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TECHNICAL ARTICLE

Use of a Distributed Micro-sensor System for Monitoring the Indoor Particulate Matter Concentration in the Atmosphere of Ferroalloy Production Plants

HÅKON MYKLEBUST ,[1,3] THOR ANDERS AARHAUG,[2,4] and GABRIELLA TRANELL[1,5]

1.—Department of Materials Science, Norwegian University of Science and Technology, Alfred Getz vei 2, 7034 Trondheim, Norway. 2.—SINTEF Industry, Postboks 4760 Torgarden, 7465 Trondheim, Norway. 3.—e-mail: haakon.a.h.olsen@hotmail.com. 4.—e-mail: thor.a.aarhaug@sintef.no. 5.—e-mail: gabriella.tranell@ntnu.no

Airborne particulate matter (PM) is a concern for both occupational health and the environment, and, in the ferroalloy industry, the level of such particles in the air can be considerable. Small, low-cost sensors for measuring PM have generated interest in recent years, providing widespread monitoring of PM levels in the environment. However, such sensors have not yet been sufficiently tested under conditions relevant for the indoor environment of the metallurgical industry. This study aims to bridge this gap by benchmarking the commercial, low-cost Nova PM SDS011 particle sensor in two different ferroalloy plants. Benchmarking was performed against the Fidas 200S, which has been suitability-tested and certified according to the latest EU requirements (EN 15267, EN 16450). Twelve Nova sensors were tested over 3 months at a silicomanganese alloy (SiMn) plant, and 35 sensors were tested during 1 month at a silicon (Si) plant. The results showed that the low-cost Nova sensors exhibited all the same trends and peaks in terms of PM concentration, but measured lower dust concentrations than the Fidas 200S. The difference was larger at the silicon plant, which is in line with expectations, due to the size and mass fractions of particles in Si dust compared to SiMn dust, and to the larger measurement range of the Fidas, measuring down to 180 nm compared to the Nova which measures down to 300 nm. Despite the difference in absolute values, the Nova sensors were found to provide data for comparing dust levels over time for different processes, at different locations, and under different operational conditions.

INTRODUCTION

Airborne particulate matter (PM) is considered a concern for both occupational health and the environment. The effects of PM on human health have been found to include asthma, lung cancer, and cardiovascular diseases,[1,2] the risk and prognosis of which relate to the size, composition, and properties of the particles. The smaller the particles, the further into the human system they can penetrate, into the bronchi for PM up to 10 μm (PM10), the alveoli for PM up to 2.5 μm (PM2.5), and even through the lungs and into the circulatory system for ultrafine particles below 0.1 μm (PM0.1).[3–5]

In metallurgical plants producing silicon and silicomanganese alloys, the level of PM can be considerable. This PM is formed both mechanically, through fines generation during raw material handling, and thermally, through reduction and oxidation of raw materials and products. Thermally-generated SiMn fumes formed by oxidation of liquid (Si) and evaporated (Mn) metals consist mainly of

Gabriella Tranell and Thor Anders Aarhaug have contributed equally to this work.

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Si, Mn, and O, forming various complex oxides. Secondary elements include Mg, Ca, Al, and K, and trace elements include Na, Fe, Zn, Cu, and Cl.[6] The main component of these fumes, SiO_2 in Si plants and MnO in SiMn plants, have molar masses of 60.08 g/mol and 70.94 g/mol, and densities of 2.096 g/cm and 5.43 g/cm^3, respectively.

The industrial average aerodynamic diameter of these fume particles, as recorded by an electrical low pressure impactor, is on average approximately 100 nm,[6] while scanning electron microscopy (SEM) analysis of fumes generated experimentally on a laboratory scale by Ma et al.[7] show that the majority of protoparticles (the singular particles, in this case mostly spheres, defined before agglomeration and clustering) have a diameter between 50 and 200 nm, although fume particles generated at higher temperatures are notably smaller. However, for agglomerate size fractions measured through laser diffraction on the same dust, the majority of particulates have a diameter in the range of 500–2000 nm, and are also less influenced by temperature. Thermally-generated Si fumes formed by the oxidation of liquid Si consists mainly of Si and O, forming silica dust.[8] Average protoparticle sizes range from 66 to 91 nm.[8] These particles also agglomerate after formation, leading to the size fractions measured through laser diffraction being much higher. Figure 1a and b shows SEM imagery of the thermally-generated fume particles from SiMn and Si production, respectively.[7,8]

According to current EU regulations, exposure to PM10 in ambient air should be limited to a maximum of 50 μg/m^3 averaged over a 24-h period, with a maximum of 35 permitted exceedances per year. The yearly average is limited to 40 μg/m^3 for PM10 and 25 μg/m^3 for PM2.5. Specific limits for other pollutants, such as SO2, NO2, Pb, As, Cd. Ni, and PAH, are also included in these regulations.[9] While dust analysis and distinguishing between different particles should be considered, these are not the focus of this study. Workplace PM exposure is often monitored by personal portable devices, while monitoring of ambient plant PM levels are often measured using one or more fixed measurement stations that measure for long periods at a time. These stations are expensive to set up, which limits the number of spatial measurement points that can be realistically achieved. The use of less-expensive, portable setups would circumvent this issue, and allow for a much higher spatial resolution, which can be of particular use in the extremely varied environment that is the case for metal production plants. A better spatial resolution allows for tracking the flow of particles in the plant, and can work as a tool for evaluating measures taken to reduce and capture PM emissions.

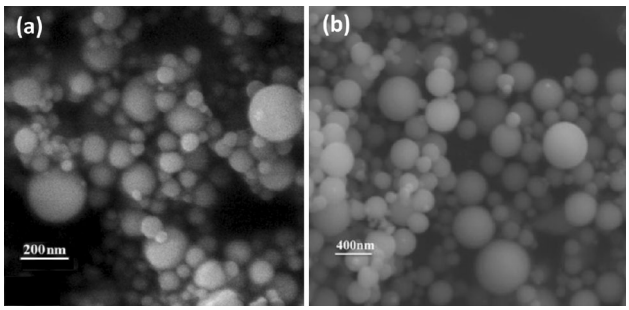


Fig. 1. SEM images showing fume particles from (a) Si filter fume generated experimentally at 1550°C[8] and (b) typical SiMn filter fume generated experimentally at 1500–1700°C.[7] Note the difference in scale.

There are several categories of low-cost microsensors available that can provide better spacial resolution at a much lower price for a single low-cost sensor, down to less than 0.1% of the price of a state-of-the-art dust sensor. In the current study, however, the aim was to investigate and benchmark the performance, in terms of precision and reliability, of a specific low-cost sensor, the Nova PM SDS11 (hereafter, Nova), in two different metallurgical plant environments. The Nova sensor, a nephelometer, which has been developed for low-cost fume monitoring, was benchmarked against the Fidas 200S (hereafter, Fidas), a state-of-the-art optical particle counter (OPC).

Small particles scatter light of varying wavelengths given their size and optical properties, and this scattered light can be measured and correlated to a PM concentration. In the case of nephelometers, particles are measured as an ensemble, and the scattered light is measured across a wide range of angles. The total scattering amplitude is correlated to a calibrated mass measurement, such as from a filter sampler.[10] OPCs work in a very similar way to nephelometers, but, instead of measuring a number of particles in an ensemble, they measure the light scattered by individual particles, and assign each pulse to a size bin based on its intensity. The optical properties, such as refraction index and particle shape, of the measured particles are of significant importance to the scattering of light, and, as such, it is equally important for nephelometers and OPCs to calibrate with the correct dust to achieve a high accuracy.

The output given by the Nova sensor is the concentration of particles with aerodynamic diameter < 2.5 μm (PM2.5) and < 10 μm (PM10), which are extrapolated through calibration values from the two size bins actually measured by the sensor, 0.3–0.8 μm and 0.7–1.7 μm, respectively. The Nova sensor does not yet have any EU certifications. The Fidas 200S measures the individual particles with aerodynamic diameters in the range of 0.18–100 μm, with the output coming in the form of the concentration of particles below certain sizes: 1, 2.5, 4, and 10 μm (PM1, PM2.5, PM4, and PM10). Precise optics, high light output from the poly-chromatic LED used, and powerful signal processing using logarithmic A/D conversion allow the Fidas to detect

particles down to 180 nm in diameter,[11] and, as it dries the sample fumes before it reaches the sensor, it is better suited for measurements in high relative humidity environments. The Fidas is approved for simultaneous monitoring of PM10 and PM2.5 according to standards VDI 4202-1, VDI 4203-3, EN 12341, EN 14907, EN 16450, and the EU Equivalence Guide GDE, and certified in compliance with standards EN 15267-1 and -2.[11] which specify maximum permissible measurement uncertainties and testing requirements.[9]

The quality of the components used is also a potentially important factor in regards to stability of measurements and lifetime for the sensor. The central technical parameters of the two sensors are described in Table I.

The Nova sensor has been the subject of several studies in varied settings. Genikomsakis et al. performed mobile field testing, comparing the Nova with a AP-370 by HORIBA suitable for constant air pollution measurements, on an electric bike in the city of Mons, Belgium. PM values ranged from 0 to 5 $\mu g/m^3$, with the resulting R^2 values ranging from 0.93 to 0.95, after taking temperature and relative humidity into account.[13] Badura et al. compared a group of three copies of the Nova sensor, together with groups of three other similarly low-cost systems in a common box, under the same measurement conditions over half a year near a park and a residential area in Wroclaw, Poland. The Nova was found to be one of the most precise in terms of reproducibility between units, and also when compared to the control unit with an R^2 value of 0.82 using 15-min averages, but it was found to be sensitive to high relative humidities (RH > 80%).[14] Liu et al. tested the Nova sensor by co-locating three of the sensors at an official, air quality monitoring station equipped with reference-equivalent instrumentation in Oslo, Norway, over a 4-month period, and found inter-sensor correlation R values higher than 0.97, and confirmed the sensor's susceptibility to high relative humidity. They concluded that, when used correctly, the Nova sensor could have significant potential for implementing dense monitoring networks in areas with relative humidities below 80%.[5] In industrial settings, there has been less work carried out to test these sensors, but the Nova sensors were found by the current authors to provide useful data in the aluminum industry, where the value of having multiple groups spaced out was shown.[15] When compared to similar low-cost sensors, the Nova sensor has been shown to be among the best in several studies,[16,17] but, as mentioned, it is less reliable at higher humidities, which was further investigated by Jayaratne et al. along with other sensors, where several showed an increase in PM level above a relative humidity of 75%.[18]

This work aims to compare how well the Nova sensor compares to the Fidas sensor when measuring the PM concentration in two different metallurgical plants. The first measurement campaign was performed at a silicomanganese (SiMn) plant, and the second at a plant producing metallurgical grade silicon (MG-Si). The thermally and mechanically produced fumes formed during the metallurgical processes at these plants, as outlined above, vary greatly, particularly in regards to size fractions, which is believed to affect the measurements. An additional objective is to study the long-term performance of the Nova sensors in high dust level environments.

INDUSTRIAL MEASUREMENTS

The complete setup for the Nova sensor system included the Nova PM SDS011 sensor connected to a microchip, together with a temperature and humidity sensor[19] placed in a closed box, as shown in Fig. 2. The system was powered with 5 V, 1 A of electricity provided from an external power source, and, while the system protects the components to a degree, the model was not airtight. During the measurement periods described in this work, locations were chosen based on the space available at the plant, particularly in regards to the large Fidas sensor, and so as not to risk equipment failure due to heat, nor that measurement equipment became a problem for the running of the plants. While available areas with varying fume loads and fumes originating from different processes were found, continued studies are expected to include measurements much closer to the relevant areas, such as near the tapping zone, given adequate protection against heat radiation in newer sensor setups.

Table I. Technical parameters for the Nova SDS011 and Fidas 200S, as given by the manufacturers[11,12]

Parameter	Nova	Fidas
Measuring output (PM)	PM2.5, PM10	PM1, PM2.5, PM4, PM10
Concentration range	0–999.9 $\mu g/m^3$	0–10,000 $\mu g/m^3$
Measuring range	0.3–10 μm	0.18–100 μm
Response time	1 s	< 2 s
Sample treatment	None	Drying and heating
Dimensions	71 · 70 · 23 mm	450 · 320 · 180.5 mm
Power consumption	Max. 0.5 W	Approx. 200 W

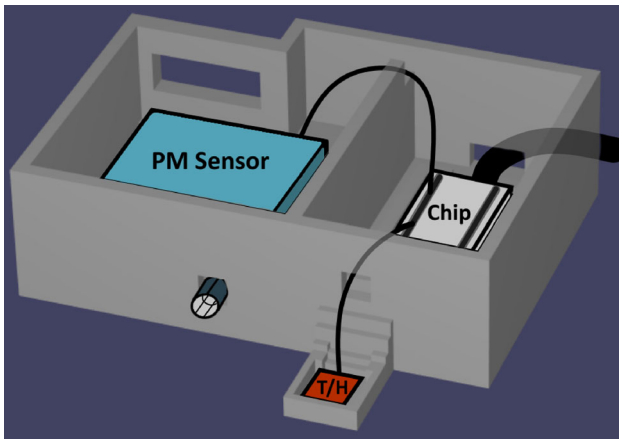


Fig. 2. Schematic of the sensor system for the Nova PM SDS011. Each box was closed with a matching lid to limit exposure.

Silicomanganese (SiMn) Plant

At the SiMn plant, the measurement period was divided into two parts. The first, extended period lasted for more than 2 months with only the Nova sensors, while the subsequent calibration period lasted for almost 24 h when the Nova sensors were placed close to the Fidas. For both periods, twelve Nova sensors were divided into three groups of four sensors stacked on top of each other. In both periods, the sensors were placed in a hallway adjacent to the metal tapping hall, with one wall section being an opening towards the furnace hall, and another being the outer walls of the furnace itself. Figure 3 shows the approximate sensor locations for the measurement periods, where the ceiling height was 6.45 m, and the entire section leading out to the smelting hall was open, allowing for free flow of fumes into the measurement area. During the middle period, four Nova sensors were each placed at points 1, 2, and 3, roughly 1.5 m above the floor along the wall section. During the last period, all twelve Nova sensors were placed together at point 3, with the Fidas sensor placed with the fume intake approximately 30 cm from the Nova sensors.

Silicon (MG-Si) Plant

At the MG-Si plant, there was one measurement period of close to 1 month, with 35 Nova sensors placed in vertical groups of 5 near the inlet for a Fidas sensor for the full duration. The sensors were placed on a mezzanine floor above the furnace body, where the electrode feeding takes place, inside the hall in which tapping is performed. Figure 4 shows the approximate location of the sensor group along with the relevant process locations. All 35 Nova sensors were placed with their fume inlets within 20 cm of the Fidas' fume inlet. There is a fume hood designed to capture most of the tapping fumes, and

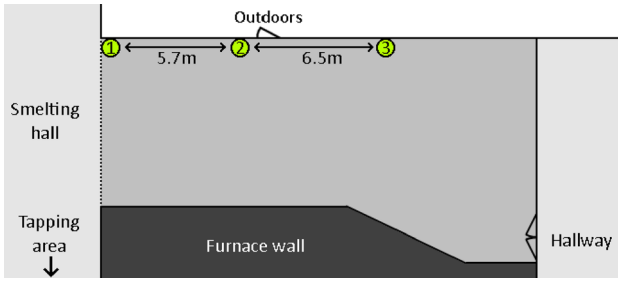


Fig. 3. Approximate sensor locations during the middle and last measurement periods for the measurement campaign at the SiMn plant.

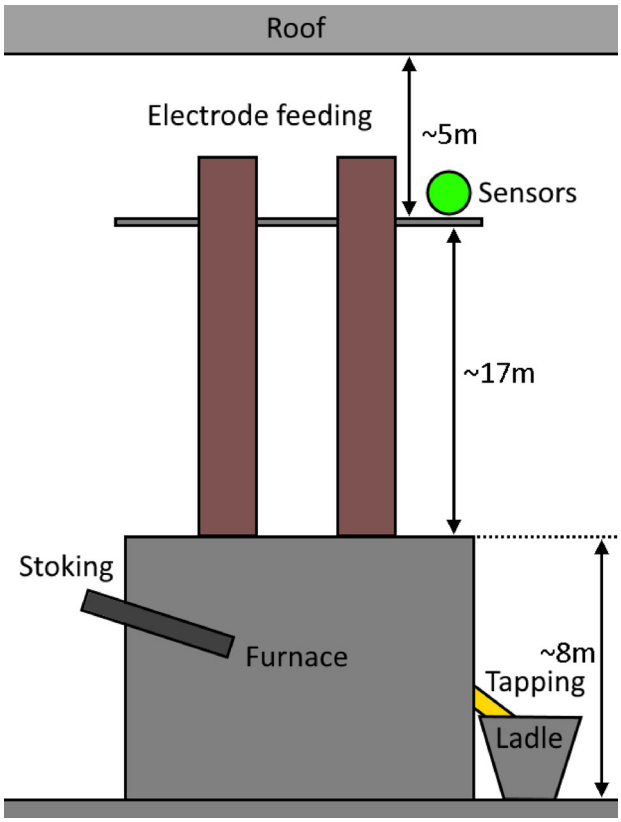


Fig. 4. Approximate sensor location (green circle near the top) during the measurement campaign at the Si plant. Redrawn from sketch provided by the smelting plant (Color figure online).

there are also several layers of partial flooring between the tapping and stoking areas and the sensors. Fumes and smoke not captured by the fume hood will eventually flow up along the sides of the furnace and reach the sensors, and fumes that gather below the roof will also be picked up by the sensors, which are only a couple meters below.

The fumes measured at the silicon plant are assumed to be mostly thermally-generated oxides originating from the Si melt during the tapping process, and during other periods in which molten Si is in contact with the open air.

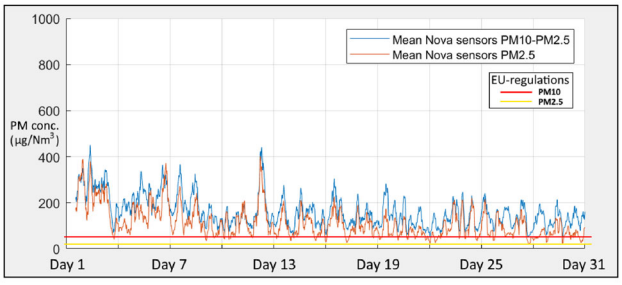
RESULTS AND DISCUSSION

PM Intensity Variations Over Time

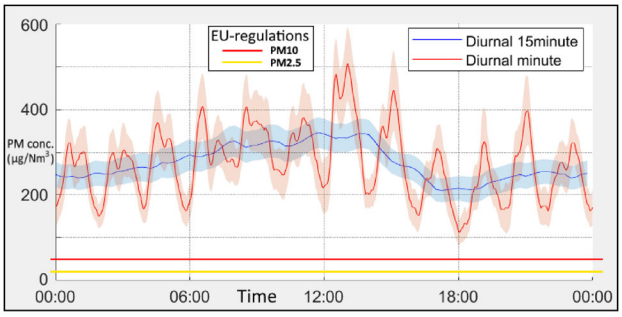
Figures 5(a, b), 6(a, b), 7(a, b), and 8(a, b) show the PM10–PM2.5 and PM2.5 values measured by the Nova sensors during the extended periods of the two measurement campaigns, as well as during a shorter period, together with the Fidas data, in addition to the diurnal patterns for PM10.

SiMn-Plant

The long-term measurements at the SiMn plant show the erratic day-to-day changes in fume levels, but from the diurnal pattern it can be seen that the PM levels are generally at a lower value in the evening and night, and at a maximum around noon. Another clear pattern is the bi-hourly peaks which likely correlate to process routines such as tapping, casting, product transportation, stoking, etc. that are relatively stable on a day-to-day basis. It is also easy to detect differences between days and periods which could be correlated to changes in the weather, internal processes, routines, or events. For instance, the first week, as well as daytime on day 12, show a clearly higher PM-level compared to the latter half of the period shown in Fig. 5a

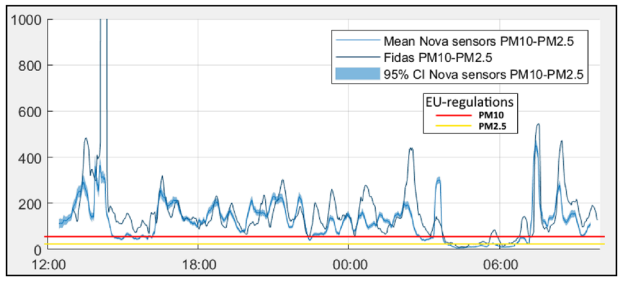


(a)

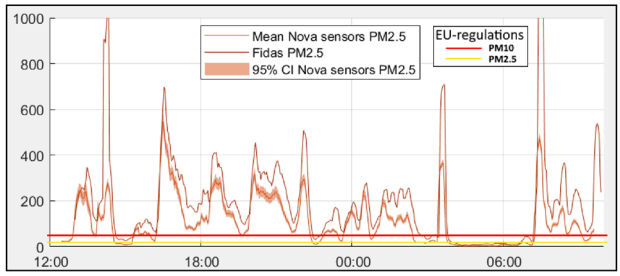


(b)

Fig. 5. PM10–PM2.5 and PM2.5 as measured by 4 Nova sensors over a period of around one month in the SiMn plant (a) and Diurnal pattern of the PM10 measurements from the same dataset (b). The data was gathered in 15-minute averages (a and b) and 1-minute averages (b) which were in turn smoothed with a sliding average spanning 6 hours and 30 minutes total respectively and are shown together with their respective 95% confidence intervals for the diurnal patterns.

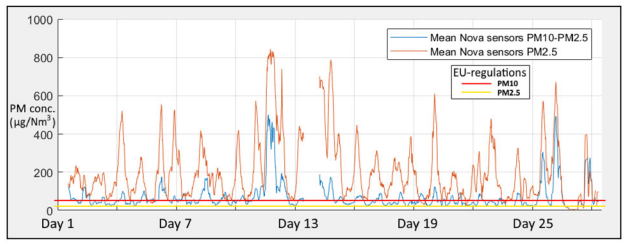


(a)



(b)

Fig. 6. PM10–PM2.5 (a) and PM2.5 (b) as measured by 12 Nova sensors and the Fidas 200S over a period of 21 hours during the final calibration period at the SiMn plant. The data was gathered in 1-minute averages which were in turn smoothed with a sliding average spanning 15 minutes total. Mean values for the Nova sensors are shown together with the 95% confidence interval and the Fidas values.



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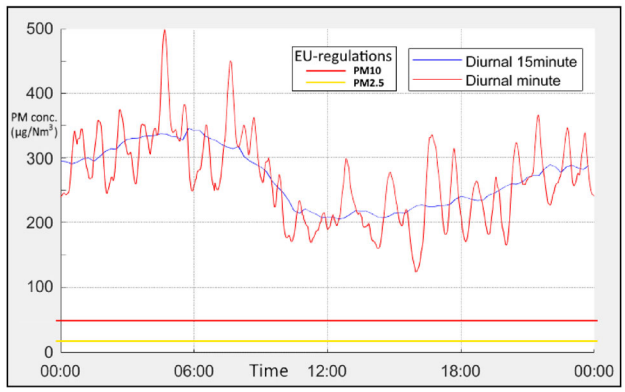


(b)

Fig. 7. PM10–PM2.5 and PM2.5 as measured by 35 Nova sensors over a period of around 1 month in the Si plant (a) and diurnal pattern of the PM10 measurements from the same dataset (b). The data were gathered in 15-min averages (a and b) and 1-min averages (b), which were in turn smoothed with a sliding average spanning 6 h and 30 min total, respectively.

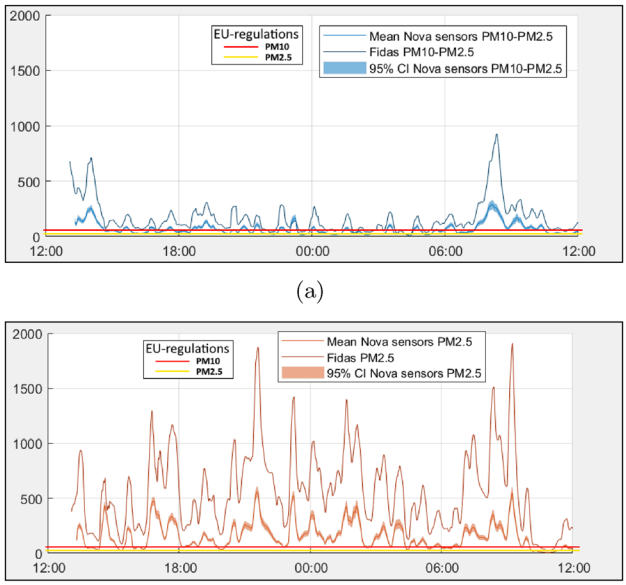


Fig. 8. PM10–PM2.5 (a) and PM2.5 (b) as measured by 35 Nova sensors and the Fidas sensor over a period of 24 h in the Si plant. The data were gathered in 1-min averages, which were in turn smoothed with a sliding average spanning 15 min total. Mean values for the Nova sensors are shown together with the 95% confidence interval and the Fidas values.

When comparing the Nova and Fidas measurements, it can be noted that the two sensors pick up on most of the same peaks and changes in dust levels, both for PM2.5 and PM10–PM2.5. While there are some peaks where the difference is large, the trends are similar for most of the period. The difference seems to be higher for PM2.5, which is natural due to the lower minimum measurement boundary on the Fidas compared to the Nova. The level of the larger fumes (PM10–PM2.5) are generally slightly higher than the level of the smaller fumes (PM2.5) on average, but there are notable spikes with a higher level of fine dust which could relate to specific process or workplace events producing and/or dispersing more fine particles.

Si-Plant

For the long-term Nova measurements at the Si plant shown in Fig. 6a, one can see that the fumes have an overall much larger fraction of PM2.5 compared to PM10–PM2.5, while the change in PM levels are slightly less varied compared to at the SiMn plant, with the average number of significant peaks per day being around one for this period. The diurnal pattern shows an opposite trend compared to the SiMn plant, with higher values in the morning and the lowest values around noon. The difference between the peak values and the baseline fume level is higher at the Si plant, which might stem from the higher proximity to the fume source at this location.

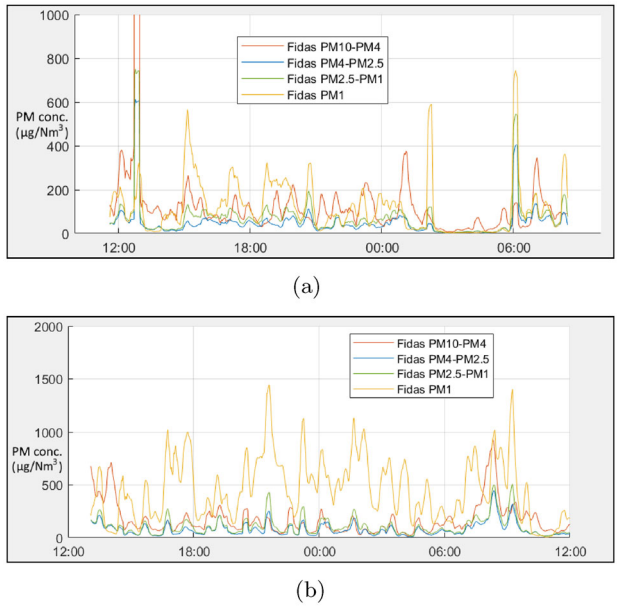


Fig. 9. Size fractions as measured by the Fidas sensor at the SiMn plant (a) and the Si plant (b).

Also at the Si plant, it can be noted that the two sensor types pick up on most of the same peaks and changes in dust levels, both for PM2.5 and PM10–PM2.5. Here, a notable difference in fume levels is apparent, with the difference being largest for PM2.5, which was also the dust fraction with the most variation over time. The larger difference in especially PM2.5 measurements at the Si plant are believed to be due to better calibration for the Fidas, which was calibrated towards SiO_2, and should therefore have quite accurate assumptions for particle density and to some degree the optical properties.

The largest fraction measured by the Fidas for most of the period is PM1, as can be seen in Fig. 9b. The fraction of PM10–PM2.5 is quite low for Si, with the exception of a few clear spikes.

When considering the dust level differences between Si and SiMn fumes, it is important to note the difference in density between the different fumes, as the measuring equipment has to calculate the mass of the detected fumes to provide the standard units for PM ($\mu g/m^3$). For the Si fumes, a typical density used is that of amorphous Si (2.2 g/cm^3).[6] For the SiMn fumes, a typical density model would be to assume pure MnO (5.37 g/cm^3) which is most prominent in the SiMn fumes, almost to the exclusion of other elements when generated from SiMn melts at below 1500° C.[7] With the sensors not being calibrated for the specific dusts and their densities, it can be assumed that there will be a similar discrepancy in the measured fume mass per volume as there is a difference in fume density. In this case, the density of the lighter fumes (Si) are less than half the density of the heavier fumes (SiMn), which speaks to the necessity in calibrating

for the correct fumes when using PM sensors to avoid getting inaccurate data.

The calibration of low-cost sensors would require a carefully designed setup, but, once in place, the time and cost of each calibration should be low. Having multiple sensors in each group makes noticing outliers and sensor drifting much easier compared to having a single sensor, and, while significant drift was not seen across the sensors during the 1–2 months they were tested in this work, re-calibration is expected to be necessary at least once during the Nova sensor's 1-year lifespan.

Size Fractions

Figure 9(a and b) shows the different size fractions measured by the Fidas sensor at the SiMn and Si plants, respectively, over a period of around 24 h. The fractions are split into 4–10 μm (PM10–PM4), 2.5–4 μm (PM4–PM2.5), 1.0–2.5 μm (PM2.5–PM1), and 0.180–1.0 μm (PM1).

As can be seen in Fig. 9(a and b), the largest fraction of PM measured by the Fidas is almost always PM1 for Si fumes, and usually by a large margin. For SiMn, the largest fraction varies between PM10–PM4 and PM1. This seems in line with the deviation found between the Nova and the Fidas, and how it differs from SiMn to Si fumes, as the Fidas measures particles in the range of 180–300 nm, which the Nova does not. It seems evident that the Si fumes have more of the smaller agglomerates, which in turn leads to a larger deviation between the Nova and the Fidas for Si fumes. The variations in size fractions over time can be related to events and activities in the vicinity of the sensors, as different fume sources are likely to produce different fumes.

Quantitative Measurement Differences Between the Nova and Fidas Sensors

Figure 10 shows the mean PM10–PM2.5 divided by PM2.5 and the PM2.5 values, as measured by the Nova sensors as a function of the same values as measured by the Fidas sensor, for both plants over a period of around 24 and 21 h.

From the comparisons between the Nova and the Fidas shown in Fig. 10, the difference between the SiMn and Si fumes in regard to the fraction of larger particles measured by the Nova compared to the Fidas becomes apparent. For the Si fumes, the relationships between the two sensors PM10–PM2.5/PM2.5 shows that the Nova, while heavily underestimating the fume concentrations in general, as seen from the PM2.5 comparisons, actually overestimates the fraction of larger particles. This overestimation is likely due to the lower average particle size of the fumes at the Si plant, as can be seen in Fig. 6(a). Due to the Nova not being able to effectively "see" particles above 1.7 μm in diameter, and instead estimating PM10 values based on its calibration settings, as previously mentioned, it overestimates the concentration of larger particles when, in reality, the fraction of large particles is much smaller than those it was calibrated for.

For the SiMn fumes, both ratios are much closer to one, showing that there was a smaller difference between the two sensor types than for the Si fumes. The Fidas also measures a larger amount of SiMn fumes, but this could be due to both the difference in calibration, with larger measurements on the low end, and the distance from the wall. For Si fumes in particular, this points to the need for better calibration of the Nova sensor.

The heavier nature of Mn fumes is likely to make the concentration measured higher in the SiMn plant compared to the Si plant when no density calibration or post-processing has been performed, and this should be taken into account when reading the data in this work. It is not known to which density the Nova was calibrated when delivered, but the Fidas was calibrated for SiO_2, and a difference in calibration could explain some of the differences between the measurements made by the sensors.

Deviations Between Individual and Groups of Nova Sensors

Figure 11a and b shows the relative deviation from the mean for the Nova sensors within one of the groups at the Si and SiMn plants, respectively, together with their 95% confidence intervals. The limited time period used for the deviation graphs is due to the failure of several sensors at the Si plant, as discussed further in the "Sensor Reliability" section, and the data from the SiMn plant were limited to a similar time period to allow for easier comparison. Due to the spacing in the placement of the three groups used at the SiMn plant, the relative deviation between the groups is not relevant here, but a figure showing the relative deviation between the groups from the Si plant is shown in supplementary Fig. S1 (refer to the online supplementary material). The data in Fig. 11a and b are presented to show how the deviation in measurements for the sensors in each group, or between the different groups, changes over time. Stable deviation curves relate to a systematic difference between the sensors that can be compensated for or be mostly eliminated through calibration.

Only one group from each plant was used here to show the trend, but the remaining groups showed similar trends over time. Thus, from Fig. 11(a and b), showing the relative deviation in and between the sensor groups, one can infer that, over time, the individual sensors within each group tend to have a relatively stable deviation from the mean value, barring changes caused by the loss of sensors. Full 2-month comparisons of relative deviations at the SiMn plant showed a similar pattern over time as the 20-h period. The individual variation of the sensors' deviation is for most of the sensors within

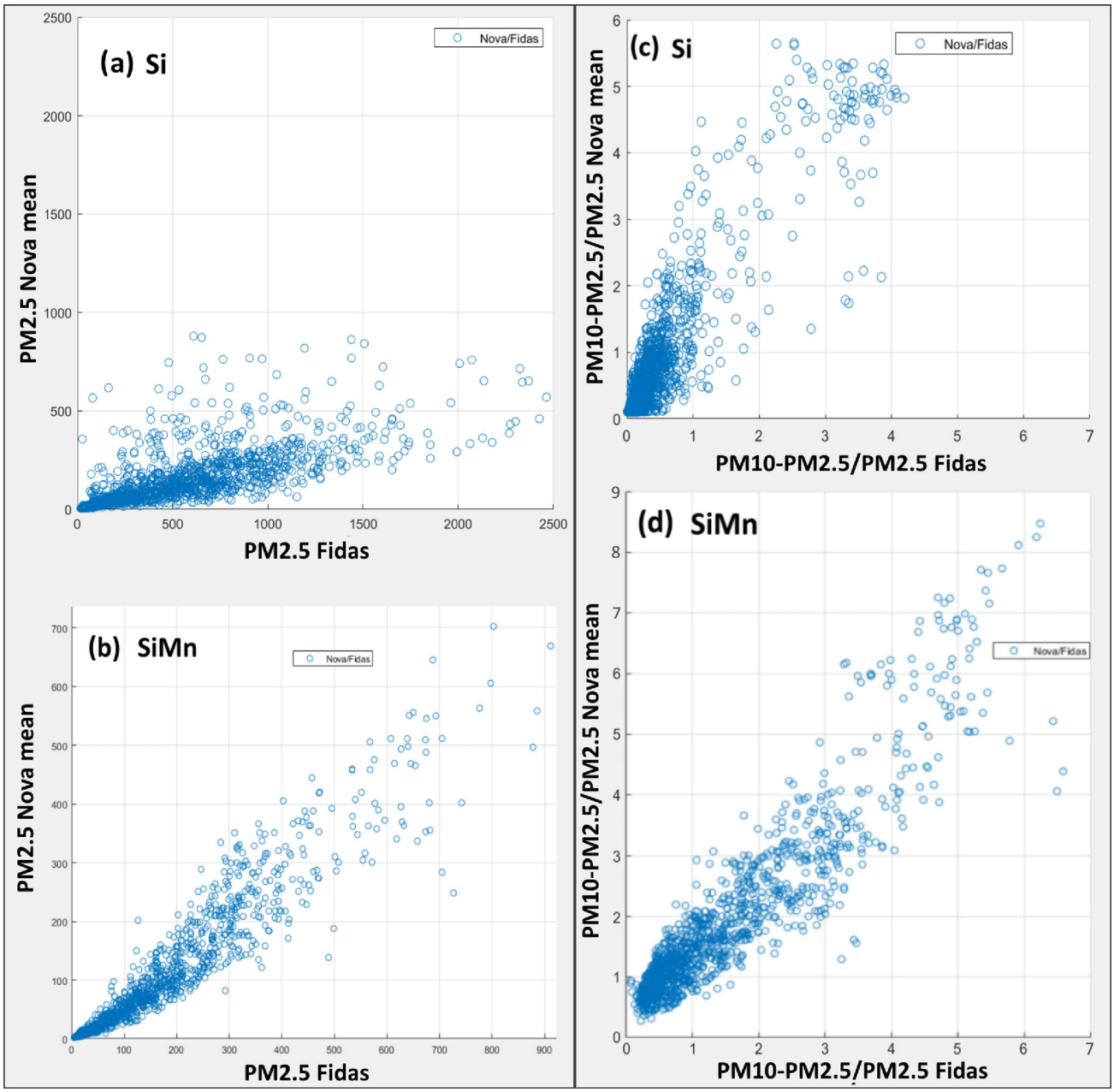
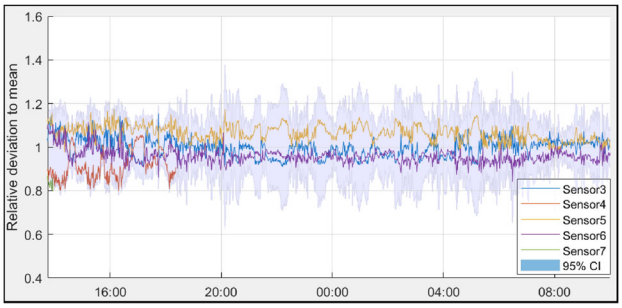


Fig. 10. Nova measurements compared to Fidas measurements over 24- and 21-h periods at the Si and SiMn plants, respectively. (a) and (b) are the PM2.5 comparisons, while ©) and (d) are the comparison of the ratio of the larger particles (PM10–PM2.5) to the smaller particles (PM2.5). Note the scale difference between (a) and (b).

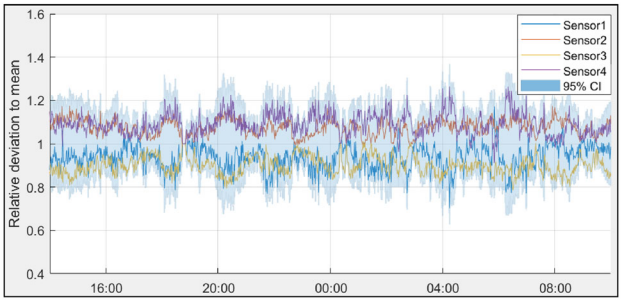
the 15% relative deviation level provided by the manufacturer.[12] It is slightly larger than the internal deviation between three Nova sensors of the maximum 5% found by Liu et al.,[1] but the PM concentrations during these measurements were around ten times lower than in this study. That the internal deviation is to a degree stable over time is very useful information, as it would imply that a large part of the deviation between the sensors could be corrected through simple calibration, where each sensor's measurements are multiplied by a correction factor or equation, which is in line with conclusions from similar work testing the viability of low-cost sensors.[20] It can be noted that the deviation is lower for the SiMn measurements, both in total relative deviation, and in the variations of that value for each sensor. This could be due to the larger fraction of smaller particles in the Si fumes, as the fraction of particles in the size range, where there is uncertainty whether they would be detected by the Nova sensor, would be much larger.

Sensor Reliability

Most of the sensors had already been used for several months in different campaigns before the



(a)



(b)

Fig. 11. Relative deviation from the mean PM10 values for the first group of Nova sensors over the first 20 h of the measurement period at the Si plant (a) and the SiMn plant (b), together with the 95% confidence intervals for the dataset.

campaign at the Si plant, and, as there was a consistent high concentration of dust in the areas where the sensors were placed in both plants, sensor failures were expected to some degree during both campaigns, particularly at the Si plant. Six sensors were removed from the pool of 35 after the measurement period at the Si plant, as the data they provided became erroneous instead of stopping completely, leading to a pool of a maximum 29 sensors. During the measurement period, more of the sensors cut out at some point, but restarting the sensors worked in getting some of them back up. Of the twelve sensors in the SiMn campaign, three did not give measurements during the entire measurement period, while almost all of them cut out at some point during the measurement period at the Si plant. Over the entire measurement period, the mean up-time of the sensors was 21.7% at the Si plant and almost 100% at the Mn plant. This limited the accessible data for the Si campaign, but, due to the many sensors placed during the campaign, the amount of data available is still considered sufficient for analysis, particularly using the periods and groups in which a larger fraction of the sensors were active. The highest measured relative humidities were below 40% at the SiMn plant and below 45% at the Si plant, which is significantly lower than the boundary of around 80% where condensation causes inflation in the PM readings for the Nova, and is therefore not considered to have influenced the PM readings in this work.

While the higher degree of failure during the Si campaign could just be due to wear over time, it is also possible that the Si fumes affected the electronics to a higher degree than the dust from SiMn, leading to a faster decay in functionality. This is also supported by the fact that the campaign at the SiMn plant lasted for more than 3 months, and that, at the end of the campaign, all 12 sensors were functional after being reset and having their system blown clear of excess dust. The sensors yielding erroneous data instead of stopping completely at the Si plant also supports this theory, as previous campaigns did not show similar signs of malfunctioning, besides a complete stop in the flow of measurements. In such a case, this problem should be solvable by using an airtight case for the sensor systems. In some of the cases, blowing through the system to clear it out is enough for the sensor to start working again, and, in some cases, just restarting the system worked, but for other sensors did not, and in such cases replacement of malfunctioning parts or wires would most likely be necessary to get the sensor up and running again.

CONCLUSION

A low-cost PM sensor for PM2.5 and PM10, the Nova PM SDS011, was tested and benchmarked against the Fidas 200S sensor during two measurement campaigns at a SiMn and a MG-Si production plant, where 12 and 35 Nova sensors in groups of 4 and 5 were used, respectively. The long-term data (around 1 month) for the Nova sensors were studied in regard to deviation within each group, and to investigate the differences between the two plants. Short-term data (around 24 h) with both sensor types were studied to compare the deviation between the sensors for both PM10–PM2.5 and PM2.5. More detailed size fraction comparisons were compiled from the Fidas data, highlighting the difference between the SiMn and Si fumes.

The main conclusions inferred within each category previously discussed are:

- For measurements in both the SiMn and MG-Si production plants, the Nova sensors picked up on almost all the same peaks as the Fidas sensor, and the increases and decreases in fume levels were similarly captured by both sensor systems.
- Over time, clear diurnal patterns emerged, which show when the greatest amount of fuming occurs during each day.
- The PM2.5 measurement comparison between the Nova and the Fidas at the SiMn plant showed a small spread and a linearity close to 1:1, with a small deviation towards the Nova measuring less than the Fidas. The same comparison at the Si plant showed more spread, and a linearity of around 1:5, with the Fidas measuring overall around five times as high values for PM2.5. This is believed to be in part due to the Fidas being well calibrated for SiO_2, and also

able to detect particles in the size range of 180–300 nm, which the Nova could not. In addition, the Nova factory calibration is possibly not adequate to accurately measure the SiO_2 fumes, although repeated attempts at getting these details from the manufacturer were unsuccessful.

- The relationship between the Nova and the Fidas for larger particles (PM10–PM2.5) divided by smaller particles (PM2.5) is strongly clustered, and shows a linearity close to 1:1 for the measurements at the SiMn plant. For the measurements at the Si plant, this relationship is more spread, with the Nova sensors measuring on average a much higher fraction of larger particles. This is believed to be due to the Nova overestimating the fraction of the larger particles (> 1.7 μm) that it cannot measure directly, which becomes prevalent with the overall low concentration of larger particles in the Si fumes.
- Deviation within each group of Nova sensors and between groups for both the SiMn and Si campaigns showed a relatively stable deviation from the mean value. Given a stable deviation over time, it would be possible to compensate for the internal deviation of the Nova sensors, through a calibration period to obtain a much lower spread of measurements. For most groups, the spread was within $\pm$ 20% relative deviation, close to the 15% relative deviation level provided by the manufacturer.
- For future industrial measurement campaigns, an improved and preferably airtight casing for the Nova system is considered important, to improve the length of life, and it is believed that using 4–5 sensors in each group, to have room for 1–2 failures before service and potential replacements are needed, would provide sufficient lifetime for the system as a whole to not cause unnecessary expense in this regard.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest

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SUPPLEMENTARY INFORMATION

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