Project Thrive Zone Amager

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1. Summary of assignment

Miljøpunkt Amager has requested the Danish Technological Institute (DTI) to evaluate how different nature-based installations influence the air quality at three different sites (Havnestaden/Artillerivej, Prismehaven, and Ørestad). This assignment is part of the project Thrive Zone Amager.

A total of 11 air quality sensors were planned to be employed and installed at carefully selected locations in this assignment to characterize the installations' potential positive effect on the air quality. The installations include green walls and domes containing plants. The installations were built by and set up by the Thrive Zone project partners.

The following tasks were DTI's responsibility:

- Plan and design of the measurement campaign
- Advising on the air pollution aspects of the different installations.
- Installation of 9 BlueSky air quality sensors
- Design of an enclosure for measurement of ultrafine particles at Prismehaven.
- Monitor the quality of the low-cost sensors and ultrafine particle measurement instrument during the field campaign period.
- Calibration of the 9 BlueSky air quality sensors.
- Data analysis and report on the air-cleaning effects of the installations during the field campaign.

The assignment was performed in the period July – October 2021. The air quality was measured at the various sites from the 11th of August to the 4th of October 2021.

The field campaign setup and results are described in Section 3, the method and instrumentation are explained in detail in Section 4 and the calibration of the sensors is described in Section 5 .

2. Conclusions

Evaluating the effect of nature-based solutions in the urban area is a non-trivial task. Significant uncertainties are introduced when performing measurement in real-life scenarios, such as wind, weather, seasonal change in emissions, human interactions (e.g., smoking) and various uncontrollable air pollution events. Hence, field campaigns designed to quantify effects on air quality typically have a very long duration, to level out the influence from the above-mentioned uncertainties. The field campaign conducted in the assignment have been compressed, which increases the significance of the uncertainties. Nevertheless, due to the great data capture percentage for almost all instruments, it has been possible to make solid conclusions for two out of three sites. However, the conclusions are to be considered indicative for the installations during the field campaign period, and not necessarily representative for effect during different seasons or locations.

At Havnevejen / Artillerivej a small positive effect from the two green walls was measured, 3 % and 5 %, for the thin and thick wall, respectively.

At Ørestad, it was not possible to draw solid conclusions on the effect of the dome and the green wall, due to lack of data from sensors not owned and managed by Danish Technological Institute.

At Prismehaven, it was found that both $PM_{2.5}$ mass concentration and ultrafine particle number concentration were lower inside the dome compared to outside the dome by respectively 13% and 12%, indicating a small reduction effect on both particle mass and number concentrations.

Moreover, the background $PM_{2.5}$ concentration (Z4) was relatively large compared to the local sensors (Z1-Z3), which indicates that local pollution is negligible when averaging over the entire field campaign period.

The overall conclusions from the field campaign are presented in Table 1.

Table 1: Overview over the assessed effect on local air quality of the different installations

Site	Installation	Conclusion
Havnestaden / Artillerivej	Thin Green Wall	3 % lower $PM_{2.5}$ concentration on the inside
	Thick Green Wall	5 % lower $PM_{2.5}$ concentration on the inside
Ørestad	Thin Green Wall and dome	No effect of installations could be characterized, due to lack of data. 4 % lower $PM_{2.5}$ concentration on the inside of the dome compared to the inside of the green wall.
Prismehaven	Dome	$PM_{2.5}$ and ultrafine particle concentration number were found to be lower on the inside of the dome compared to the outside. $PM_{2.5}$ concentration was on average 13 % lower and ultrafine particle number concentration was on average 12 % lower

3. Field campaign

In the project Thrive Zone Amager, three installations have been set-up: One green wall with two thicknesses (thin and thick) at Havnestaden/Artillerivej, one green wall with uniform thickness (thin) plus a dome at Ørestad station, and one dome at Prismehaven.

The Danish Technological Institute has carried out a measurement campaign from 11th of August to 4th of October 2021 at all three sites which contains one or more installations. Moreover, a sensor for measuring the urban background concentration has been installed at a roof next to Prismehaven, which thus constitutes a fourth location.

The sensors and ultrafine particle instrument were installed at the sites on 11th of August. The sensors and ultrafine particle instrument then measured continuously at different installations (with plants) from 12th of August until 20th of September.

As a direct quantification of the effect of the vegetation, measurements have been performed at the Havnestaden/Artillerivej and Ørestad locations without the vegetation (green wall or plants) in the period 21st of September until 4th of October. This serves as a baseline period for the measurement campaign. At Prismehaven the vegetation was kept in the dome for the full period.

At all four locations, TSI BlueSky Air Quality Monitor sensors were used to measure particle mass concentration as $PM_{2.5}$. Measurements with these kinds of instruments are subject to significant uncertainties in terms of absolute $PM_{2.5}$ concentration. These are categorized as so-called “low-cost sensors” and have therefore been calibrated in a test chamber at Danish Technological Institute after the field campaign, to ensure that the $PM_{2.5}$ concentrations measured with each sensor could be compared in relative terms to its counterpart (e.g., sensor pairs measuring inside and outside of a dome wall).

In addition to the 9 TSI BlueSky sensors employed by DTI, 2 additional Air Quality sensors were set up and managed at Ørestad by AFA JCDecaux. This means, that Danish Technological Institute did not have the possibility to monitor the quality of these low-cost sensors during the field campaign period. At Prismehaven, ultrafine particle number concentrations were measured using a TSI Ultrafine Condensation Particle Counter (UCPC).

Table 2: Overview of the sites, sensors, and particle instrument

Site	Sensorcode	# sensor	Installation	Sensor/instrument placement
Havnestaden /Artillerivej	Z1	4	Thin green wall Thick green wall	Z1D inside, Z1B outside Z1C inside, Z1A outside
Ørestad	Z2	4	Thin green wall Dome	Z2A inside, DC1 outside Z2B inside, DC2 outside*
Prismehaven	Z3	2	Dome	Z3A + UCPC-A inside Z3B + UCPC-B outside
Background	Z4	1	-	-

* DC2 is located on top of a bus-stop sign and not directly outside the dome. See Section 3.2.2 for more details

3.1. General results and discussion

The $PM_{2.5}$ concentration measured for all BlueSky sensors for the full field campaign period is presented in Figure 1. The $PM_{2.5}$ concentration profiles are grouped for each site (Z1-Z4). The $PM_{2.5}$ concentration throughout the period was mostly below 10 µg/m^3, though frequent peaks as high as 50 µg/m^3 were also observed.

Some peak values can be identified as non-local sources of pollution, by comparing the background $PM_{2.5}$ concentration (Z4) with the concentration measured locally at each site (Z1-Z3). For example, on day 2021-09-08, an increase in concentration for all four sites was observed to occur simultaneously, which allowed for identifying this event as an external pollution source rather than local.

Detailed discussion on the influence of the installations is presented in the following paragraphs below.

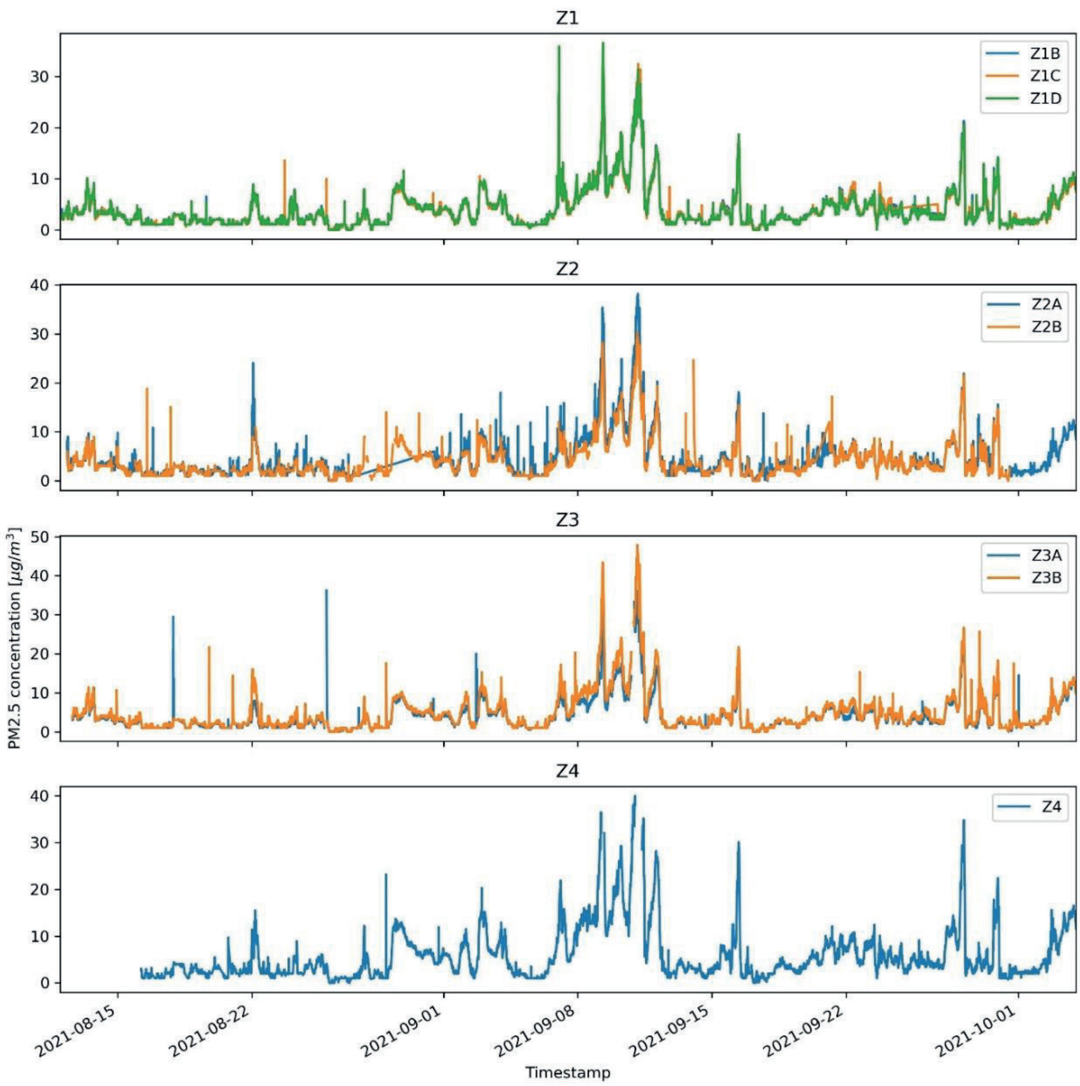

Figure 1. $PM_{2.5}$ concentration profiles for the entire field campaign for all BlueSky sensors.

3.1.1. Weekly variation

A weekly pattern was demonstrated by averaging all concentrations measured on each weekday per sensor from Mondays to Sundays. In Figure 2, the $PM_{2.5}$ concentration on an average week for each sensor is presented.

All $PM_{2.5}$ concentration profiles from the three sites (Z1-Z3) demonstrated the same trend, namely increasing concentration during workdays (Monday – Friday), while decreasing during weekends.

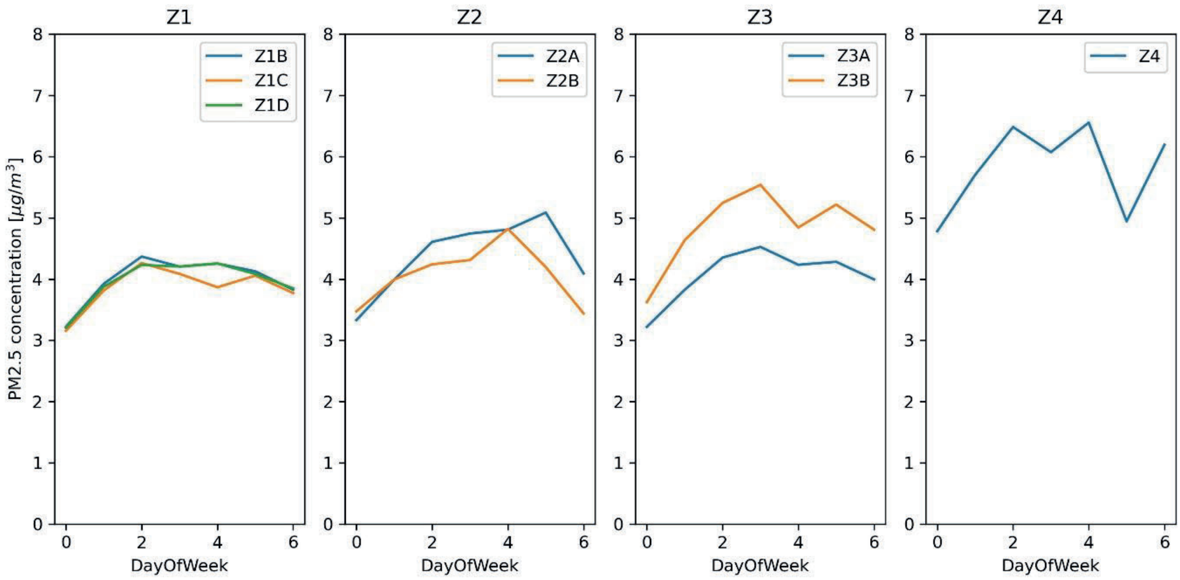

Figure 2: $PM_{2.5}$ concentration presented as day-by-day weekly average at the four sites Z1 (Havnestaden/Artil-lerivej), Z2 (Ørestad), Z3 (Prismehaven) and Z4 (background). The weekdays are presented as Monday=0, Tuesday = 1, Wednesday = 2, Thursday = 3, Friday = 4, Saturday = 5 and Sunday=6.

3.1.2. Diurnal variation

For each sensor an average day was calculated by averaging all data measured in hourly intervals. That is, for all days the concentrations measured between for example midnight and 1 am was averaged into one datapoint. The data points for all sensors are presented in Figure 3.

All $PM_{2.5}$ concentration profiles from the three sites (Z1-Z3) demonstrated the same trend, namely increasing concentration during morning and afternoon, while decreasing during midday.

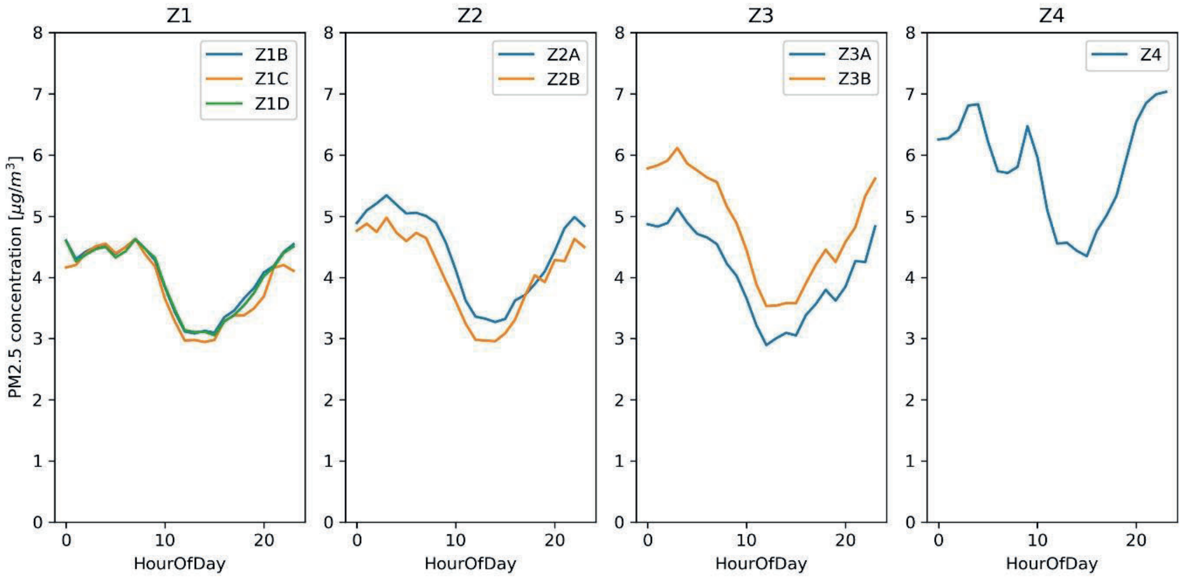

Figure 3: $PM_{2.5}$ concentration presented as diurnal pattern at the four sites Z1 (Havnestaden/Artillerivej), Z2 (Ørestad), Z3 (Prismehaven) and Z4 (background).

3.2. Locations

3.2.1. Havnestaden/Artillerivej

3.2.1.1. Setup

Havnestaden/Artillerivej is a roadside site, where four BlueSky sensors Z1A, Z1B, Z1C and Z1D were installed. Z1 refers to the location (Havnestaden/Artillerivej) and A-D refers to the individual sensor.

An image of the installation at the site is shown in Figure 4, and the location of the individual sensors is marked with red stars in Figure 5. The four sensors have been placed as two sensor pairs to evaluate the effect of the two types of green wall (a thick and a thin green wall) which has been installed at the location. Through comparing the sensor inside and outside the green wall, an indication of the effect of the wall can be obtained. All sensors have been installed at a height of approximately 160 cm above ground to be as representative as possible towards adult breathing height.

3.2.1.2. Results

Due to sensor Z1A (outside thick green wall) malfunction, it was decided to define Z1B (outside thin green wall) as the outside $PM_{2.5}$ concentration for both sensor Z1C (inside thick green wall) and Z1D (inside thin green wall).

In Figure 2 and Figure 3 it was observed that no significant influence of the two green walls on $PM_{2.5}$ concentration levels could be identified.

This was further evaluated by calculating the relative concentration ratio. In Figure 6 the ratio between Z1D and Z1B (inside vs. outside) was found to be 0.97 throughout the period both with and without the green walls installed. Hence, on average there was a small positive (3 %) effect observed on the $PM_{2.5}$ concentration between the inside and outside side of the green wall.

Similarly, it was found that the average ratio between Z1C and Z1B (inside vs. outside) was slightly below 1.0 throughout the period (0.95 exactly) (Figure 7). Consequently, the thick green wall resulted in a 5 % average decrease in $PM_{2.5}$ concentration.

Figure 4: Installation at Havnestaden/Artillerivej site, where the thin green wall is visible on the left side, whereas the thick green wall is visible on the right side.

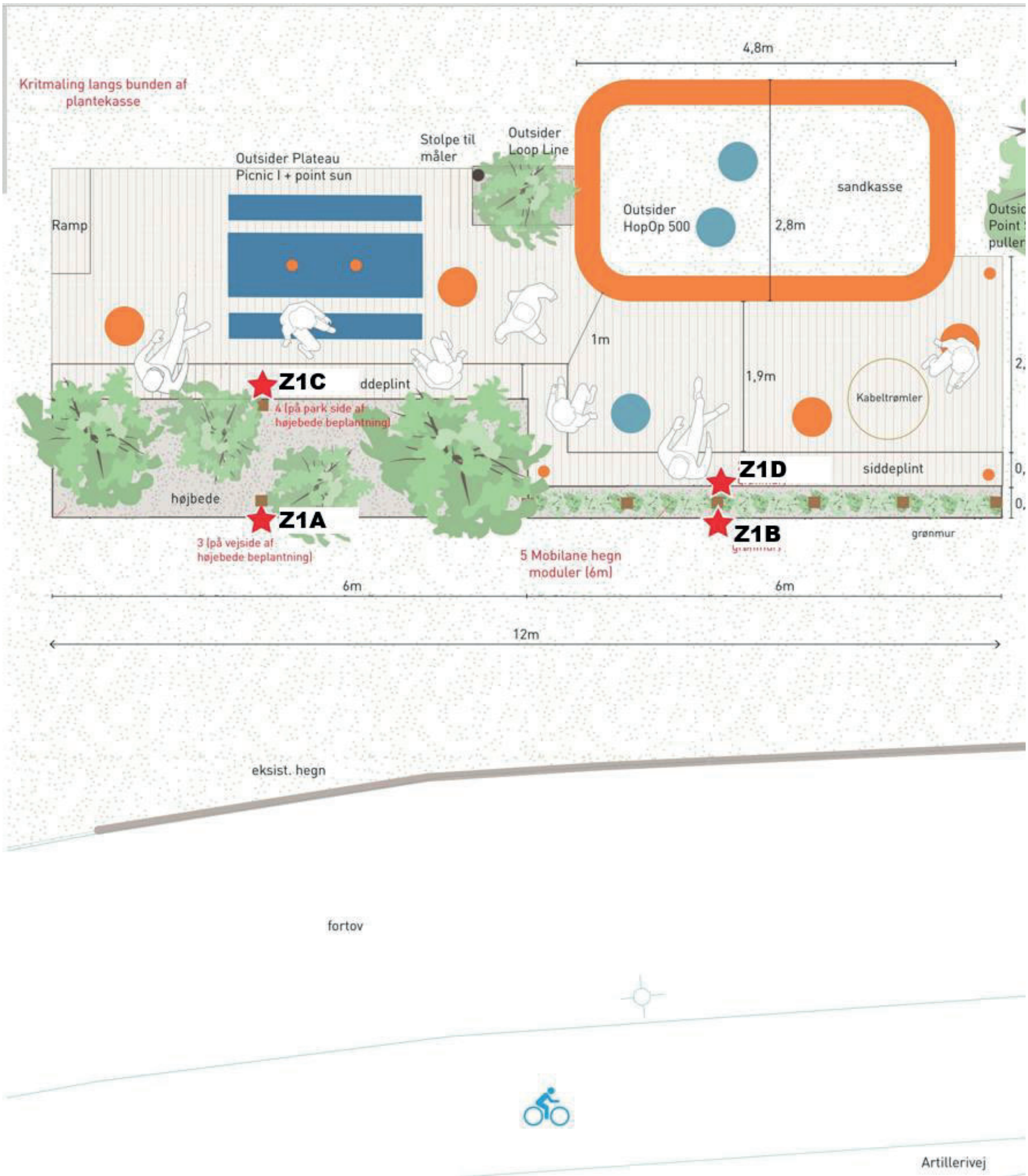

Figure 5: Schematic overview of Havnestaden/Artillerivej site

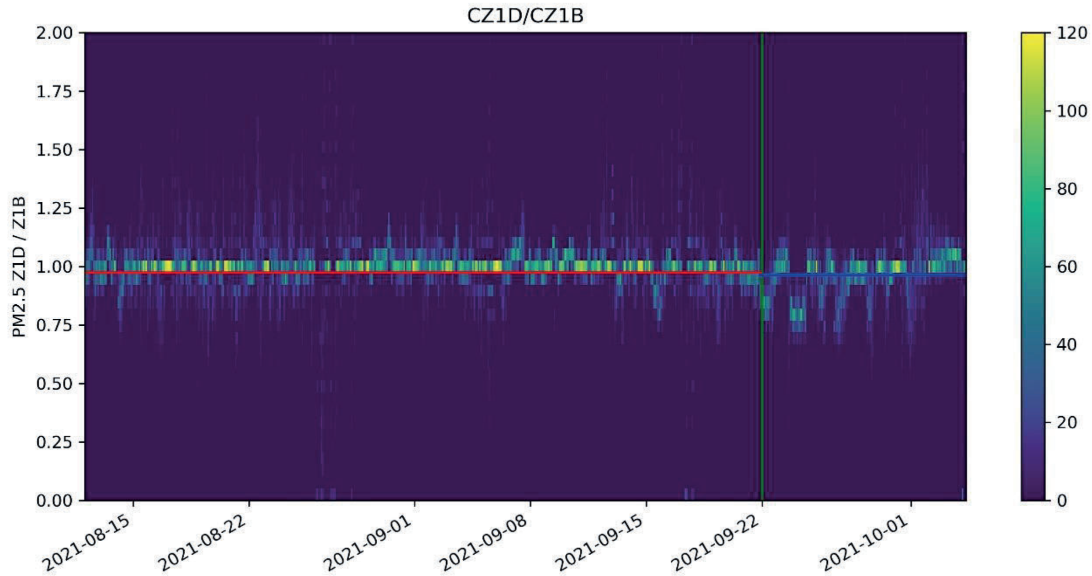

Figure 6: Concentration ratio at Z1 measured between inside (Z1D) and outside (Z1B) of thin green wall. The red line indicates the average ratio. The green line indicates the start of the baseline period (without the installations) and the blue line indicates the average ratio during the baseline period.

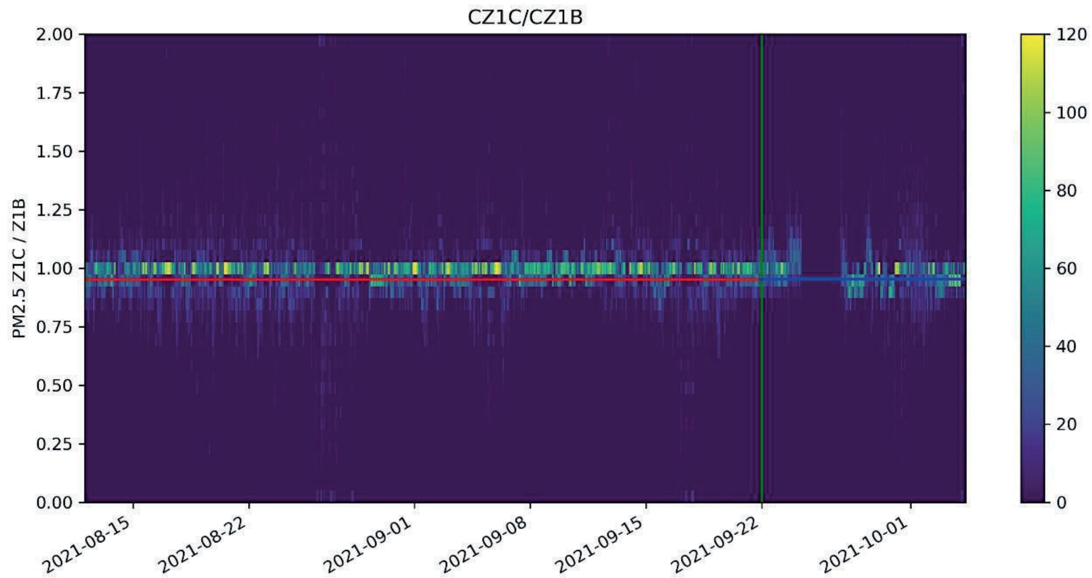

Figure 7: Concentration ratio at Z1 measured between inside (Z1C) and outside (Z1B) of thick green wall. The red line indicates the average ratio. The green line indicates the start of the baseline period (without the installations) and the blue line indicates the average ratio during the baseline period.

3.2.2. Ørestad

3.2.2.1. Setup

Ørestad is a site next to a bus-stop and a heavy-traffic road (Ørestads Boulevard) (Figure 8-Figure 9). At this site, there were installations of both a thin green wall and a dome.

At Ørestad, four sensors were also installed: two BlueSky sensors, one AirNode from Airlabs and one sensor from Decentlab. The two BlueSky sensors have been named respectively Z2A and Z2B, where Z2 refers to the location. The two sensors form Airlabs and Decentlab has been named DC1 and DC2, as a reference to the fact that they are owned, set up and managed by AFA JCDecaux.

The plan for monitoring the effect of the two installations was as described below, however due to lack of data from DC1 and DC2 sensor, evaluation of the two installations were not possible.

The two sensors Z2A and DC1 has been installed in the same way as the sensors at Artillerivej, with the aim to evaluate the effect of the green wall. The sensors Z2B and DC2 has been installed as a comparison between the exposure from waiting in the existing bus stop versus the exposure from waiting in the dome. This is however not a direct comparison, since DC2 has been installed in the sign for the bus stop and is thus installed remarkably higher above the ground than Z2B (Figure 8). Moreover, Z2B is placed several meters further away from the road compared to DC2, which would also result in a reduced concentration. The comparison between these two sensors should thus only be interpreted in qualitative terms.

3.2.2.2. Results

At the Ørestad site, data from the DC (AFA JCDecaux) sensors were unavailable. Thus, the direct effect of the dome and the green wall could not be assessed. Rather the difference in $PM_{2.5}$ concentration inside the green wall (Z2A) and inside the dome (Z2B) was evaluated.

The weekly and diurnal patterns for the two sensors were practically identical, indicating that there was no difference in exposure to PM2.5 between the inside of the dome and the inside of the green wall.

Additionally, looking at relative concentration plot in Figure 10, it was found that the average ratio between Z2A and Z2B was very close to unity (1.04) during the period with the installations in place. Which corresponds to a 4 % decrease in $PM_{2.5}$ concentration on the inside of the dome compared to the inside of the green wall. During the baseline period the ratio was found to be 1.00.

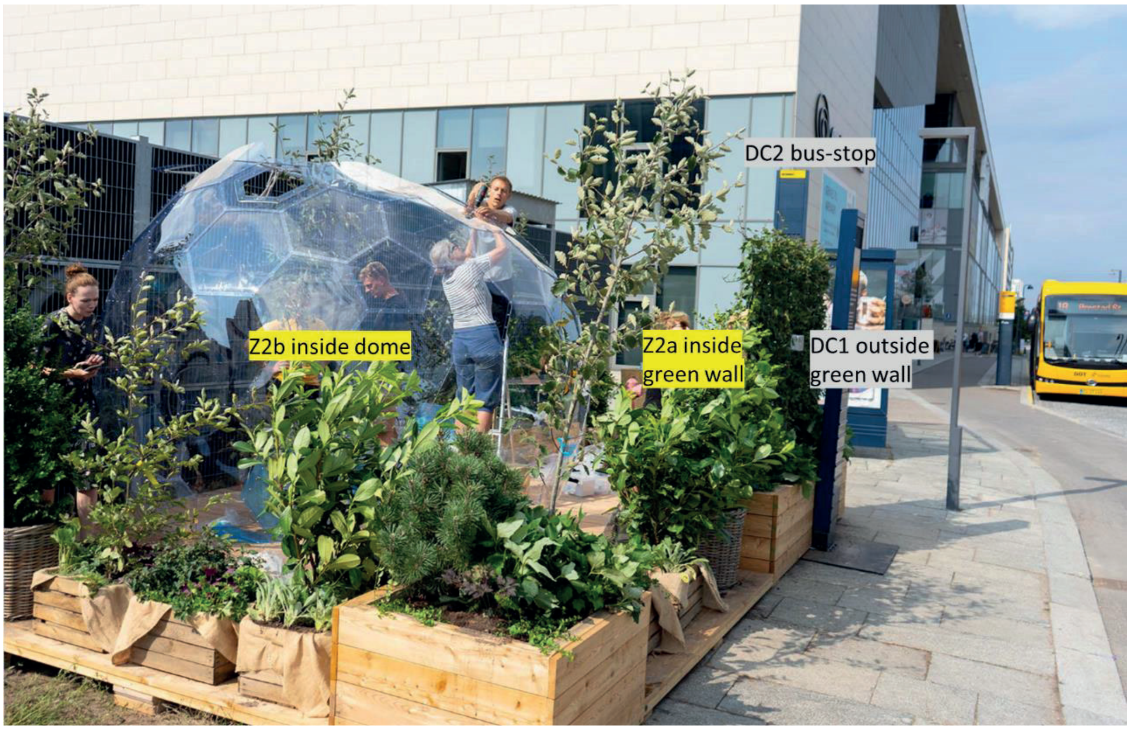

Figure 8. Installation at Ørestad, with a thin green-wall and a dome.

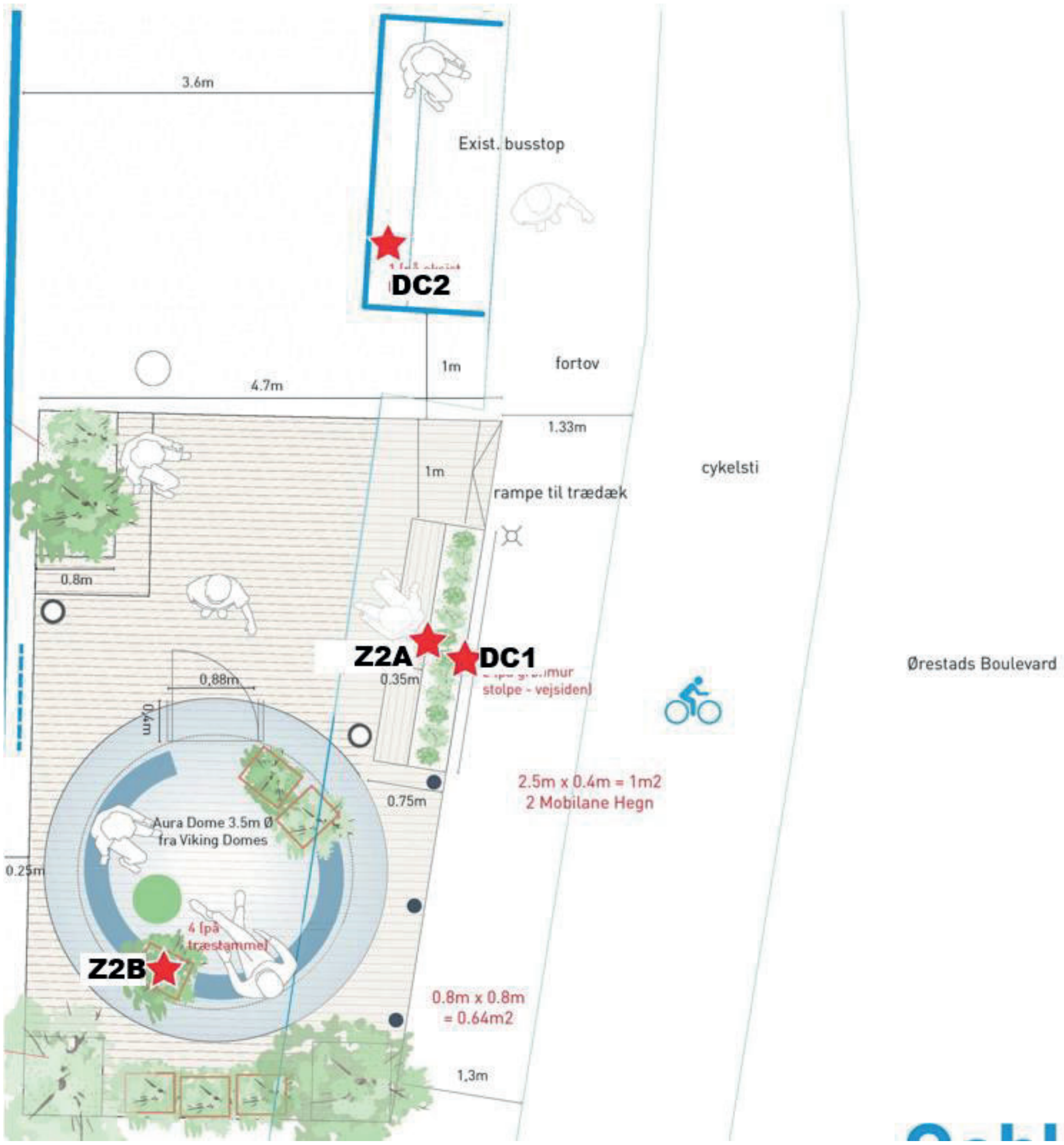

Figure 9: Schematic overview of Ørestad site

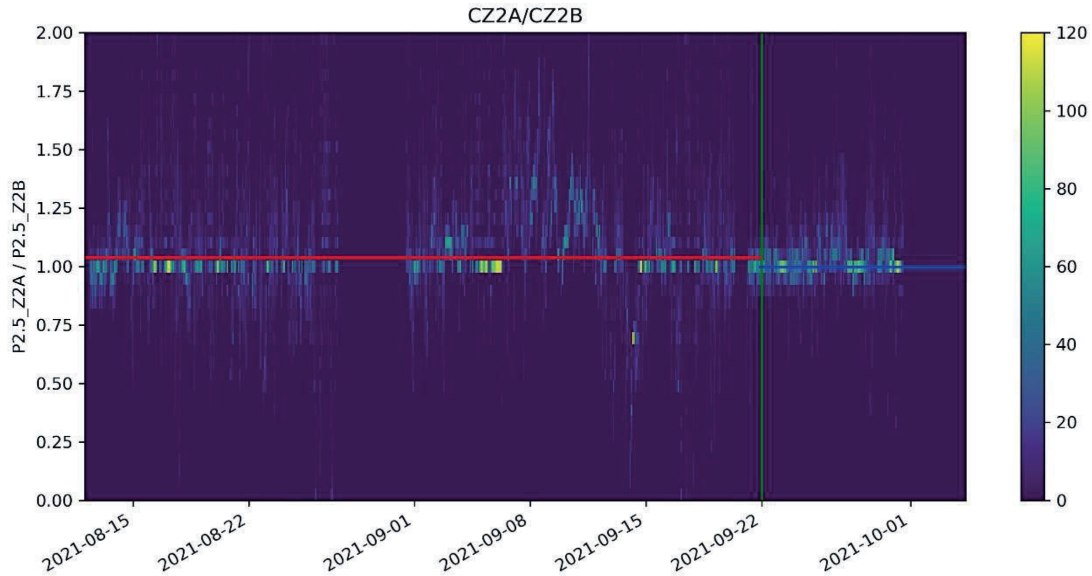

Figure 10: Concentration ratio at Z3 measured between the inside of the green wall (Z2A) and the inside of the dome (Z2B). The red line indicates the average ratio. The green line indicates the start of the baseline period (without the installations) and the blue line indicates the average ratio during the baseline period.

3.2.3. Prismehaven

3.2.3.1. Setup

Prismehaven is a site located in the middle of a green area, close to a main road (Ørestads Boulevard), surrounded by residential buildings. There was a dome installed at this site (Figure 11).

At Prismehaven, two sensors, named respectively Z3A and Z3B where Z3 refers to the location, have been installed. These are installed respectively at the inside and outside of the dome to quantify the "screening" effect of the dome towards air pollution. The installation height of these sensors is approximately 1 m above ground since the dome has been envisioned as a room mainly used for sitting. The lower installation height thus corresponds to approximately to the breathing height of a seated adult.

At this location ultrafine particle number concentrations have been measured as well, with the air inlet located as close to the air inlet of the BlueSky sensors as possible. These have been named UCPC-A (inside dome) and UCPC-B (outside dome). Ultrafine particle number concentrations have been measured from two inlets with an instrument using a changing valve which rotates between the two inlets at an interval of 578 seconds (approximately every 10 minutes). The data are therefore not exactly simultaneous, but only approximately simultaneous. It is assessed that this should not influence the results due to the long measurement period.

Figure 11: Prismehaven dome being in use. (Picture source: https://amagerliv.dk/artikel/borgere-eftersp%C3%B8rger-ren-luft)

Figure 12: Schematic overview of Prismehaven

3.2.3.2. Results

In Figure 2 and Figure 3 it was observed that a positive effect of the dome could be identified, as the inside $PM_{2.5}$ concentration (Z3A) generally was lower than the outside $PM_{2.5}$ concentration (Z3B).

From the relative concentration it was found that the average ratio was 0.87. This corresponds to an average decrease in $PM_{2.5}$ concentration of 13 % on the inside compared to the outside (Figure 13).

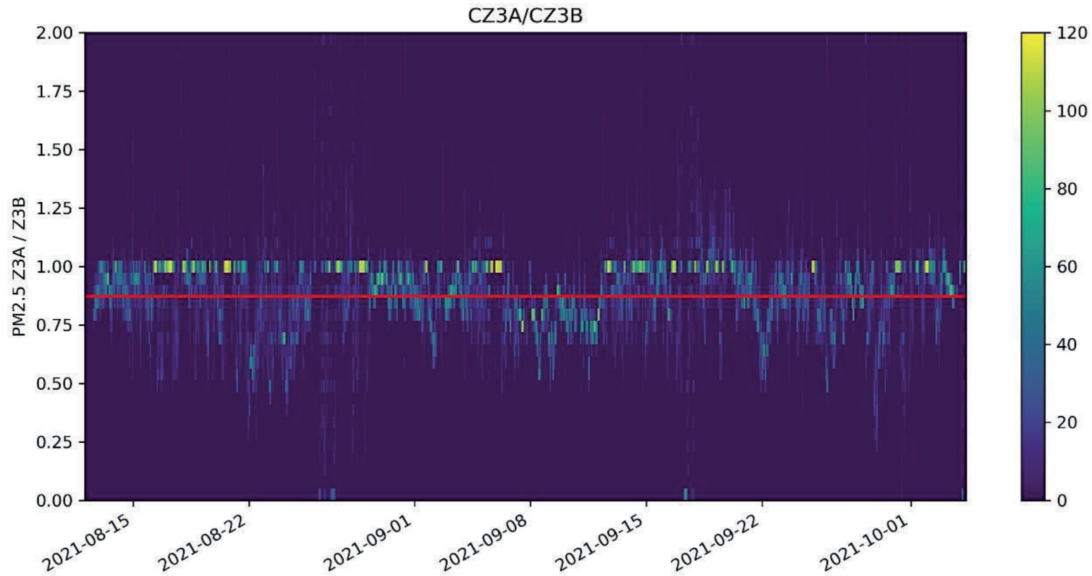

Figure 13: Concentration ratio at Z3 measured between inside the dome (Z3A) and outside the dome (Z3B). The red line indicates the average ratio.

In Figure 14 the number concentrations of ultrafine particles (UCPC data) are presented for the entire field campaign period. Throughout most of the period the particle number concentration was below 7500 particles/cm^3, however with frequent events exceeding this. From this figure, it was not possible to determine the effect of the dome.

Thus, the relative concentration ratio between the inside (UCPC-A) and outside (UCPC-B) was calculated (see Figure 15). When quantifying the effect of the dome wall by the ratio between the inside and outside concentration, it was found that during the field campaign period the inside concentration of ultrafine particles was on average 12 % lower compared to the outside concentration.

Furthermore, at some individual events the inside concentration was up to 50 % lower than the outside concentration. However, at certain events the inside concentration was higher than the outside concentration. Therefore, the average difference in concentrations is the most reliable result for the effect of the dome.

It should be noted that while the BlueSky sensors measure $PM_{2.5}$ fractions as particle mass concentration, the UCPC measures particle number concentration. These are two different concepts, which do not contradict but do not necessarily follow the trend of each other. For example, smaller particles could contribute significantly to particle number concentration, while contributing little to mass due to their smaller size. On the contrary, larger particles are important contribution to particle mass, while their numbers tend to be lower than the smaller particles. The results therefore indicate that the dome seems to have a positive effect on reducing both larger and smaller particles. A person sitting in the dome at Prismehaven therefore would be exposed to both lower particle mass and particle number concentration.

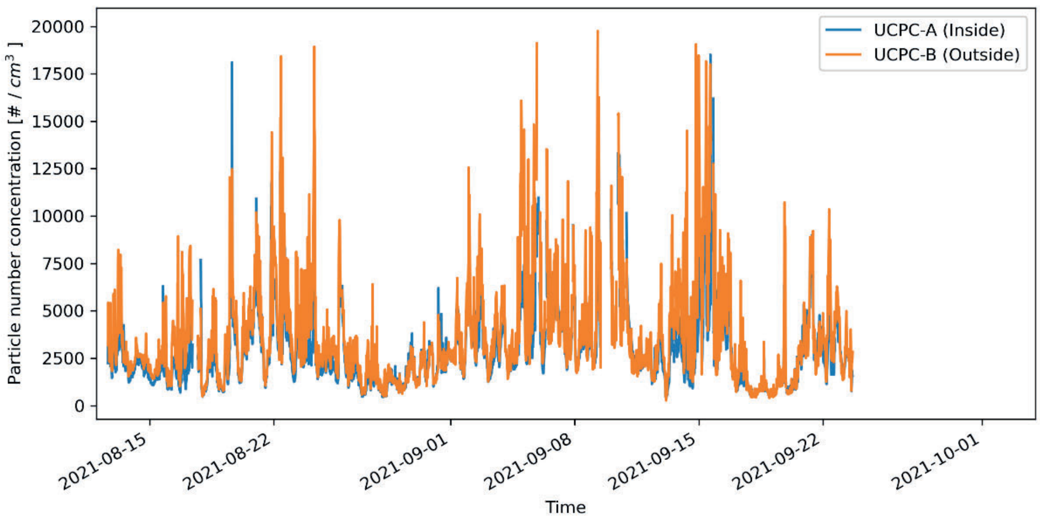

Figure 14: Measured particle number concentration inside (blue) and outside (orange) the dome, respectively.

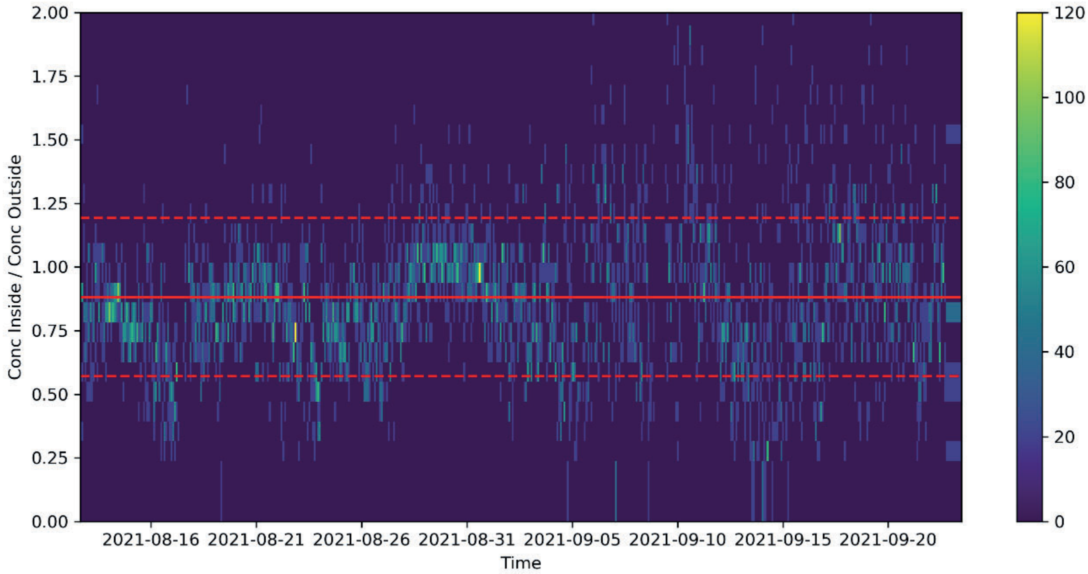

Figure 15. Particle number concentration ratio measured with the UCPC. Concentration ratio at Z3 measured between inside the dome (Z3A) and outside the dome (Z3B). The red line indicates the average ratio during period <u>with</u> installations. The dotted lines represent the standard deviation from the average ratio.

3.2.4. Background

3.2.4.1. Setup

At the background location located on top of one of the residential buildings at Prismehaven, a BlueSky sensor named Z4 was installed Figure 16. It should be noted that urban background concentrations must be measured at a roof to avoid the influence of local air pollution sources.

Figure 16. Z4 sensor installed at the background site on top of one residential building at Prismehaven area.

Figure 17. Schematic overview of background site

3.2.4.2. Results

It was observed that the $PM_{2.5}$ background concentration was of a similar size compared to the $PM_{2.5}$ concentration measured at the three sites (Z1-Z3) (see Figure 1, Figure 2 and Figure 3). However, as noted before, the absolute concentration measured with BlueSky sensors is subject to high uncertainty. Nonetheless, this result indicates that most of the air pollution origins from non-local sources, which furthermore provides an explanation to as why little or no effect was measured for the green walls.

The Z4 sensor was apparently subject to an error in measuring absolute concentrations compared to the other sensors. A meaningful background subtraction was not possible because of this.

4. Method and Instrumentation

4.1. BlueSky sensors

9 BlueSky Air Quality Monitor sensors were acquired from TSI Inc. The sensors are cloud-based, laser-based particle instrument designed to simultaneously measure $PM_{2.5}$ and PM_{10} mass concentrations. The sensors log data once every minute.

Figure 18. A BlueSky Air Quality Monitor sensor

4.2. Ultrafine Condensation Particle Counter (UCPC)

Measurement of particle number concentrations was conducted using an Ultrafine Condensation Particle Counter (UCPC 3776, TSI Inc.). This instrument detects particles down to 2.5 nanometre (0.0025 µm) in diameter and designed to detect rapid changes in aerosol number concentration.

The UCPC uses butanol as a condensing vapour to allow growing of particles into detectable sizes, which are then detected by an optical counter. The UCPC model 3776 uses a laser diode light source and a diode photodetector to collect scattering lights from particles. The instrument was set to measure continuously under the measurement campaign at the low flow mode (0.3 L/min).

Figure 19. UCPC 3773 (TSI Inc.)

The UCPC was set to measure from two different sampling ports, inside (UCPC-A) and outside (UCPC-B) the dome installed at Prismehaven. The sampling ports were 3D-printed in cone-shaped form to avoid rain and water splashing effect. An automatic valve changes between the inside and outside port every 578 s (approximately 10 minutes).

4.3. Data capture

Various challenges were associated with continuous measurement of data. Such challenges were expected and typical of long field campaigns. The data capture percentage was calculated to ensure that the conclusions can be considered as representative for the period. The data capture percentage was calculated as the relative ratio between the number of data points for each individual sensor / instrument and the theoretical number of data points assuming a 100% data capture.

Table 3: Overview of data capture percentage for each sensor.

Site	Sensor / Instrument	Number of data points	Data Capture (%)	Explanation
Havnestaden /Artillerivej	Z1A	37428	49.0	Most likely sensor malfunction occurring from the 7th of September
	Z1B	76633	100	
	Z1C	73233	95.9	Brief loss of power
	Z1D	76605	100	
Ørestad	Z2A	70482	92.4	Brief loss of power
	Z2B	69770	91.4	Brief loss of power
Prismehaven	Z3A	75958	99.5	
	Z3B	75949	99.5	
	UCPC	6167	77.9	Most likely episodes with high temperature affecting condensation of butanol vapour
Background	Z4	68961	90.3	Brief loss of power

4.4. Data processing

4.4.1. UCPC Data

The continuously measured particle number concentration was split into an inside and an outside fraction according to the 578 s valve change. Datasets measured before and after periods of data lose were stitched together based on a manual evaluation. For each section of 578 s an average concentration was calculated.

A temporal average of the measured particle number concentration was conducted over each valve period. The UCPC data have furthermore been modified by removing peaks deemed to occur from instrument artifacts or unexplainable events. Peaks were automatically identified by Python scipy peakfind with a height of at least 20,000 #/cm^3 and a threshold of 2. This likewise removed 20 minutes of data on each side of the time stamp of the peak.

A concentration ration was calculated between the concentrations measured inside and outside.

4.4.2. BlueSky sensor data

The BlueSky data have been modified by removing peaks deemed to occur from instrument artifacts, as low-cost sensors are well known to generate artificial peaks in PM concentration. Peaks were automatically identified by Python scipy peakfind with a height of at least 50 µg/m^3 and a threshold of 2. 20 minutes of data on each side of the of the peak were removed. This likewise removed effects of people using the dome for smoking.

A temporal average of the measured particle mass concentration was conducted with a rolling average over 10 minutes.

According to the calibration data the sensor Z1A has a much higher gain compared to the other sensors. This could be a sign of a malfunction of that specific sensor. Applying the Z1A calibration values to the raw data results in $PM_{2.5}$ concentrations twice as high compared to the rest of the sensors after calibration.

Moreover, the sensor measuring the background concentration (Z4) had significant different calibration factors. Hence, a meaningful background subtraction was not possible.

The concentration ratio was calculated for the relevant sensor pairs. They can be seen in Figure 6, Figure 7 and Figure 13 in the form of a histogram where the colours indicate the number of measurements falling in a time bin of two hours and a ratio bin of 0.05. Yellow colours indicate many measurements in a bin and dark blue colours few or no measurements in a bin. Hence looking at e.g., Figure 13 (Z3A/Z3B) the ratio of almost all the measurements is 1.0 or smaller, which is seen by a large number of yellow spots below the 1.0 line. This indicates, that the sensor Z3B almost always measures higher concentrations compared to Z3A. The red line indicates the median of the measured ratio.

5. Sensor Calibration

This section describes the calibration of the BlueSky sensors in the laboratory at Danish Technological Institute. Calibration of low-cost sensors is essential to ensure that the absolute particle mass concentrations measured are correct.

Furthermore, sensor calibration is important to minimise the sensor-to-sensor variation, which ensures that the identified relative differences in particle mass concentrations between sensors are trustworthy.

5.1. Experimental setup

In the experiments, a 3% potassium chloride (KCl) solution was used as a source of atmospheric particles. Particles were generated using a particle generator (PALAS GmbH AGK 2000). The experiments were carried out in a test chamber with a volume of 20 m^3. The walls of the test chamber were covered by Teflon foil to reduce the adsorption of particles. The test chamber was kept air-tight and non-ventilated and is therefore suitable for testing the performance of low-cost sensors. An external ventilator set on lowest fan speed was used to circulate the air in the test chamber during the experiments to ensure homogeneous mixing.

Two experiments were performed at different relative humidity. One with a high relative humidity starting point (RH> 80%), where the relative humidity slowly decreased to RH 65% during the 12-hour experiment. In the other experiment, the relative humidity was constant at RH 50 ± 5%.

The BlueSky Air Quality Monitor sensors were placed inside the test chamber and were continuously monitoring the PM concentrations. The reference instruments are placed outside the test chamber with sample probes placed in the vicinity of the BlueSky sensors.

A description of the BlueSky sensors can be found in Section 4.

5.2. Analytical method

5.2.1. Particle Mass Concentration

Two different instruments were used to measure particle mass concentration and mass size distribution.

A TEOM (1405 TEOM™ Continuous Ambient Particulate Monitor, Thermo Scienfitic) was used. The TEOM directly measures the mass of the particulate matter using a Tapered Element Oscillating Microbalance. Different particle mass fractions can be measured using various sample inlets, e.g., the $PM_{2.5}$ fraction.

The TEOM is generally considered to be the state-of-the art instrument for continuous real-time measurement of particulate matter. The TEOM instrument was equipped with the $PM_{2.5}$ sample inlet during the sensor calibration experiments.

The particle mass distribution was measured with an Optical Particle Sizer (OPS, TSI 3330), which is a laser-based light scattering instrument. The OPS was set to measure the particle size distributions in different size bins, which subsequently was grouped into the five particle mass fractions ($PM_{0.5}$, PM_1, $PM_{2.5}$, PM_5 and PM_{10}) based on spherical particles with density equal to 1.

5.2.2. Temperature og Relative Humidity

Temperature and relative humidity were measured in the test chamber using a Chauvin Arnoux Air Quality Monitor (C.A 1510) with a time resolution of 15 seconds.

5.2.3. Data processing

The mass fraction of the individual size bin from the OPS was used as a measure of the particle size distributions. This was subsequently multiplied with the corresponding mass fraction from the TEOM. In this way, respectively $PM_{2.5}$ and PM_{10} was measured with the TEOM to a high accuracy, and an estimate of the particle size distribution was calculated from the OPS measurements.

The sensors were calibrated to the all the reference data through linear regression.

5.3. Calibration results

The sensor calibration was concluded by obtaining calibration factors for each individual sensor. The calibration factors were found by applying linear fits (gain and offset) between the reference (TEOM and OPS) and sensor data. The factors are presented Table 4.

It can be seen from the calibration results that the unit-to-unit variance was relatively low for all sensor except Z1A and Z4. The calibration results for Z1A resulted in excluding this sensor from the further data analysis.

Especially, it was found for the three relevant sensor pairs (Z1D vs. Z1B, Z1C vs. Z1B and Z3A vs. Z3B) that the calibration factors for each individual pair was the same. Thus, the relative ratios calculated for the sensor pairs are considered to be reliable.

Table 4: Calibration factors from linear fit between reference instruments and sensors

Sensor	$PM_{2.5}$ Offset	$PM_{2.5}$ Gain	PM_{10} Offset	PM_{10} Gain
Z1A	-5,3	12,0	-4,5	11,6
Z1B	-7,6	2,7	-11,2	2,6
Z1C	-7,2	2,7	-10,6	2,7
Z1D	-6,7	2,7	-10,1	2,6
Z2A	-7,3	2,7	-10,9	2,7
Z2B	-7,5	2,8	-11,0	2,7
Z3A	-7,8	2,4	-11,7	2,4
Z3B	-8,5	2,5	-12,6	2,4
Z4	-7,8	1,9	-11,8	2,0

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