consumption [kg/h].

ID/Alias	Intervention	before	after	Δ	rel. change
A	new stove + chimney	1.8	1.6	-0.3	-15%
B	new stove	2.1	1.4	-0.8	-36%
C	filter	1.7	1.9	0.2	+10%
D	filter	2.1	2.1	0.1	+3%
E	training	2.8	2.1	-0.7	-27%
F	training	2.2	2.4	0.2	+10%
G	draft fan	1.3	1.6	0.3	+27%
H	draft fan	1.6	1.7	0.1	+8%
I	chimney	1.9	1.7	-0.3	-13%

Appendix 4.2 Sensor reliability

As outlined in the methodological section of the report, the employed sensors have been affected, in different extensions, by an aging process that in some cases severely degraded their performances, preventing us from performing any type of calibration and making therefore their data of no use for the analysis. A graphical representation of the reliability of each sensor's measurements on a monthly basis can be found in FIGURE 50.

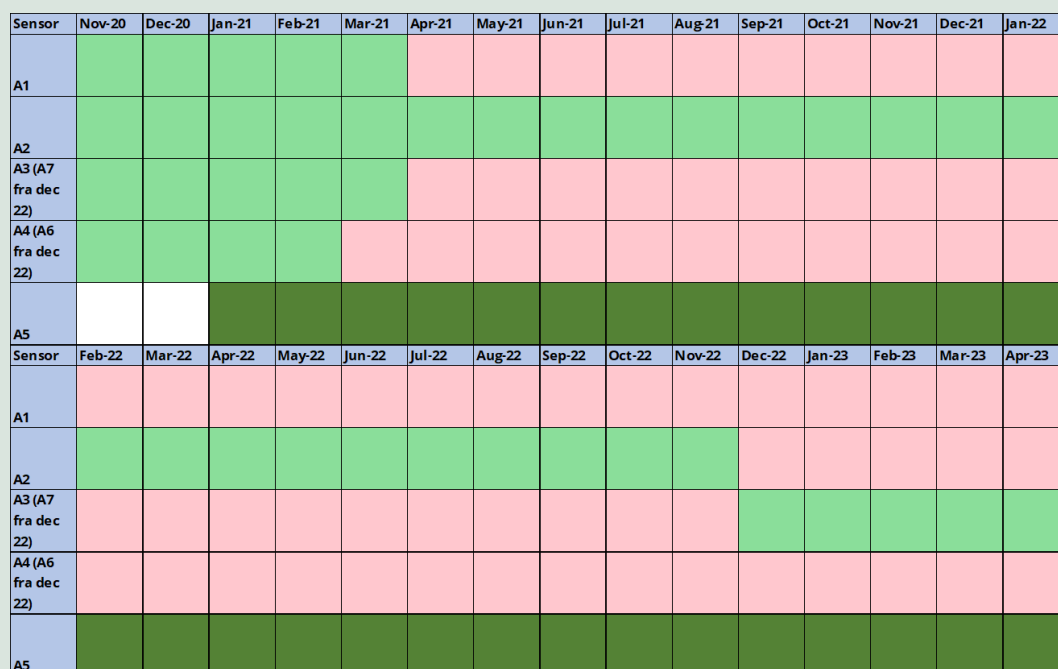


FIGURE 50. Timeline representing the reliability of the sensor data along the project duration.

Such a timeline was obtained by visually inspecting the timeseries measurements for the entire duration of the project and comparing the appearance (or not) of so-called “global events” across the different sensors (FIGURE 50, FIGURE 51). We defined “global events” as the episodes characterized by a significant, sudden, and persistent rise in the particulate concentration, thus considered to be the consequence of important meteorological changes and/or long-range pollutant transport phenomena and therefore assumed to be observable in a comparable intensity by all the sensors employed in the project. Specifically, we chose to use the background sensor A5 as reference, since the visual inspection of its measurements over time didn't show such a significant aging process as observed for the other sensors. This means that the global events were first identified in the background sensor data series and subsequently looked for in the other sensors' timeline. Using this definition, the presence or absence of these characteristic patterns in a specific sensor's timeseries was used for marking the concerned period (using a monthly granulation) with green, representing an interval with reliable sensor measurements, or with red, when the sensor measurements were considered to be unreliable.

The inspection of FIGURE 50 makes evident that some of the sensors, like for example sensor A4, were characterized by a very early aging, while others, for example sensor A2, continued to deliver reliable measurements for a longer period of time. Nonetheless, none of the sensors, apart from the background sensor A5, was unfortunately active and reliable for the entire duration of the project, therefore preventing us from analysing the change in local emissions in the specific area monitored by each sensor (reported in FIGURE 6 in paragraph 3.2.2) across all the three considered firing seasons.

Global events during project

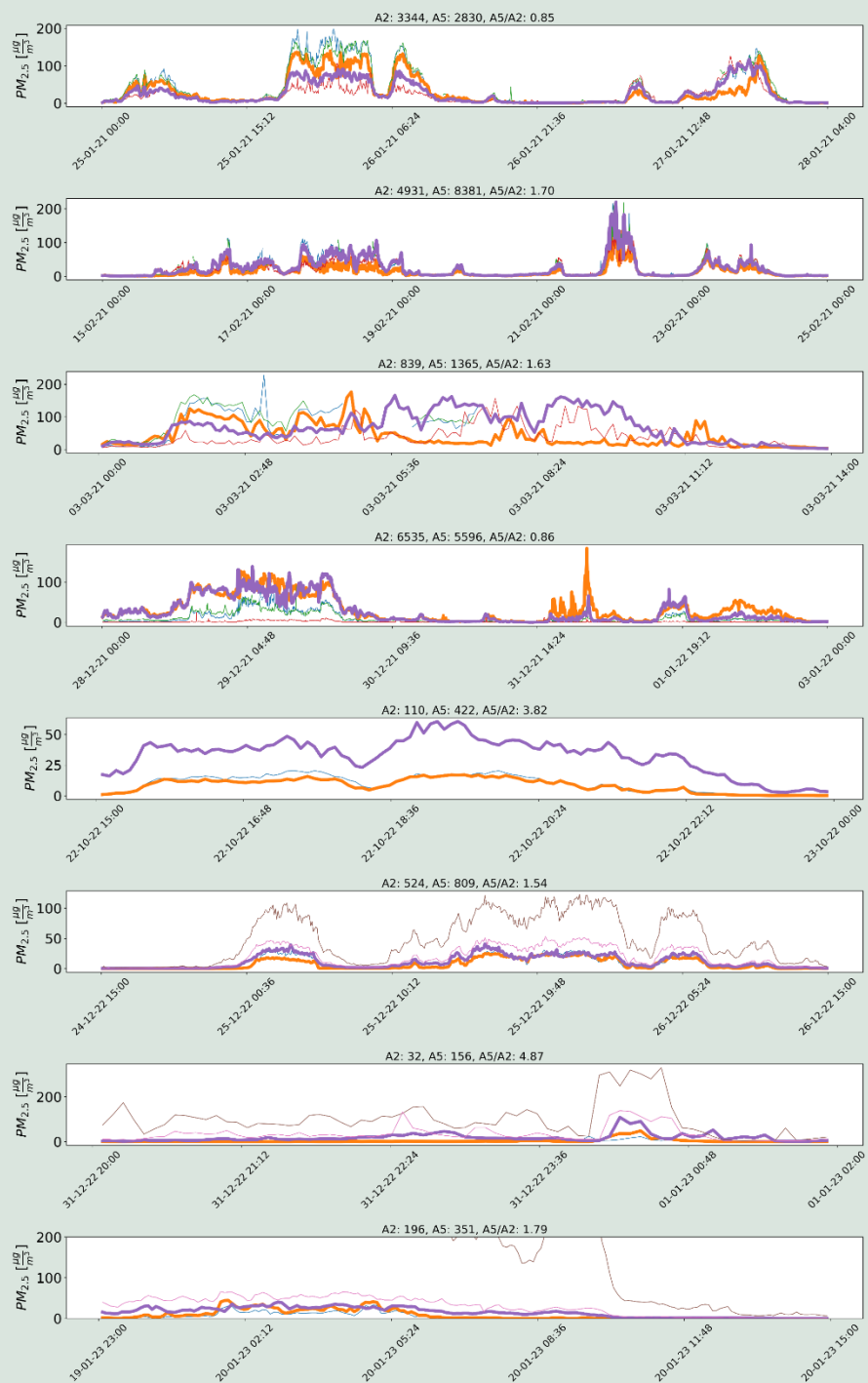


FIGURE 51. Global events identified during the project and employed for assessing the reliability of the sensor data.

These ratios were subsequently plotted with respect to the date of the global event and a regression line was calculated, with an imposed intercept of 1.0 at the date of sensor A2 installation. This constraint simply expressed that the responses of the two sensors were expected to be exactly the same when sensor A2 was brand new. Using the inverted form, $x = \frac{y - \text{intercept}}{\text{slope}}$, the signal of sensor A2 could be “de-aged”, thereby enabling the use of its sensor measurements throughout the subsequent data analysis to assess the impact of the interventions.

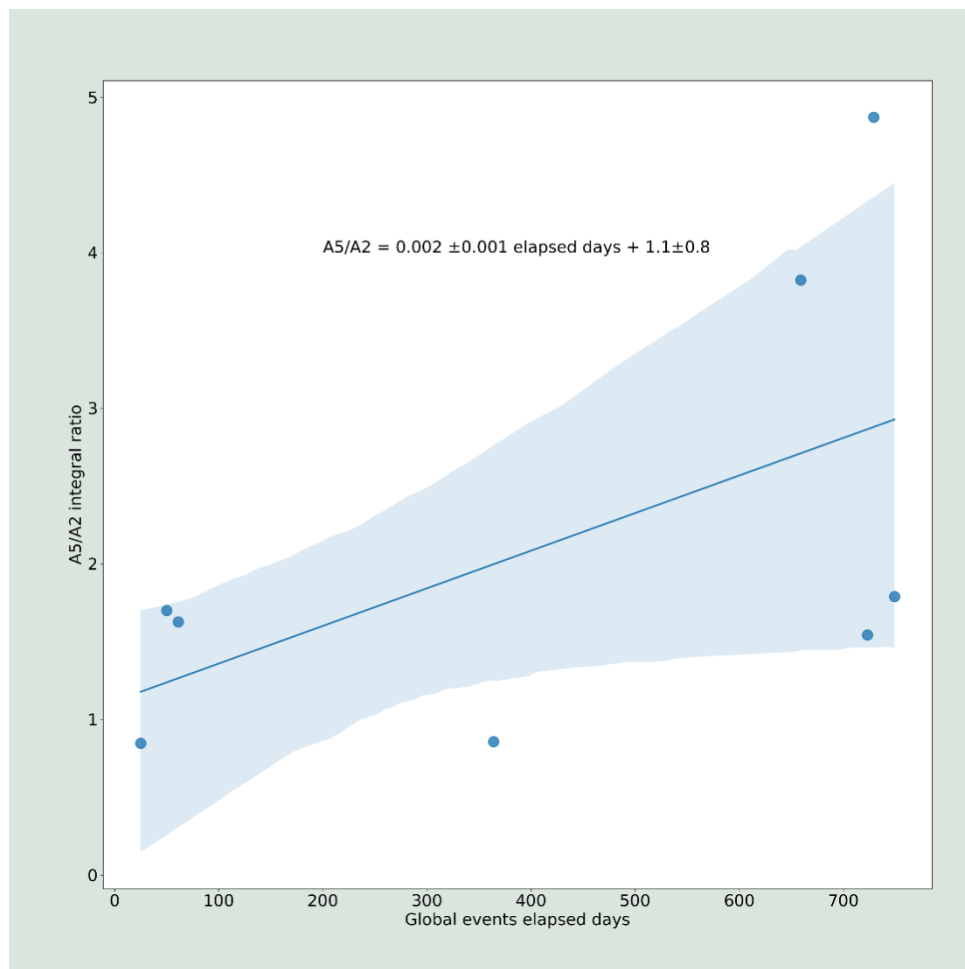


FIGURE 52. Algorithm employed for the “de-aging” of the sensor data.

Appendix 4.3 Local and background particle concentrations

FIGURE 53, FIGURE 54, and FIGURE 55 depicts the average amount of PM₁, PM_{2.5} and PM₁₀, respectively, detected on a weekly basis for particulate concentrations attributed local contributions (red color) and background levels (cyan color).

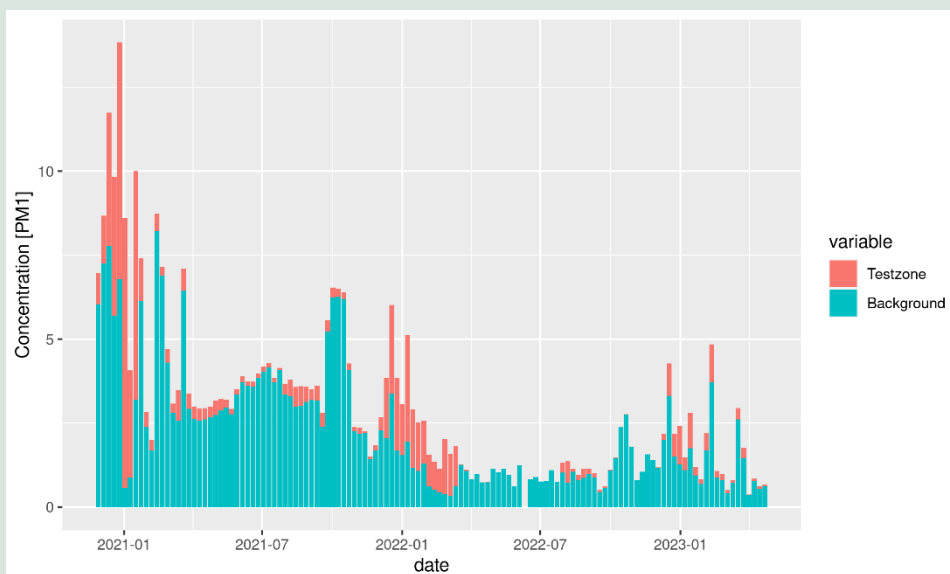


FIGURE 53. PM₁ weekly concentrations divided into background and local contributions.

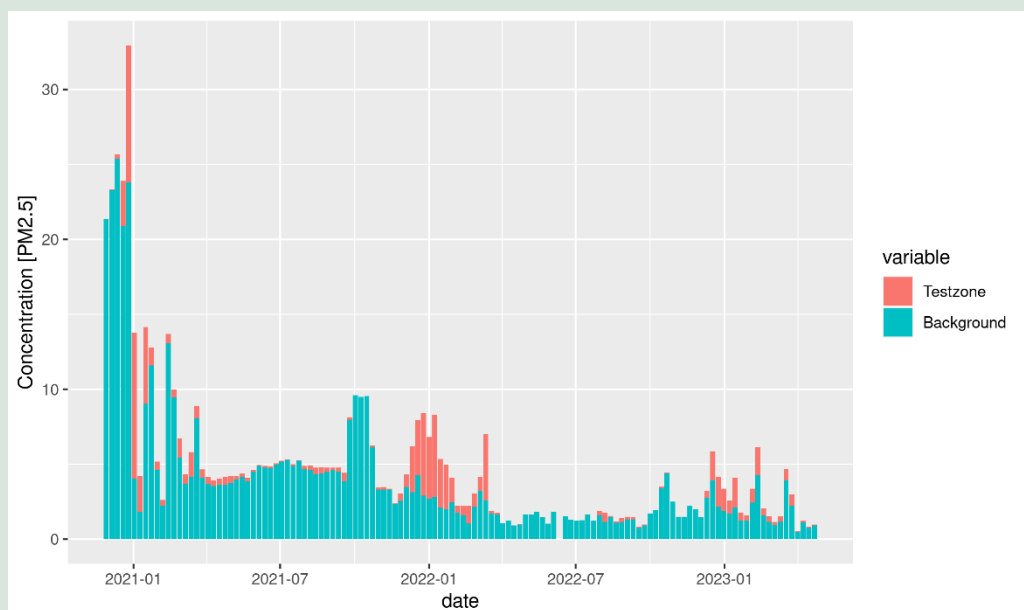


FIGURE 54. PM_{2.5} weekly concentrations divided into background and local contributions.

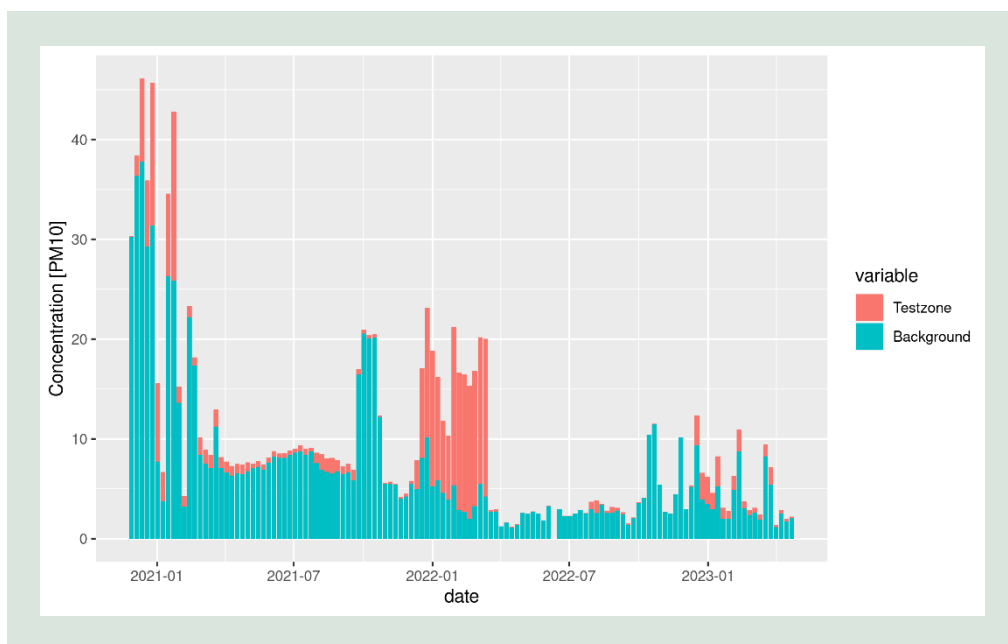


FIGURE 55. PM₁₀ weekly concentrations divided into background and local contributions.

Appendix 5. Models for emissions

Appendix 5.1 Buoyancy

Buoyancy occurs when cold air warms up and thus expands. This means that warmer and thus lighter air at the bottom of the chimney will seek upwards and push past the colder and thus heavier air that lies at the top of the air column bounded by the chimney. The formula underlying the classical theory of buoyancy looks like this:

$$q_V = A \sqrt{\left(\frac{2\Delta P}{\rho \zeta}\right)} \quad [\text{m}^3/\text{s}], \quad (1)$$

Where q_V is the velocity of air flow up through chimney. This is initially determined by the opening area at the bottom of the chimney - in the case of wood-burning stoves, a damper opening A . Next, it is determined by the pressure difference ΔP between chimney base and chimney pipe. Conversely, it dampens the buoyancy that the air has a density ρ and that the air encounters resistance through dampers and chimneys, but also the house around it. It is expressed in the resistance coefficient ζ .

The pressure difference ΔP is in turn determined by the temperature difference between bottom and top, T_i and T_o , in force at any given time:

$$\Delta p = \frac{\rho_o g H_n (T_i - T_o)}{T_i} \quad [\text{N}/\text{m}^2], \quad (2)$$

The equation also includes pressure ρ_o , a gravitational acceleration g , and a height H_n , which refers to the vertical distance between the so-called neutral plane in the housing and the damper opening. The location of the neutral plane is determined by the ventilation conditions in the house in which the stove is installed. Note, that the room temperature, which is typically set to 22°C, appears in both numerator and denominator, in the denominator with the difference that Kelvin must be calculated here, i.e., 22 + 273. If the two formulas are brought together, we get the expression:

$$q_V = A \sqrt{\left(\frac{2\rho_o g H_n (T_i - T_o)}{\rho \zeta T_i}\right)} \quad [\text{m}^3/\text{s}], \quad (3)$$

If we combine the constants, the expression for buoyancy looks like this:

$$q_V(t) = Ak \sqrt{\left(\frac{(H_n(T_t - T_o))}{T_t}\right)} \quad [\text{m}^3/\text{s}], \quad (4)$$

Here, $q_V(t)$ refers to the fact that the formula for buoyancy in principle provides the graph image that tells how large the buoyancy is at any point in time t in a combustion cycle, where the temperature T_t at that time is known. The temperature at a given point in a combustion cycle is known from temperature curves in laboratory measurements. It may vary, but for a modern furnace that is fired correctly, it will look as shown in FIGURE 56.

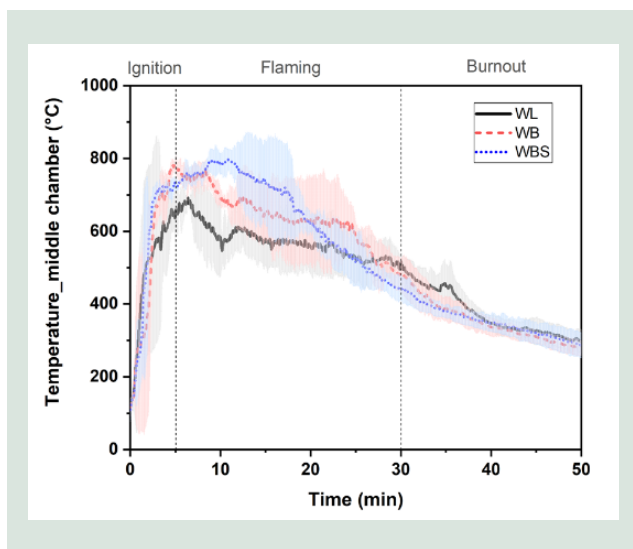


FIGURE 56. The mean temperature in the combustion chamber measured over time in a typical wood-burning stove. This diagram shows the development in temperature for three types of fire-wood: firewood without bark (WL), firewood with bark (WB) and firewood released from the bark (WBS). Depending on the firewood type, reach the maximum temperature within or shortly after the first 10 minutes have passed (reproduced from Du 2022¹⁴).

Based on the red curve for a standard temperature development (firewood with bark), data from this was transferred to the formula for buoyancy. Here, the constant k (pressure, gravitational acceleration, and neutral plane) was calculated 0.0046, considering the neutral plane height of a single-story house (0.75m). With a combustion cycle of 50 minutes and a continuous reduction for the damper opening A from first 100% opening to 60% opening in the incandescent phase, the result if where the damper opening is reduced every 10 minutes is shown in FIGURE 57. Compared to the starting point shown, the neutral plane height, pressure and outside temperature can be changed, although this is only of minor importance due to the course of the buoyancy function.

¹⁴ Du, Yifan (2020): Pollutant formation and control in wood stoves. PhD Thesis. Technical University of Denmark

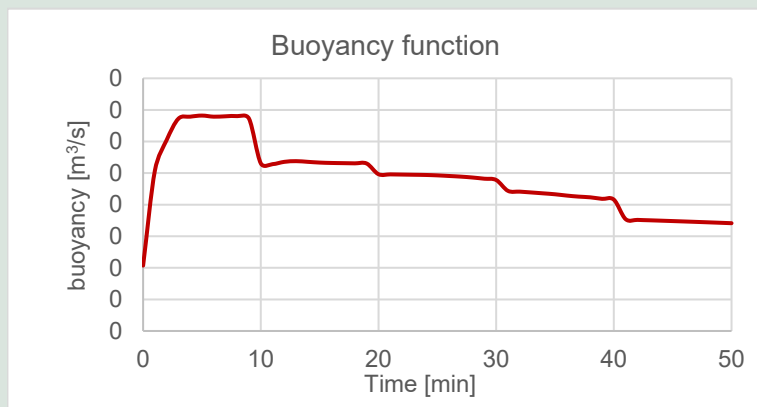


FIGURE 57. The figure shows how buoyancy will typically be distributed over a charge of 50 minutes if the damper opening is reduced approx. every 10 minutes.

Appendix 5.2 Release of particles

The release of particles is linked to the combustion that takes place in the combustion chamber and, as buoyancy increases, increases with increasing temperature, or rather by the fact that as buoyancy increases, more air and thus more oxygen passes through the combustion chamber to nourish the combustion. However, combustion increases at a greater rate than buoyancy, as evidenced by a much steeper curve for the combustion rate, in the sense as the amount of firewood traded per unit time. See FIGURE 58.

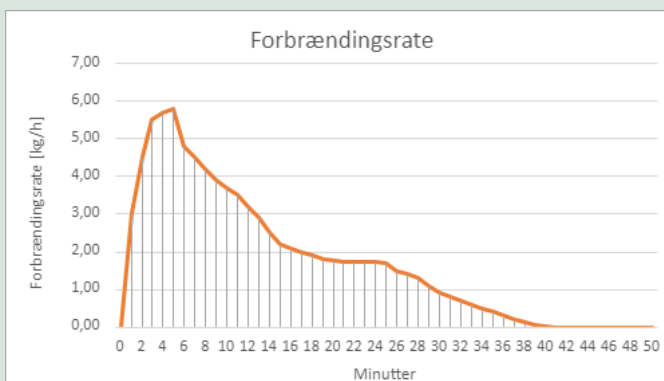


FIGURE 58. Standard figure for the combustion rate, i.e., how many kg of firewood per hour transformed. The model assumes that the particle rate is directly proportional to the combustion rate, in the sense that the amount of particle produced per unit time follows the amount of wood burned. (reproduced from Du 2022¹⁵).

¹⁵ Du, Yifan (2020): Pollutant formation and control in wood stoves. PhD Thesis. Technical University of Denmark

Appendix 5.3 Model for particle emission

This way, we approach the particle model whereas particle emission is a result of buoyancy and combustion rate. So, aside of respecting buoyancy and combustion rate, it is about attributing the right factors to the individual incineration plant, i.e., current chimney, the current house, and the current wood-burning stove.

Thus, the particle model arises by connecting buoyancy with the particle rate. Thus, if we start from the particle rate:

$$P(t) = P \cdot m/s \quad [\text{kg/s}], \quad (5)$$

It indicates the number of particles that combustion induces at time t . Divided by the buoyancy at time t , we get a formula for the evolution of the particle of this configuration:

$$p(t) = f_p \frac{P(t)}{q_v(t)} = \frac{P(t)}{Ak} \sqrt{\left(\frac{T_t}{h(T_t - T_o)}\right)} \quad [\text{kg}] \quad (6),$$

i.e., the mass of particles inventoried, e.g., in mg, that is induced at time t . The particle factor f_p indicates how much per thousand of the dry matter in the firewood ends up as particles. If we enter the buoyancy minute values shown in FIGURE 57 and use the corresponding minute values for the combustion rate FIGURE 58, we get a curve for particulate emissions, as shown in FIGURE 59.

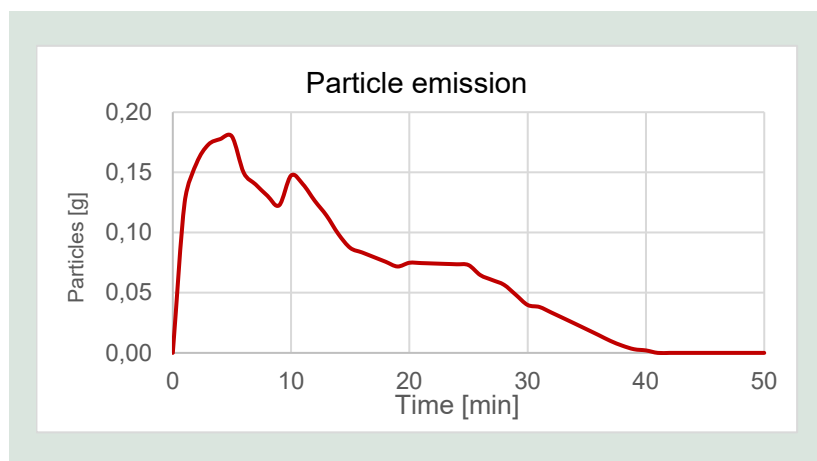


FIGURE 59. The particulate emission curve calibrated so that the total particle emission by one charge amounts to 3.27g.

The particulate emission curve broadly follows the combustion rate curve. A perfect coincidence will be achieved by right supplying air during the entire combustion process. This can be achieved by electronic control and the use of temperature sensors with lambda probe. But several other conditions, ranging from poorly insulated chimney, over friction or resistance in the furnace to the amount of firewood, type, and quantity of firewood, will distance the emission curve from the ideal curve. If possible individual factors must be added to chimney, house, stove, and firewood, to calibrate the particle model for a current wood-burning stove installation.

Appendix 5.4 Base line

The starting point for the number of particles emitted by a wood-burning stove is set at 3.27g per kg of firewood for a modern stove with an output of between 3 and 8 kW, corresponding to 2.09 mg per kg dry matter, which in turn corresponds to 217 mg/MJ. This is what according to

Norwegian standard NS3058 collected in dilution tunnel applies to a modern wood-burning stove and fits well to the measurements referred to by Vincente and Alves (2018).

This further on corresponds to a particle factor of 3.27‰. Put otherwise, 3.27‰ of the amount of firewood that is added during a charge ends up in particles. A normalization factor in the model used of 0.00194 ensures that the particle model delivers an output of precisely 3.27 mg per kg firewood. With this baseline, the particle model can be attributed several factors linked to the specific conditions surrounding the individual stove installations. In the first place, it is the size of the stove, and thus the amount of firewood that the stove can convert per hour, that matters. With reference to the three most common furnace sizes of 3, 5 and 8 kW, the normalized amount of firewood is set to 0.6, 1.0 and 1.5 kg of firewood, respectively.

Another important factor is the height and quality of the chimney. The height may vary, but all other things being equal, a chimney height of 6 meters is optimal, although poor or lack of insulation reduces the draught and hence the combustion. In the worst case, the number of particles must be increased by a factor of 2. The default value in this case is set to 1.5.

A third important factor is the resistance of the air flow through the house. This is determined by the density of the house, which in turn is determined by the age of the house. From 2006, requirements for the tightness of houses were introduced. This is a prerequisite for being able to control the air change. Conversely, a dense housing will make it difficult to provide enough air to ensure optimal combustion. This means that new houses built after 2006 are subject to a factor of 1.2 unless there is direct air intake. The same applies to the presence of mechanical ventilation. If this is the case, an additional factor of 1.5 is applied to the combustion unit concerned.

Finally comes the wood-burning stove itself. Here, tests over time show that wood-burning stove manufacturers have succeeded in increasing the power and reducing emissions of particles (PM_{2.5} and PM₁₀). This in turn means that stoves from before 2000 must be given a factor of 1.2 and stoves manufactured after 2020 a factor of 0.8. This gives a default factor of 1 for stoves manufactured in the period 2015-2020. The factors for wood-burning stove age reflect the tests that have been made over time. By precisely knowing the particulate emissions of the current stove model during testing, the model can be calibrated in relation to the stove's current test certificate.

A relatively new technology applied by developing of wood-burning stoves is the use of automatics. Thus, automatic systems means that furnaces with electronic control can achieve a factor of 0.8 in terms of particulate emissions, furnaces with mechanical control (bimetallic) can achieve a factor of 0.9, while stoves without automatics, which are the most widespread, are expressed in default value 1.0. As known from all measurements of particles linked to the quality of firewood, the purest combustion is achieved by using dry firewood of the right size. With a default value of 1, the model of particulate emissions can be corrected both up and down, so that optimal firewood triggers a factor of 0.8, while reverse use of only partially dried or otherwise not optimal firewood triggers a factor of 1.2. See TABLE 6 for an overall overview of additional factors.

TABLE 25. Additional factors for particulate emissions associated with the various components of a wood-burning stove installation.

48 Additional factors for particle emission	Values	Default value
Size of stove: 3, 5, and 8 [kW]	0.6 – 1.0 – 1.5	1
Amount of wood 0.6 – 1.0 – 1.5 [kg]		
Height of chimney from stove to pipe [m]	3.0 – 4.5 – 6.0	4.5 m
Quality of chimney: insulation, distance to roof ridge etc.	0.8 – 1.0 – 1.2	1
Resistance of house: tightness, erected before or after 2006	1 – 1.2	1
Mechanical ventilation: established/not established)	1 – 1.5	1

48 Additional factors for particle emission	Values	Default value
Age of wood-burning stove: new/elderly/old (2020-2015-2000)	0.8 – 1.0 – 1.2	1
Wood stove regulation: IHS, bimetal or no automatics	0.8 – 1.0 – 1.2	1
Wood quality: optimal/medium/poor	0.8 – 1.0 – 1.2	1

Appendix 5.5 Unit of measurements

The model and the baseline used for the model are basically the number of measurable particles (dust), i.e., PM_{tot} and $PM_{2.5}$. These are the fractions of particles that also form the basis of tests on wood-burning stoves, as testing is carried out on the number of particles that can be captured by a filter in-tended to capture all particles larger than $PM_{2.5}$, i.e. 2.5 micrometers. An outstanding question is how the distribution over a charge is between different particle fractions such as PM , PM_{10} , $PM_{2.5}$, $PM_{0.1}$ and number of ultrafine particles. This is crucial for the wood-burning stove model to be used when assessing different types of local and regional air pollution from wood-burning stoves. The thesis is that the distribution is relatively the same for all types of wood-burning stoves and combustion units with a slight tendency for dust in the form of large particles to decrease the better combustion (high temperature in the combustion chamber). On the other hand, the number of ultrafine particles and the number of particles in general will increase.

TABLE 26. Typical emissions of PM_{tot} , PM_{10} , $PM_{2.5}$.

	Mean mg/MJ	Max mg/MJ
PM_{tot} (NS3058)	200	500
PM_{10}	150	400
$PM_{2.5}$	150	750

Clean Air Testzone

Mens nye teknologier til renere forbrænding i brændeovne er blevet udviklet og testet i laboratorier, er deres reelle emissionsreducerende effekter under faktiske driftsforhold hos forbrugere mindre veldokumenterede. "Clean Air Testzone" projektet blev etableret for at evaluere de lokale miljømæssige påvirkninger ved implementering af avancerede brændeovnsteknologier, emissionsfiltre, skorstensoptimering og brugeruddannelse i korrekte fyringsteknikker.

Projektet blev gennemført i en forstad til Aarhus, Danmark, og involverede 25 husstande over en periode fra 2020 til 2023. Testområdet blev valgt baseret på en høj tæthed af brændeovne med hyppig brug og en placering, der var afskærmet fra andre forureningskilder. Dette setup gav mulighed for at vurdere effekten af forskellige tiltag under virkelige forhold.

Samlet understreger resultaterne af dette projekt vigtigheden af en kombineret indsats, der omfatter teknologiske forbedringer, optimering af installationer og ikke mindst uddannelse af brugerne.

Alle de afprøvede interventioner - herunder nye ovne, skorstene, filtre, trækoptimering og brugeruddannelse - viste potentiale til at reducere emissioner. På baggrund af målingerne foretaget i projektet er der ikke en enkelt type af intervention der skiller sig ud som den mest effektive. Det konkluderes i stedet at de opnåede reduktioner i høj grad afhang af den enkelte installations tilstand og ikke mindst brugerens fyringsvaner. Dette understreger vigtigheden af en helhedsorienteret tilgang til problemet.



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