Ref. Ares(2024)743306 - 31/01/2024

CANMILK

GREENHOUSE GAS REDUCTION IN AGRICULTURE
USING PLASMA-BASED SOLUTIONS

DELIVERABLE D4.1

TEST REPORT ON THE BARN AS OPERATIONAL ENVIRONMENT FOR METHANE ABATEMENT PROCESSES

PROJECT GRANT AGREEMENT NO	DUE DATE OF DELIVERABLE:	ACTUAL SUBMISSION DATE:	START DATE OF PROJECT:	PROJECT DURATION:
101069491	31.01.2024	31.01.2023	01.09.2022	48 MONTHS

Funded by the European Union

Work Package	WP4
Associated Task	Task 4.1
Deliverable Lead Partner	Valio, VTT
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Internal Reviewer(s)	Pekka Simell (VTT)
Version	V1

DISSEMINATION LEVEL		
PU	Public, fully open, e.g., web (Deliverables flagged as public will be automatically published in CORDIS project's page)	X
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Classified S-UE/EU-S	EU SECRET under the Commission Decision No2015/444	

CHANGE CONTROL

DOCUMENT HISTORY

VERSION	DATE	CHANGE HISTORY	AUTHOR(S)	ORGANISATION
V0	19.01.2024	Document drafted	Jasmiina Palo, Johanna Kihlman	VTT
V1.0	31.1.2024	Document submitted	Johanna Kihlman	VTT

This deliverable is part of a project that has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101069491.

EXECUTIVE SUMMARY

This deliverable reports the results of WP4 Task 4.1 in which the air from a dairy barn was analysed in order to gather understanding of the operational environment for the methane abatement technology. Two test campaigns were performed together with a subcontractor Aeromon: first winter season campaign during January – March 2023 and second summer season campaign during June – July 2023. The dairy barn, that was chosen by Valio, housed 240 dairy cows. The barn was of modern design with natural ventilation through curtain walls up to ridge chimney. The main objective of the measurements was to understand the effect of seasonal variation in the methane level, verify if the theoretical methane levels were present in the barn and learn if there were significant fluctuations in the methane levels during long term measurements.

The methane levels were found to be lower than expected. According to theoretical calculations the emitted methane from the cows was expected to be around 200 ppm. However, the structure of the barn with strong ventilation diluted the methane efficiently even down to level of 20 ppm. Only on those very cold days in the winter when the curtain walls were completely closed, the methane levels increased to levels around 175 ppm. The methane was well dispersed in the barn as the measurements could not find any locational differences within the barn. However, there were strong daily fluctuations. During wintertime these were strongly dependent on the outside temperature. During summertime, when the curtain walls were constantly open, there was clear daily pattern visible with methane levels increasing always during nighttime.

The experiments were successful and provided useful data for the design of the CANMILK technology. As next steps, the data will be analyzed and utilized by the project partner DU to create a model of the barn. The results from the measurement campaigns will also be published as a scientific paper during year 2024.

DEVIATIONS

There were no major deviations from the workplan. The workplan, as stated in the Description of Action (DoA), was:

"Monitoring of methane and other impurities (possibly NH_3) in real dairy barn will be performed by a campaign lasting ca.6 months. Monitoring will be done with a method that gives continuous data on emission content in the whole interior of a barn, like laser dispersion spectroscopy (LDS). The measurements thus will give information on the daily and seasonal variation of the impurities in the barn air in addition to simultaneous humidity and temperature measurements."

After discussions with the subcontractor Aeromon, who performed the measurements, and Valio, who provided the barn, the plan was refined to include two different types of measurements: 1) Manual and drone measurements at different levels and locations inside the barn mapping the entire barn area and immediately outside the barn. These measurements required on-site personnel and were done for few days during both winter and summer season. 2) Continuous monitoring of several weeks in two different locations inside the barn both during winter and summer time. Methane was the main measured component but also NH_3, H_2S, CO_2 and NO_2 were monitored during the mapping measurements. The aim of these changes (compared to the DoA) was to improve the quality and versatility of the obtained data considering that there was specific budget allocated for this action.

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LIST OF ABBREVATIONS

ACRONYM	DESCRIPTION
D	Deliverable
DoA	Description of Action in Grant Agreement
DU	Durham University (project partner)
EC	Electrochemical
FEP	Fluorinated ethylene propylene
GHG	Greenhouse gas
LDS	Laser Dispersion Spectroscopy
MB	Mass balance
NDIR	Non-dispersive Infrared (sensor)
TDLS	Tunable Diode Laser Spectroscopy

VTT	VTT Technical Research Centre of Finland Ltd (project coordinator)
WP	Work Package (of CANMILK project)

1 INTRODUCTION

In 2019, the amount of methane produced by agricultural resources in EU area was 231 Mt CO_2 eq. representing 52% of total methane emissions and 5.1% of total European GHG emissions. The agricultural methane originates from various sources but 80% of it is produced by enteric fermentation of livestock. 85% of the enteric methane is produced by cattle, which is also the reason to focus the CANMILK project on the emissions from the cattle. Significantly smaller sources for the enteric methane are swine, sheep and other livestock.

Reducing methane emissions is vital for tackling climate change in both the short-term and long-term. During 20-year period the global warming potential of methane is 84 - 86 times stronger than that of CO_2, and 28 - 34 times stronger in 100-year period. In addition to global warming, methane in the atmosphere also promotes the formation of tropospheric ozone which is hazardous.

There are two significant challenges with the methane produced by the cattle. First, there are ca. 1.8 million farms in the EU area holding ca. 77 million bovines and each of these is a tiny point source of methane. Secondly, the methane is highly dilute in the barn air which limits the technical methods suitable for its removal.

For the purpose of understanding the operational environment of the CANMILK technology, the workplan of the project included an on-site measurement campaign to investigate the level of methane inside a real dairy barn. There are already highly reliable calculation models available to estimate the amount of methane produced by the cows, but we also needed to study how different external parameters affect the concentration of methane inside the barn. As the CANMILK unit is inherently “end-of-the-pipeline” type on installation, we need to know how much of the methane could potentially reach the unit. Based on those above-mentioned calculation models, we estimated the level of the produced methane to be ca. 50 – 200 ppm within the barn. However, there is always some type of ventilation system in the barn which could have a strong effect on the dilution of methane. Only in a fully closed systems we can expect methane levels to be the same in the barn outlet as produced by the cows.

The design of a dairy barn depends on the local climate. The cows produce heat, moisture and CO_2 which requires ventilation to keep the temperature of the barn comfortable. Therefore, the barn is well-ventilated even during the winter season when the outside temperatures can drop below 0 °C. The cows are also sensitive to excess heat, as temperatures above 25 °C during daytime and above 20 °C can already affect the milk production negatively. Therefore, they need protection during summer from direct sunlight and extreme heat.

To maximize the effect of the natural ventilation, the modern European dairy barns have often open side walls and roof which is either partially open or has row of chimneys. The actual structure of the walls varies from fully open to such which have mechanisms to close the wall partially or fully to control the ventilation inside the barn. An example of this type of barn is presented in the Figure 1. The incoming air is flowing through the walls, mixes inside the barn and moves out from the ridge chimneys. It is also possible, that there is out-going flow of air through the wall especially in windy weather conditions. Due to this ventilation mechanism, we needed to study how methane dilutes with the ventilation air in a real dairy barn.

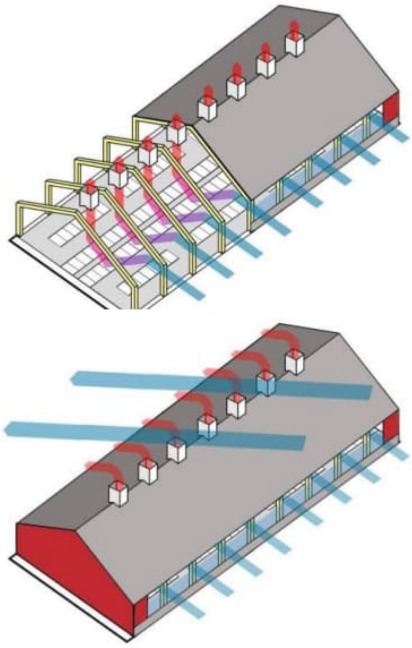

Figure 1. Example of a naturally ventilated barn with curtain walls [1].

This Deliverable 4.1 covers the methane measurement campaigns which were carried out at Arvela dairy barn in Finland during winter – summer 2023. In this deliverable we describe the site, explain the methodology, present the results and discuss about the key findings and how they impact the development of the CANMILK technology. The test campaign and this deliverable are joint effort of VTT and Valio. The role of the subcontractor Aeromon was to carry out the analysis in the barn and produce raw data. VTT and Valio interpreted the analysis data and estimated its scientific impact on the project.

2 RESEARCH METHODOLOGY

The purpose of the air measurements was to monitor methane and other impurity levels at a real barn site continuously and for a longer period of time. This data would help to better understand the operational environment and design the proof-of-concept unit. The results of the measuring campaign would also support the techno-economical and lifecycle assessments done in WP5 (DU). It is worth noting that there is limited literature available on methane emissions levels emitted from cattle barns, especially with regard to seasonal variations over longer periods.

In Task 4.1, Aeromon Oy, a Finnish subcontractor, performed monitoring of methane and other impurities. They offer emission monitoring services such as emission mapping, leak detection, and emission spreading measurements for various industrial sectors. Two emission monitoring campaigns were executed during the year 2023, one in winter between 18th January 2023 and 3rd March 2023, and one in summer between 7th June 2023 and 13th July 2023. Concentrations of various gases, including methane (CH_4), ammonia (NH_3), hydrogen sulfide (H_2S), carbon dioxide (CO_2), and nitrogen dioxide (NO_2), were measured during the campaigns. These gases were chosen based on literature and discussions with VTT, Valio, and DU.

2.1 RESEARCH SITE

The test site for the measurement campaigns was chosen by specific parameters which were decided in discussions between VTT, Valio and DU. The aim was to find a dairy farm that could provide versatile data, and which would represent modern European design so that the produced data would be reasonably useful also in the future and potentially applicable for wide range of farms.

As described in the Introduction, the modern European dairy barn is often an open-wall structure with a roof. These types of barns are also built nowadays in Finland instead of old-type barns with solid side walls. Due to cold season in Finland the open-wall barns have curtain mechanisms to close the wall when needed. The curtains are light structures which do not block completely the airflow. Finland was chosen as the location for the measurement campaign as the project partner Valio has many collaboration farms in Finland. Also, the effect of seasonal changes were naturally easier to study in Finland where the average winter temperatures are typically below 0 °C even in southern parts of the country.

Another parameter for the test site was the size of the cattle. In Europe, almost 2/3 of agricultural methane emissions originate from larger farms with over 50 cows (ca. 500 000 farms). The current trend is towards larger cattle sizes, in other words fewer farms with larger cattle, which could be beneficial from the emission control point-of-view. Therefore, our aim was to find a modern, open-wall dairy barn with cattle of over 50 cows and of course ability and interest to host our campaigns.

A commercial dairy barn which could meet these criteria was found from Pöytyä in the Southwest region of Finland (Figure 2). Arvela dairy farm has a new barn built in 2019. It is an example of a modern curtain-walled barn housing 240 cows. The animals are kept inside the barn for the entire year. The barn has natural ventilation with automated curtains walls to control the amount of inflowing air and 15 rigde chimneys for exhausting of the warmer air (Figure 3). Building dimensions were 33 x 91 meters. The animals are kept in the alcove, on a concrete floor (Figure 4). On the north-west corner of the barn there is also an alcove system covered with litter (long wheat straw) for pregnant and sick cows. The building was not heated and has 12 large fans inside the barn to mix the air (Figure 5).

The 240 cows in the barn were of 60% of Ayrshire and 40% of Holstein breed with typical milk production rate around 36 l/day. The cows were fed with grass fodder mixed with for example mash and rapeseed but which did not include any methane reducing additives. The feeding times were at 7 – 8 am and 5 – 6 pm. The cows had free use of the automatic milking systems and they could move freely around the barn excluding specific areas reserved for pregnant or sick cows. The manure was removed from the barn floors by an automated manure scrape, which moved through the length of the barn.

Figure 2. Orthophoto maps showing the location of Pöytyä dairy barn where the measurements were taken (Source: Google Maps).

Figure 3. Side walls of the Arvela dairy barn. Curtain walls are completely open in the for the main area, but closed for the area where pregnant cows are housed. Ridge chimneys are also visible.

Figure 4. Inside view to the Arvela barn.

Figure 5. Example of a large fan mixing the air inside the Arvela barn.

2.2 MEASURING TECHNOLOGY

2.2.1 MEASUREMENT TECHNOLOGIES AEROMON BH-12

Due to its modular design, the BH-12 can measure multiple target parameters (gases, particulates, and noise) with a wide range of sensor combinations fulfilling the customer's requirements. The BH-12 pumps sample air through its several sensors. Lightweight design of the device makes it highly versatile and suitable for hand-held or portable use with e.g., drones. In addition to measuring concentrations of target compounds, the device continuously measures its position, altitude, time and sample RH%, temperature and pressure and transmits data in real time to data storage, visualization, and reporting software Aeromon Cloud Service (ACS). BH-12 transmits one measurement point per second; hence the data acquisition frequency is 1 Hz.

Sensors for specific target compounds are selected based on comparative testing of sensor components from various manufacturers in both controlled and field conditions. Today, Aeromon procures state-of-the-art sensors from 6 different leading sensor developers and manufacturers.

2.2.2 USED SENSOR TECHNOLOGIES

Sensor technologies for each compound are presented below in Table 1. The technology principle for each sensor is also briefly explained. Used technologies are the best available for each target compound. The sensors used are provided by the leading manufacturers in the world and integrated to be used in Aeromon BH-12 measurement setup by Aeromon. For all measured compounds, cross effects with other measured compounds are compensated in analysis phase if they are present.

Our methane and ammonia sensors use laser-based absorption technique, Tunable Diode Laser Spectroscopy (TDLS). TDLS is a common technology used for detecting concentration in gaseous mixtures that enables low detection limits. Our methane and ammonia sensors are highly selective.

Our carbon dioxide sensor is a Non-Dispersive Infrared sensor (NDIR). NDIR's are spectroscopic sensors commonly used in gas detection purposes. Carbon dioxide's detection limit is 20 ppm over the background concentration defined on site by Aeromon personnel.

Nitrogen dioxide and hydrogen sulphide are measured with Electrochemical (EC) sensors. Electrochemical sensors produce an electrical signal proportional to the target gases concentration.

Table 1. Sensor technologies for measured compounds.

Target compound	Calibration gas	Calibration gas uncertainty	Detection limit	Sensor technology
Ammonia (NH_3)	NH_3 10 ppm	10 %	0,1 ppm	TDLS
Hydrogen sulphide (H_2S)	H_2S 10 ppm	10 %	0,05 ppm	EC
Carbon dioxide (CO_2)	CO_2 5000 ppm	10 %	20 ppm over background	NDIR
Nitrogen dioxide (NO_2)	NO_2 10 ppm	10 %	0,05 ppm	EC
Methane (CH_4)	CH_4 1000 ppm	10 %	0,2 ppm	TDLS

2.2.3 DATA COLLECTION

If the BH-12 is transported by a drone, the sample is always taken outside the propeller air flow, either with a 1 m long rigid probe always pointing towards the prevailing wind direction or with a 10 m long inert hanging sample line with its end outside the area of influence of the down wash. Sample tubing material is Fluorinated ethylene propylene (FEP). Typical sampling range by drone is from 5 to 150 m at altitude and we always apply the flight permits to cover +30 m from the known source altitudes. Normal measurement distance from the source starts from 5 m to 250 m depending on the measurement task and source features. These sample intake options have been tested in field conditions and validated for performance in several reference measurements. Also, the hanging sample line is in accordance with US EPA OTM-51 (UAS/Drone Application of Method 21 for Surface Emission Monitoring of Landfills).

In this project, majority of the result were collected with an extendable pole and attached long sample line to collect data about methane concentration inside the cow shelter. This data collection method enabled collecting data with a height information, providing additional information about the lateral distribution of methane.

2.2.4 METHODOLOGIES USED FOR DATA COLLECTION AND ANALYSIS

2.2.4.1 CONCENTRATION MEASUREMENTS

The sensors selected for use are calibrated and their operation is always checked at least at the beginning and end of the measurement campaign. The calibration gases are certified and traceable. Wherever possible, gases certified with ISO 6142 from manufacturers with ISO 17034 accreditation are used. Sensor span level check is also conducted when measurement conditions change during the measurements or field operatives have any reason to suspect non-conforming sensor behavior.

Furthermore, all BH-12 devices and sensors are tested regularly (every 6 months) in controlled conditions for correct performance and output.

2.2.4.2 FENCE LINE MEASUREMENTS

Emission fence line measurements are carried out to understand the dispersion of emissions and to identify the emissions which are transported to investigated areas from outside. In emission fence measurements, the wind speed should be between 2 and 10 m/s to ensure that emissions are transported coherently in each prevailing direction. In emission fence measurements, the same measurement line is repeated at several different altitudes, starting from below the emissions and the highest measurement lines are measured above the emissions. The altitude difference between the measurement lines is typically between 1 and 10 m. Fence line measurements are also well suited for emission mapping for sites with no-fly zones, e.g., because of EX restrictions such as in refineries. In this case, measurements can be made along the edges of EX areas, unless a temporary fire work permit is obtained for operating within the areas. Also with emission fence measurements, as in emission mapping, the spatial resolution (grid size) of the reporting is pre-selected. During the measurements we collect at least 10 measurement points in each grid cell.

2.2.4.3 STATIONARY MEASUREMENTS

For stationary measurements weather cabins can be installed to a fixed location to protect the measurements device while point source measurements are conducted for several days or weeks at a time. In these measurements a long, heated sample line is used to avoid condensation on the sample line. This technique can be used to measure methane concentration from one point for long periods of time and is used in this project to monitor the cow shelter methane levels for several weeks. The data quality is monitored remotely. Filter changes and regular checks on the device and its performance level are done at a minimum of every 2 weeks. The used technology is the same that was utilised in other monitoring techniques during the project.

2.2.4.4 QUANTIFICATION OF MASS FLOWS

When we detect a plume during emission mapping or fence line monitoring, we either return to measure it separately for mass flow analysis or measure it immediately separately for mass flow analysis and continue mapping thereafter.

Mass flow analysis can be conducted through Mass Balance (MB) method. The MB method is based on a direct measurement of local wind field speed and target gas enhancement above ambient background in all the measurement points in the upwind and downwind measurements. Using target gas molecular masses, these combined wind and concentration measurements can be translated into mass flows.

Local wind and weather conditions are measured with fixed (Vaisala WXT, 2D wind measurement) and onboard (Trisonica Mini, 3D wind measurement) weather stations for the reliable performance of MB.

Measurements are conducted both upwind and downwind from source areas. These upwind and downwind measurements are conducted consecutively or simultaneously. Aeromon mass flow analysis can be utilized for all source types, point and area sources.

The measurements are performed almost similarly to emission fence line method, but with a very dense height spacing between measurement lines. The mass flow measurement approach is visualized in Figure 6. Reference measurements are done upwind of the source area to understand the background concentration level over which the emission from the measurement source is spread. For each detected plume, the local background below, above and on sides of the plume is considered. The upwind reference measurement is identical to the downwind measurement. In case the wind direction changes during the measurements, the upwind and downwind measurement lines are adjusted accordingly. Also, in cases where source location might be difficult to identify with one wind direction, we can measure these areas with another wind direction to enable more accurate pinpointing of approximate source location.

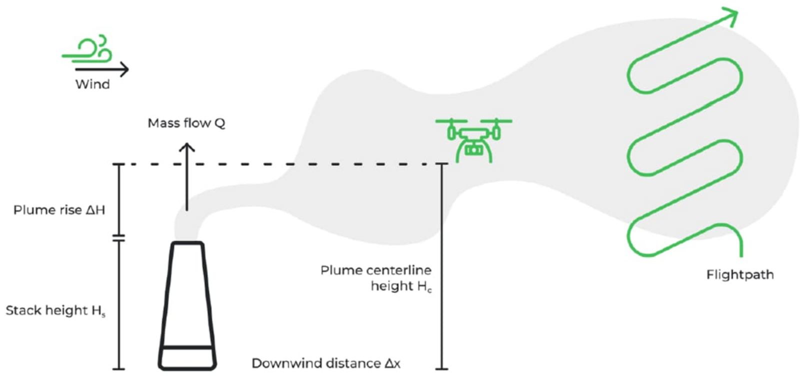

Figure 6. Schematic view to mass flow quantification measurement approach.

Figure 7. An anemometer on the roof of the drone.

Mass flow analysis requires the wind speed to be between 1 to 15 m/s, with optimum conditions of 2 to 10 m/s. The stability of the wind during the measurement is directly transmitted to the uncertainty of the result. Measurements of source dilution are optimally performed between 20 and 250 m from the source to allow the emission to form a typical spatial distribution (x, y, z). We can determine the mass flux of target compounds with an uncertainty of 30% in good and stable conditions. The uncertainty of the mass flow result is based on varying weather conditions during plume detections repeatability of plume concentration profile during several transects and detected concentration levels in relation to system detection limit.

2.3 METHODOLOGY OF THE MEASUREMENTS

As previously mentioned, we conducted emission monitoring campaigns during both winter and summer seasons. In both cases, three different approaches were employed to:

1. Identify areas where methane and other impurities could potentially accumulate and study their spreading within the barn.
2. Understand spreading of these emissions from the barn to the surrounding environment.
3. Monitor methane concentration levels for a longer period of time.

In the following text, we will refer to these three methods as:

1. Inside Area Mapping
2. Outside Area Mapping
3. Long-term Monitoring of CH4

Each of methodology is explained in the following chapters to provide a better understanding of the results and their interpretation.

2.3.1 INSIDE AREA MAPPING

The aim of the inside area mapping was to identify the areas where methane gas could potentially accumulate and spread within the space. The hypothesis was that methane could be more strongly located to specific areas, for example around feeding stations, or that the airflow inside would lead to formation of some accumulation points. During the inside area mapping, the concentration of methane and other impurities (H_2S, NH_3, CO_2, and NO_2) was measured manually at three different heights (2 m, 4 m, 7 m) by moving the device and telescopic arm with a sample line along the corridors of the barn (Figure 8). These measurements were repeated twice during day. Cows were present inside the barn throughout the measurements. Figure 9 shows the layout of the barn, as well as the measuring levels and the travelled route. The measurement levels and route are illustrated with purple lines. The travelled route was timestamped with GPS to create a mapping of the measurement points. As these measurements required on-site personnel, they were only conducted on specific days during daytime.

Figure 8. Lefthand side: Aeromon employee during indoor measurements holding a telescopic arm with a sample line and the measuring device. Righthand side: Picture of the Aeromon BH-12 measuring device. Figure reprinted with the permission of Aeromon Oy.

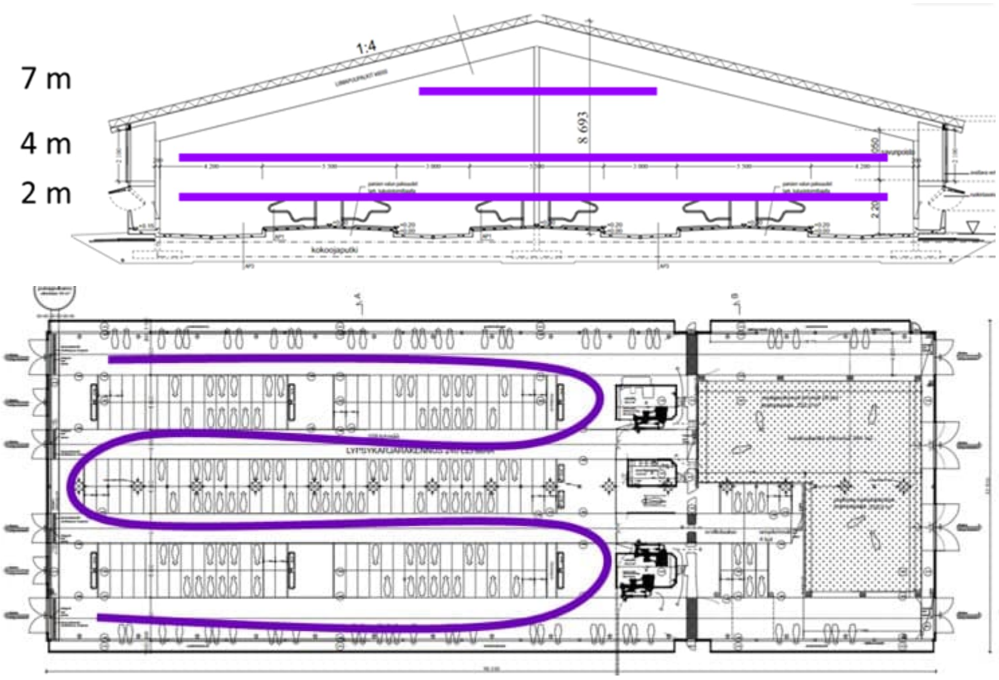

Figure 9. Barn layout showing the three different measuring heights (top) and the path travelled around the barn (bottom), both indicated by purple lines, where impurities were measured during mapping of the inside area.

2.3.2 OUTSIDE AREA MAPPING

Outside measurements were used to map the dilution of target gases (CH_4, H_2S, NH_3, CO_2, and NO_2) into the surroundings. Spreading of these gases was measured in the same way as for inside area mapping, i.e., carrying the measuring device in hand while walking next to the barn and taking samples with sample line connected to the telescopic arm, and with a drone that was used to transport the measuring device around the barn and over its rooftop to access ridge chimneys (Figure 10).

Figure 10. Lefthand side: Flight assisted measuring on the emissions using drone. Righthand side: Picture of Aeromon employee during outdoor measurements holding a telescopic arm and the measuring device.

2.3.3 LONG-TERM MONITORING OF CH_4

After completing the mapping of both the interior and exterior of the barn, two measuring devices were placed in fixed locations to monitor methane emissions for a period of 2–3 weeks. During the monitoring period, only the concentration of methane was measured. The positions of the devices were determined based on the inside measurements. The first measuring device was placed in the middle of the barn to a height of 3 m and the second one was positioned inside a ridge chimney at the south-end corner of the barn. The air sample was drawn to a measuring device via heated sample line to avoid water condensation. Positions of the two devices and heated sample lines (red dashed line) are shown in Figure 11.

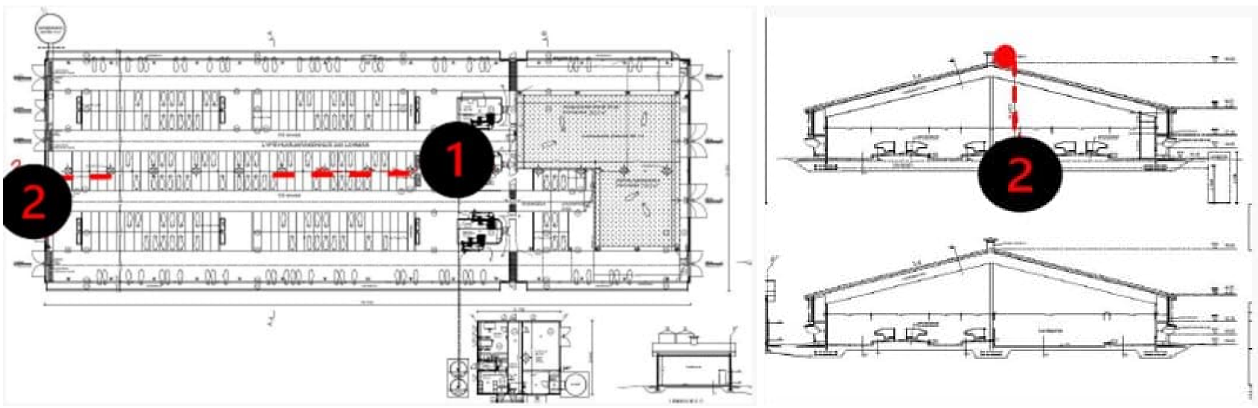

Figure 11. Barn layout illustrating the positions of the two fixed measuring devices during long-term measuring of CH_4 emissions.

2.4 AIR FLOW MEASUREMENTS

As a part of the measuring campaigns, we also conducted exhaust air flow measurements from the barn ridge chimneys. The purpose of these measurements was to create supplementary data for modelling work done in WP5 (DU). Air flow velocities were measured by VTT on two consecutive days, 14.3. – 15.3.2023, during the winter campaign.

2.4.1 RIDGE CHIMNEYS AT BARN SITE

In barns that rely on natural ventilation, such as Pöytyä, the amount of air that flows in and out is determined by the difference in temperature between the inside and outside of the barn. Warm air is expelled through the ridge of the barn, while fresh air is naturally drawn in through ventilation panels or curtains (as shown in Figure 1). To maintain a consistent inside air temperature of around 5°C, which is optimal for milk production and animal welfare, the openings of the curtain walls and flaps inside chimneys (as shown in Figure 12) are automatically adjusted according to the indoor and outdoor temperature and weather conditions. Pöytyä barn is equipped with automated curtain walls on each side of the barn for air intake, and 15 covered ridge chimneys for air exhaust (as shown in Figure 13). Each chimney measures 900 mm x 900 mm in size and had a chicken wire with a mesh size of 20 x 20 mm inside them for bird-proofing.

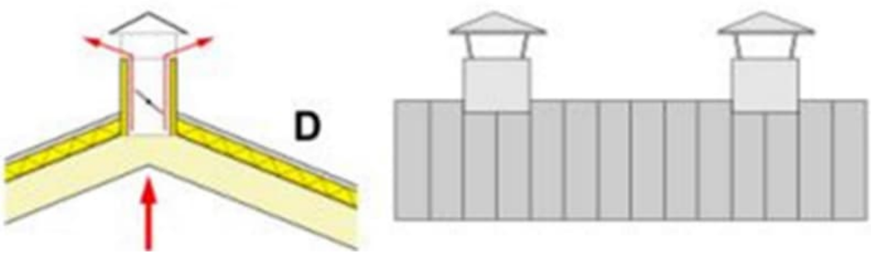

Figure 12. Scheme of the covered ridge chimney with automated flaps [1]. Similar structures are found in Pöytyä dairy barn.

Figure 13. Picture of Pöytyä dairy barn and VTT worker conducting the air flow measurements on rooftop of the barn.

2.4.2 METHODOLOGY

The air flow velocities of the exhausted air were measured by taking manual measurements from each chimney twice a day. A hot wire anemometer (Testo 435-3, HVAC multifunctional measurement instrument) equipped with a hot wire probe head and a telescopic handle was used as measuring tool. The hot wire probe was capable of measuring velocities from 0 to 20 m/s with an accuracy of ±0.03 m/s + 5% of the measured value. Due to a relatively large size of a chimney, the measurements were taken inside the chimney from nine different points (Figure 14). To take the measurements, the probe head was pointed approximately 15 cm below the chimney top, and air velocity readings were taken for five seconds at each point. The variation in readings was typically between 0.05 m/s to 0.2 m/s, depending on the wind conditions at the time of measurement. The measured average velocities at each point were then used to estimate the average velocities (and flow rates) for each chimney. The exhaust air temperature was also measured with the same hot wire anemometer.

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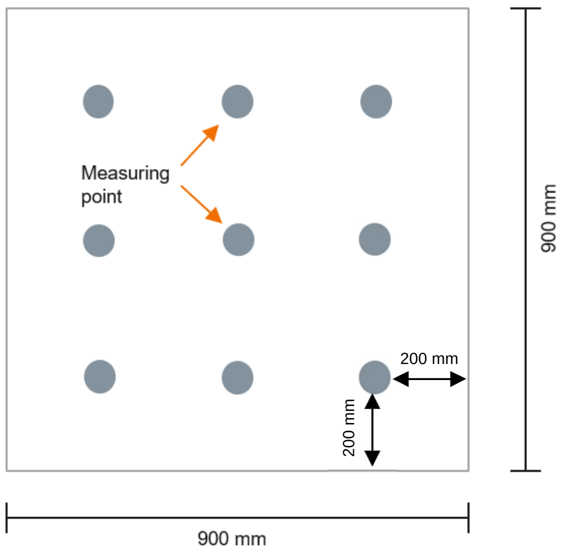

Figure 14. Measuring points inside a ridge chimney.

3 RESULTS

The following text describes the main outcomes of the emission monitoring campaign. In chapters 3.1 and 3.2, the manually measured CH_4 concentrations from both inside and outside the barn are presented, and the results for the winter and summer campaigns are compared. Chapter 3.3 presents the detected CH_4 concentrations during long-term measurements in the two seasons. The measured concentrations of other impurities (H_2S, NO_2, NH_3, and CO_2) are gathered in section 3.5. Finally, Chapters 3.6 and 3.7 contain the supplementary data from air flow measurements and estimations of the CH_4 mass flows from the barn to the environment.

3.1 INSIDE AREA MAPPING

Area mappings of the target gases were done manually, meaning that the measuring device and sampling system were carried in hand and moved along the barn corridors. During outside area mapping, also drone was used to access rooftop and ridge chimneys from above. For more detailed description of the used methodology, please see to Chapters 2.2 and 2.3 The main results of the area mapping are presented as choropleth maps (e.g., Figure 15), where the detected CH_4 concentrations are placed over a satellite image of the barn. The color scales of the maps vary between the images, especially between the two seasons, and the color scales have been chosen so that they best represent the results. In the maps, the transparency of the colors reflects the number of measurement points, meaning that darker areas have more datapoints.

As described previously, inside and outside area mappings required on-site personnel and were thereby done on specific days during working hours. Measurements were done twice a day. For winter campaign there were 6 days when these manual measurements were conducted and in the summer period 4 days were used for mapping of the target gases. In naturally ventilated barns, such as Pöytyä, temperature difference inside and outside the barn (and also wind conditions) dictates the opening position of automated curtainwalls for fresh air intake. This was also expected to have an impact on the concentrations of methane and other impurities within the barn, and their spreading to the surroundings. The prevailing weather conditions for each day of area mapping, along with the visual observation made about the opening degree of the wall-curtains, was collected by Aeromon using their own portable weather station located on the barn site.

3.1.1 MEASUREMENTS AT DIFFERENT HEIGHTS

Methane levels were measured from three different heights, 2 m, 4 m, and 7 m to study spreading and mixing of the gases inside the barn and to locate potentially concentrated areas. Figure 15 shows the measured concentrations per height on 6th February, 2023 from the two measuring rounds. The two measuring rounds were executed in the same way, covering the corridors of the barn's interior at three different heights. We note that at 7 m, it was not possible to cover the outermost corridors of the barn, because the structures prevented the use of the telescopic arm at its highest point. On that day, the average outside temperature was −1°C and the curtain-walls were 50% open.

According to the measurements, there was no significant difference in the CH_4 concentrations between 2 – 7 m, which indicated the barn air and thus methane is well mixed inside the barn. In addition, there was no clear difference between the corridors in terms of measured concentrations. On 6.2.2023, the methane levels varied from 0 to 80 ppm, and the average concentration of the two measuring rounds was between 40 and 60 ppm. We note that in Figure 15, the traveled path seems to have moved somewhat outside the barn. This was due the variation of the GPS signal level as the measurements were done indoors and therefore affecting to the strength of the signal. As a result, the locations of different corridors in some of the pictures may seem to have shifted.

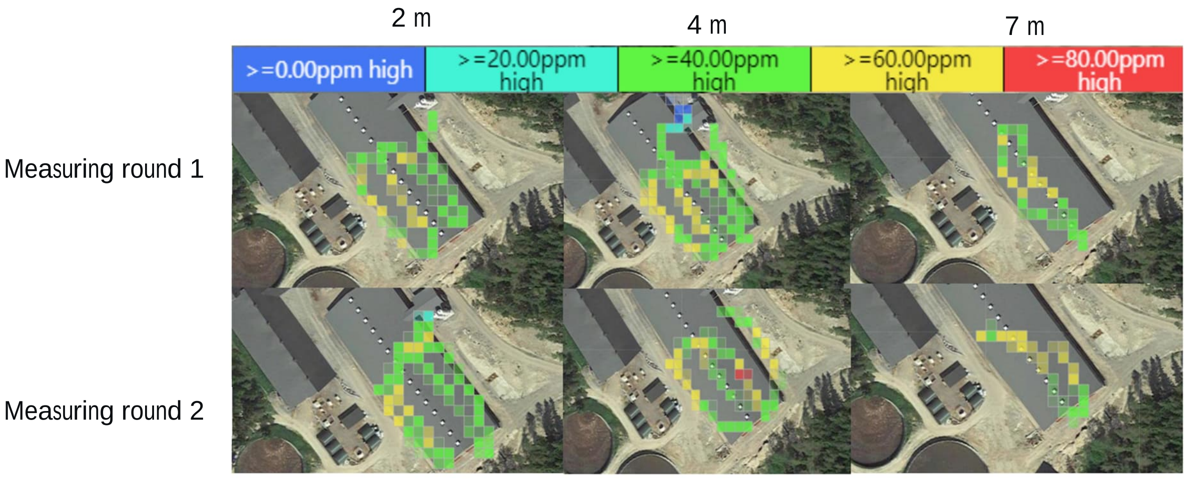

Figure 15. Detected CH4 concentrations (ppm) on 6th February 2023. Measurements were done manually twice per day and from three different heights (2 m, 4 m, and 7 m).

3.1.2 EFFECT OF THE WEATHER CONDITIONS ON THE METHANE LEVELS INSIDE THE BARN

As described previously, the amount of vented air from the barn is dictated by the weather conditions. We knew that the outside temperature and wind conditions affect to the position of automated curtainwalls, which were the main source of controlling air intake. According to barn owner, on warmer days (above 0 °C) the wall-curtains of the barn are typically completely open, whereas below -8 °C they are automatically fully closed.

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Figure 16 shows the measured methane concentrations from winter campaign and on three consecutive days when the weather conditions and therefore opening of the wall-curtains varied. Please note that the daily concentration data overlays all datapoints from three different heights. Lighter shade of a color refers to less datapoints. On 18th of January, the outside air temperature was 2 °C and the curtains were fully open to lower the temperature inside the barn. According to the measurements done on 18th, the barn air was found to be rather diluted, resulting to an average CH_4 concentration of 0 – 20 ppm. In addition to dilution by intake air, the lower methane concentrations could result from the wind blowing the methane from inside the barn to surroundings in vertical direction. On 19th and 20th, the outside air temperature was 0 °C or below and the opening degree of curtains varied from 50 to 75% open. On colder days, the concentration inside the barn increased up to 80 ppm.

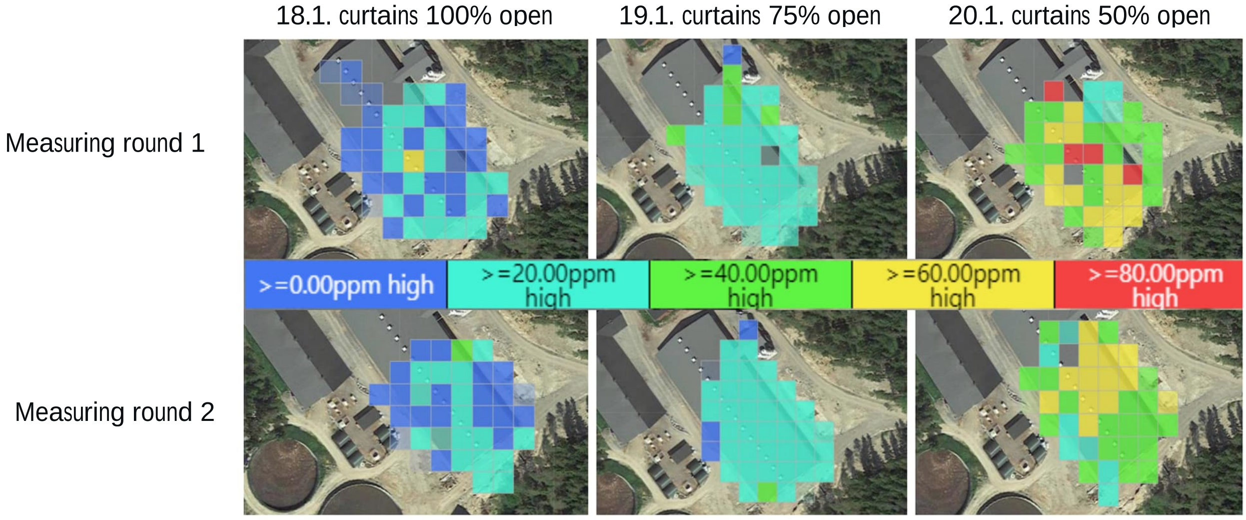


Figure 16. Detected CH_4 concentrations (ppm) during winter campaign between 18th and 20th of January 2023. Main difference between images is the opening degree of wall-curtains. Data includes measurements from three different heights.

3.1.3 METHANE LEVELS IN SUMMER CONDITIONS

During the winter campaign, it was observed that the methane levels inside the barn were affected by the position of the wall-curtains. Based on this observation, it was expected that during summertime when the curtains were completely open, the concentrations of methane would be overall lower. In winter, the average methane concentration was measured to be around 50 ppm. In summertime, the methane concentration varied between 0 – 20 ppm and the average CH_4 level was approximately 5 ppm. These results were found to be consistent with the data obtained in winter with fully open curtains. Figures 17 and 18 represent winter and summer campaign data for days with fully open curtains. Note that the scales in Figures 17 and 18 vary from each other. It is also important to mention that at Arvela dairy barn all cows remain inside through the summer.

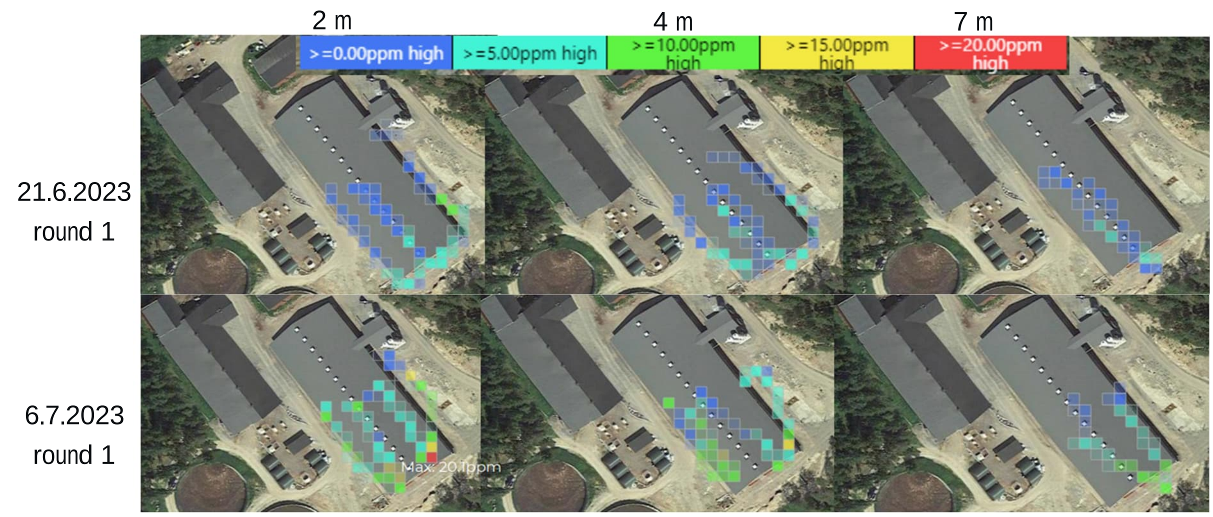


Figure 17. Detected CH4 concentrations (ppm) during summer campaign on 21st of June and 6th of July 2023. Curtains were fully open.

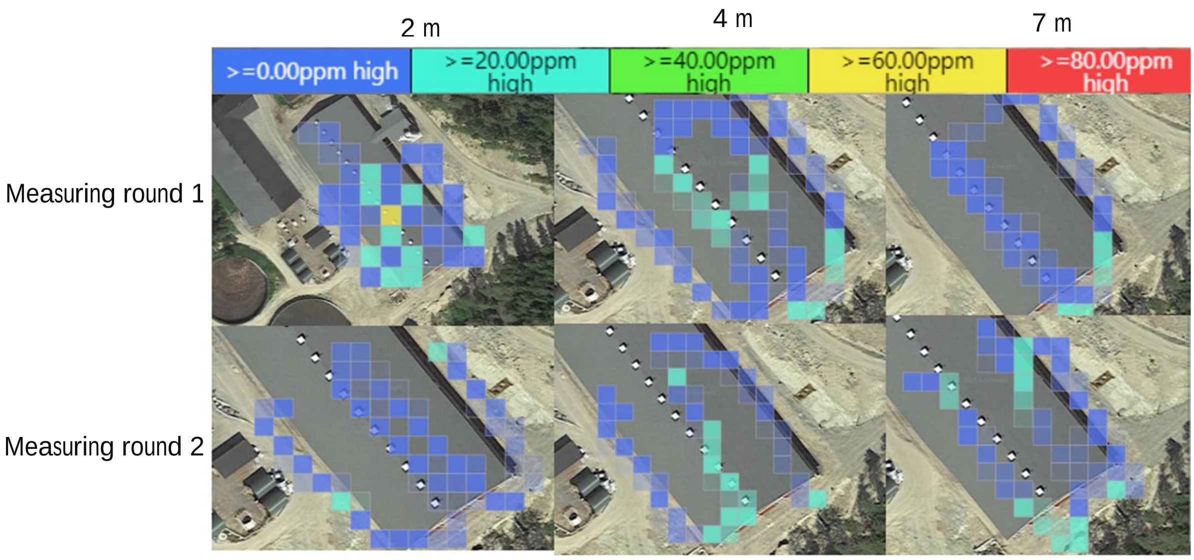


Figure 18. Detected CH4 concentrations (ppm) during winter campaign on 18th of January 2023. Curtains were fully open.

3.1.4 MEASUREMENTS FROM THE COVERED ALCOVE AREA

Measurements from area designated for pregnant and sick cows, where also the number of animals was lower, was conducted. The measurements were taken at a height of 2 and 4 meters, and the results were compared to the average concentration detected in the corridors. Measured methane concentrations for the alcove during summer and winter campaign is showed in Figures 19 and 20. The study verified our previous observations made about the air mixing inside the barn, and that the methane concentration is consistent regardless also of the number of cows in the area, and not only of the height. For example, on 20.1., the mean CH_4 concentration measured in the alcove area was found to around 40 ppm (Figure 19), which correlated well with the data from the corridors (Figure 16).

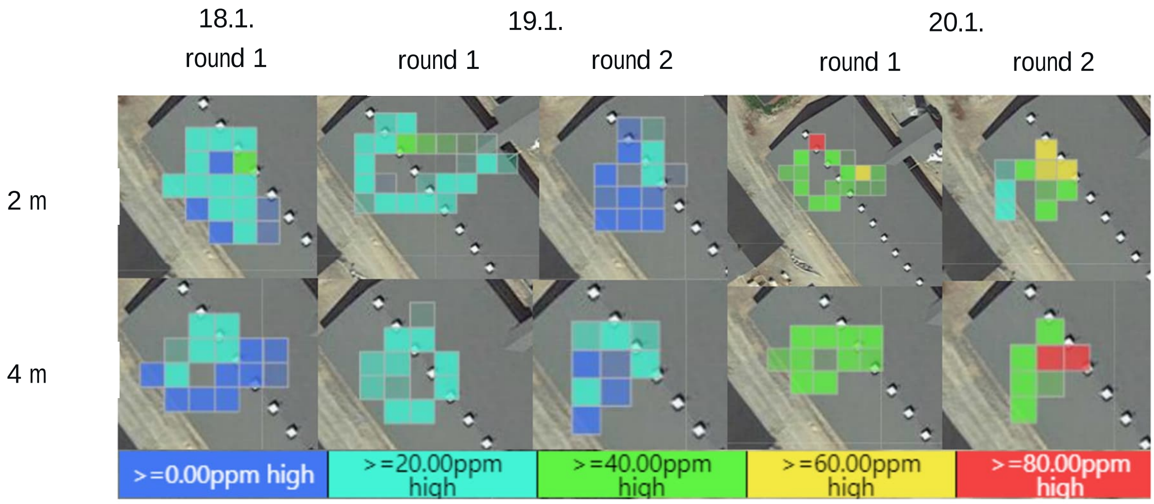


Figure 19. Detected CH_4 concentration (ppm) from the alcove area reserved for sick and pregnant cows. Measurements were taken during inside area mapping (winter) with curtains fully open.

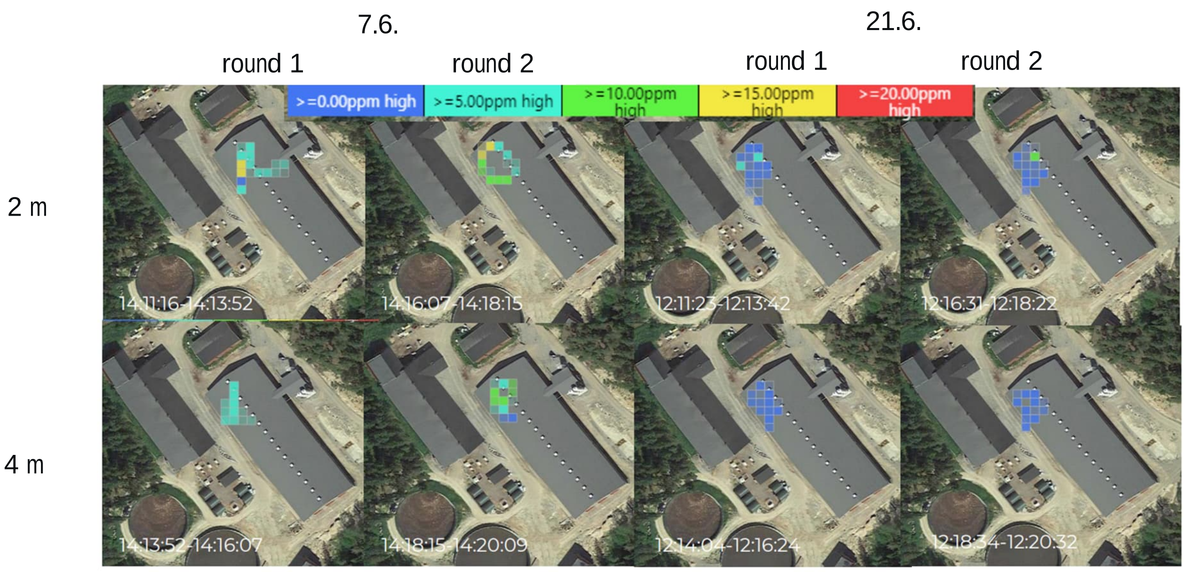


Figure 20. Detected CH_4 concentration (ppm) from the alcove area reserved for sick and pregnant cows. Measurements were taken during inside area mapping (summer) with curtains fully open.

3.2 OUTSIDE AREA MAPPING

The manual measurements were conducted to track the spreading of methane and other impurities to the environment outside and over the barn. To do this, a hand-held measuring device was used, which was transported next to the barn exterior at different heights. The barn ridge chimneys and rooftop were accessed using a sample line with a telescopic arm and drone. Figure 21 shows the CH_4 emissions measured close to the barn exterior on 18.1. and 2.2 using the drone, as well as the wind direction at the time of measurement.

Similarly, Figure 22 shows the detected CH_4 concentrations measured from the barn exterior during the summer season. According to the measurements, there was no specific direction identified where methane would spread or be transported to. Instead, this was affected by the prevailing weather conditions. Further measurements were taken over the ridge chimneys and from the nearby surrounding (forest and road area) to study the methane spreading. Figure 23 shows the results of these measurements. Please pay attention to the scales.

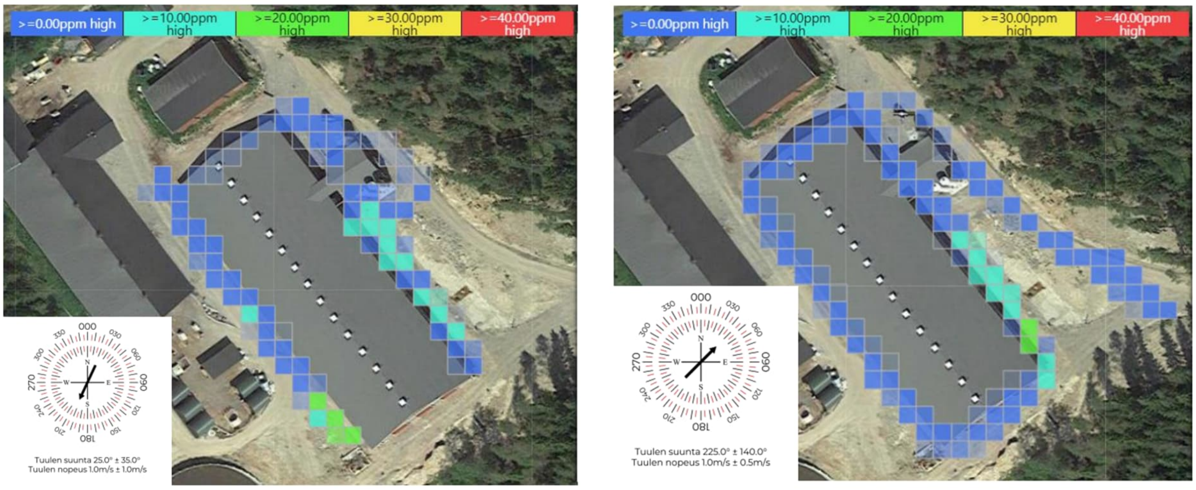


Figure 21. Methane concentrations measured close to the barn exterior on 18.1. (left) and 2.2 (right). Measurements were done with drone from 2 m, 5m, and 8m, and the data is overlapped for the Figures. Direction of the wind is marked to the Figures.

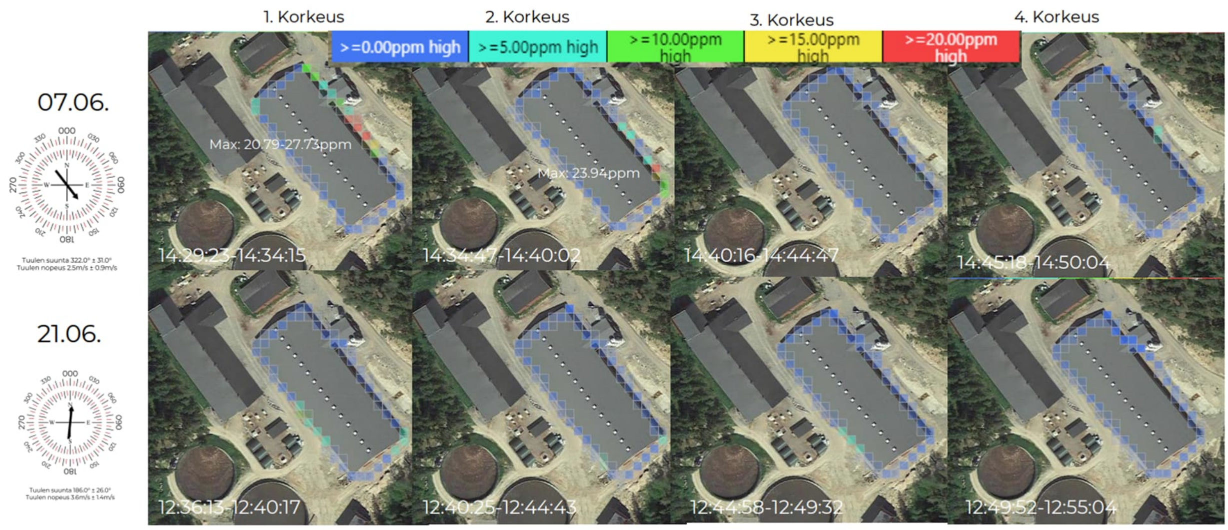


Figure 22. Methane concentrations measured close to the barn exterior on 7.6. and 21.6. Measurements were done with drone from 2 m, 5m, and 8m, and the data is overlapped for the Figures. Direction of the wind is marked to the Figures.

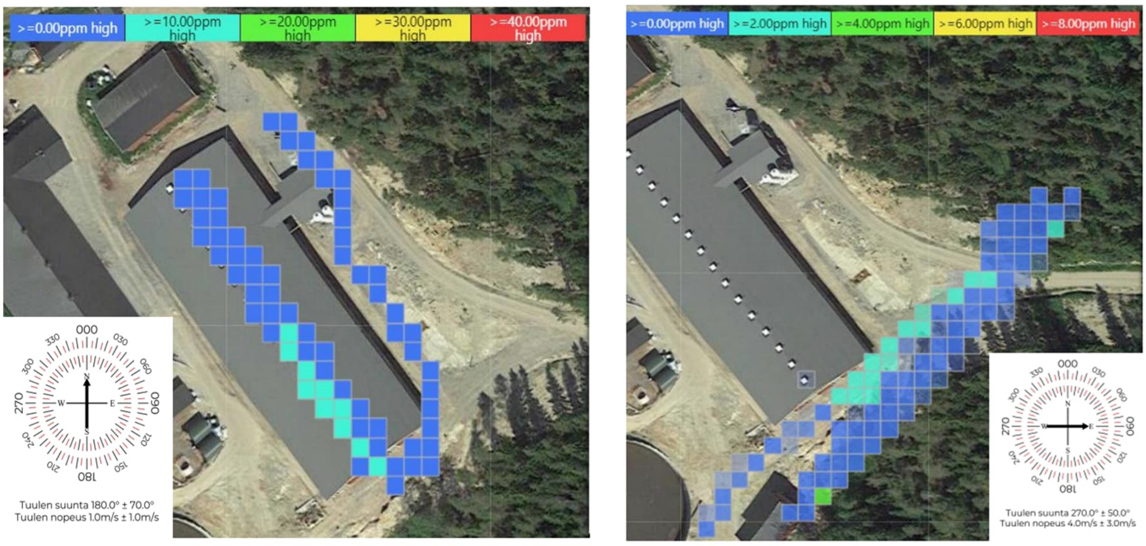


Figure 23. Left hand side: CH_4 concentrations measured above the ridge chimneys (20.1.2023). Right hand side: Spreading of the methane to the surroundings (3.3.2023). Both measurements were drone assisted.

3.3 LONG-TERM METHANE MONITORING

As described earlier in section 2.3.3, two measuring devices were monitoring the barn air for long-term analysis both during winter and summer season. The main findings are presented in the following Figure 24 - Figure 31. The raw data from the monitoring devices contained methane concentrations of every second during the entire length of the measurement time. To allow easier handling of the data, an average over every operational hour was calculated, which reduced the number of datapoints significantly but also reduced the level of details likewise. To look more in detail the changes in the methane concentrations, specific time periods are also presented representing both high-concentrations periods and low-concentration periods.

As the outside temperature determined the opening of the curtain walls and thereby affected the methane concentration inside the barn, the outside temperature was compared with the measured methane levels. Reliable data for the local temperature at Arvela barn was not available. Instead, open-source data from the Finnish Meteorological Institute [2] was used. The closest official measurement point to the Arvela dairy barn was ca. 40 km south at the Turku Airport. The data frequency was one minute. It should be considered that the momentary temperature at Arvela barn can have been significantly different, but the overall temperature level and directions in the temperature changes have been similar.

Figure 24 and Figure 25 show the methane measurement during winter season inside the barn and in the ridge chimney, respectively. During the measurement period from 15th of February to 3rd of March, the temperature was about half of the time around 0 °C, more specifically between -2 °C and 4 °C. In the middle of the testing range, there was a colder period during which the temperature fluctuated between -14 °C and 0 °C. The first main finding from the long-term measurements was that the methane concentration followed the temperature changes especially during the colder period. The colder it was, the more closed the curtain walls were and the more methane remained in the barn.

The highest momentary peak of 178 ppm was measured by the device inside the barn on 27th of February at 6:11 am when the temperature outside had been below -10 °C whole night (Figure 27). This is very close to 200 ppm which was the estimated production of methane from cows. However, the momentary high peak does not give reliable description of the overall methane level in the barn. Therefore, the one-hour averages were calculated from the data. As can bee seen in the Figure 24 and Figure 25 the methane one-hour averages ranged between ca. 50 – 125 ppm during colder period. On warmer days when temperatures were at or above 0 °C, the methane one-hour averages remained below 50 ppm, although momentary values could reach up to 80 ppm.

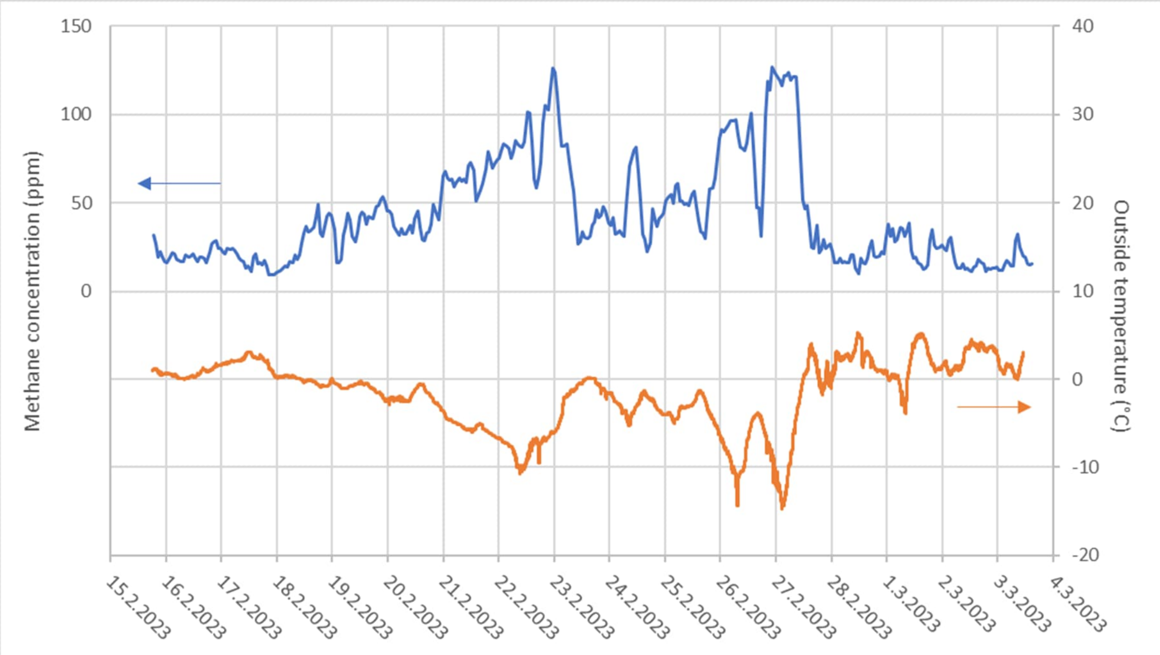


Figure 24. Wintertime long-term methane measurement ***inside the barn*** *compared to outside temperature from the nearest public recording place, Turku Airport [2]. The methane concentration shown here is an average over one hour of measurement.*

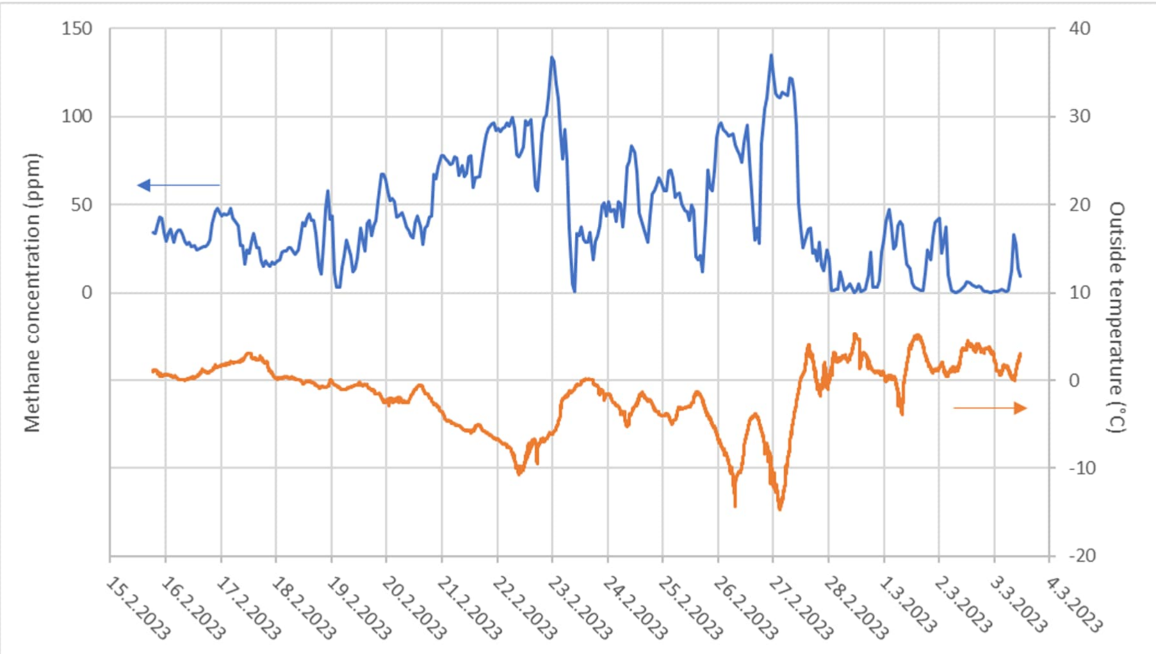


Figure 25. Wintertime long-term methane measurement in the ***ridge chimney*** *compared to outside temperature from the nearest public recording place, Turku Airport [2]. The methane concentration shown here is an average over one hour of measurement.*

Figure 26 shows the comparison of the devices measuring methane inside the barn and in the ridge chimney. The one-hour averages are mostly on the same levels, which indicates that the gas composition inside the barn mixes well and reaches the chimney without major losses. The occasional differences seen in the graph are not possible to explain reliably with the available data. They can be momentary differences, perhaps for example due to stronger wind, or simply within measurement error.

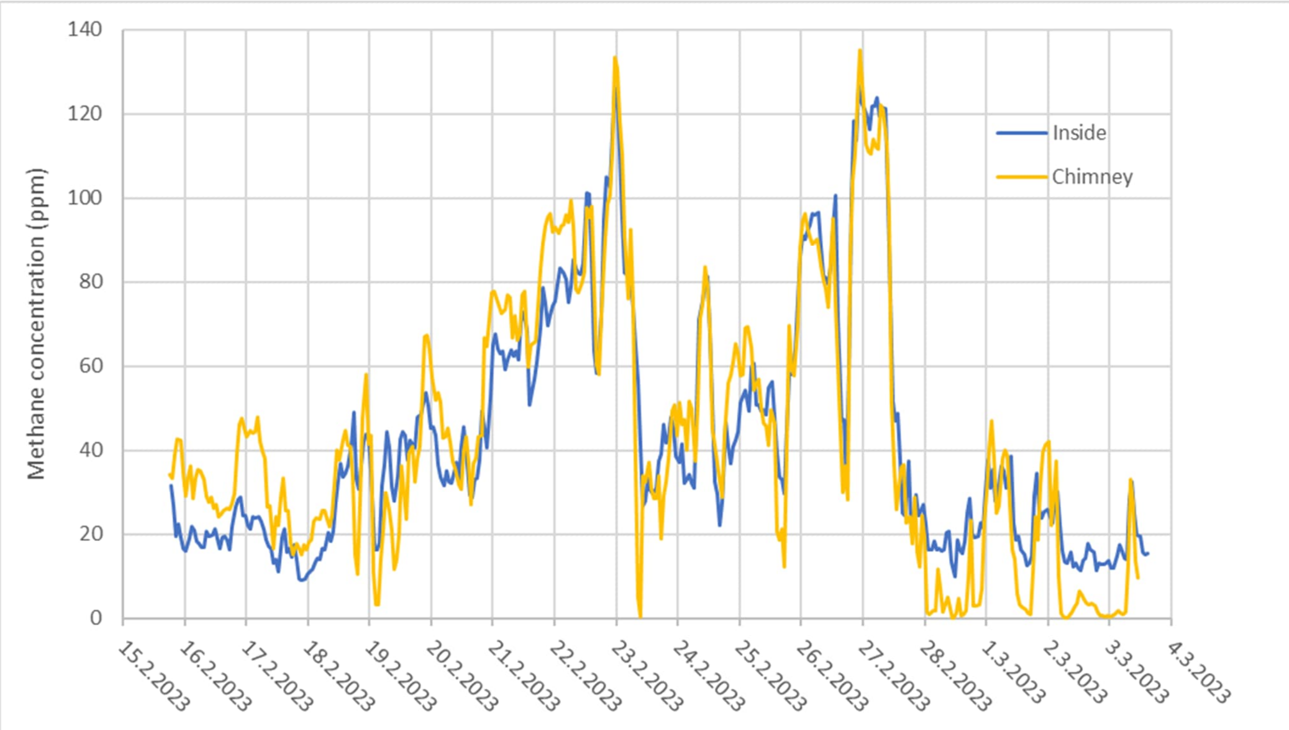


Figure 26. Comparison of wintertime long-term methane measurement inside the barn and in the ridge chimney. The methane concentration shown here is an average over one hour of measurement.

Figure 27 and Figure 28 show every measured data point (i.e. one per second) in both inside the barn and in the ridge chimney on colder period of 26. – 27.2. and warmer period of 28.2. – 1.3.2023. These Figures show that the highest momentary peaks are measured inside the barn. The methane levels at both measurement points are on same level and show similar trends, but especially on the warmest days the methane levels in the ridge chimney drop below the ones measured inside the barn. When the methane level inside the barn decreases to 20 ppm and below, the level in the ridge chimney is close to 0 ppm. On the warmest days the curtain walls have been completely open which has probably increased the sideways drift of the gas and thereby reduced the amount of methane reaching the ridge chimney.

Other observation which is visible in Figure 27 is that the level of methane is fairly stable around 125 ppm from the evening of 26th to the morning of 27th. During this period the temperature has also been at lowest, below -5 °C whole time. The curtain walls at Arvela barn are known to be fully closed when temperature outside reaches ca. -8 °C. Therefore, this stable period can be explained by the curtain walls being closed constantly through the night which has stabilized the atmosphere inside the barn.

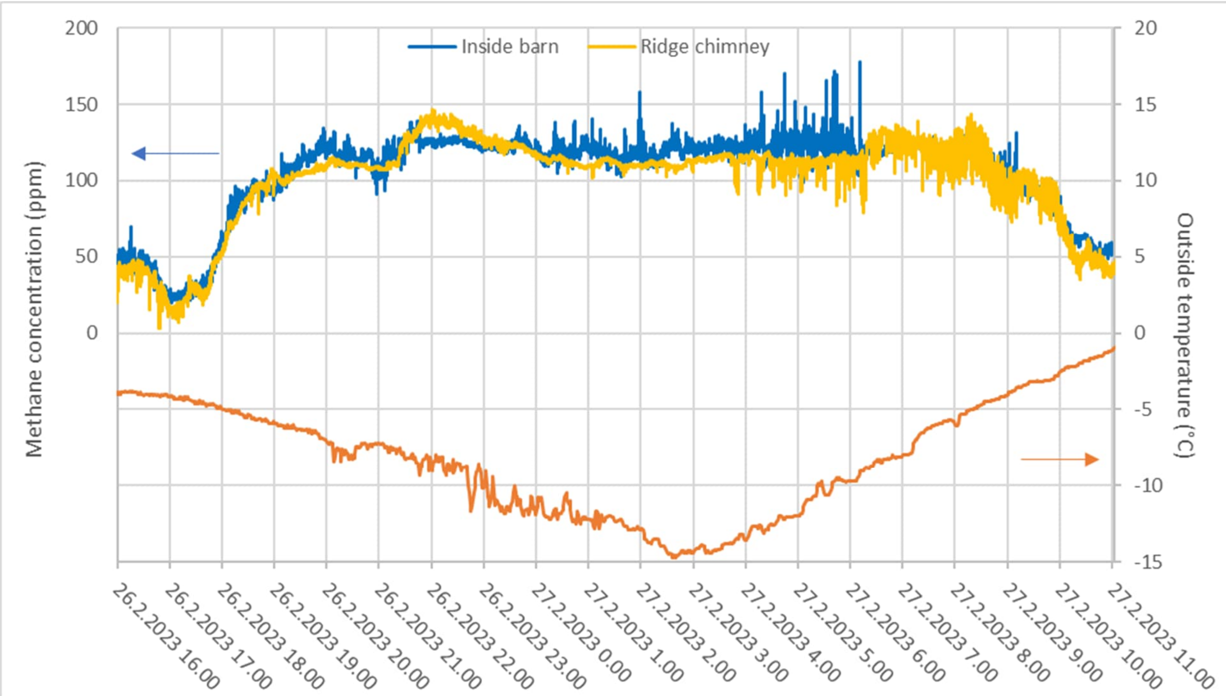


Figure 27. Wintertime long-term methane measurement in the ridge chimney and inside the barn compared to outside temperature from the nearest public recording place, Turku Airport [2]. Detailed look on 26. – 27.2.2023. The methane concentration is directly from raw data, showing one point per every second.

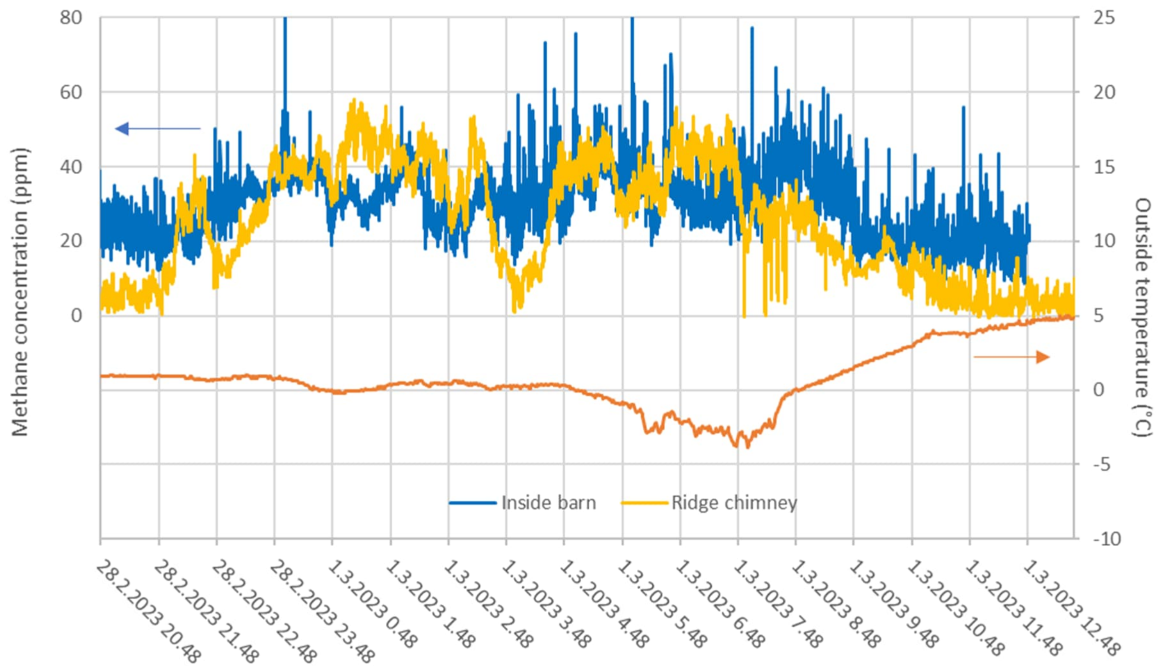


Figure 28. Wintertime long-term methane measurement in the ridge chimney and inside the barn compared to outside temperature from the nearest public recording place, Turku Airport [2]. Detailed look on 28.2. – 1.3.2023. The methane concentration is directly from raw data, showing one point per every second.

During the summertime the device inside the barn was measuring for bit over three weeks on the duration from 21st of June to 14th of July (Figure 29). The ridge chimney equipment was installed earlier on 7th of June due to practical reasons (Figure 30). The measurement was continued for five weeks and ended on the same day, 14th of July, as the other device. The temperature during this period was at or above 20 °C during daytime and the night temperatures were usually between 10 and 15 °C. The first few days in early June were colder, with temperatures remaining below 20 °C through the day and the coldest night temperature reaching momentarily 1 °C. Through the measurements the outside temperatures were sufficiently high to keep the curtain walls fully open.

The results from the summer measurements show patterns which were not observed during the winter measurements. The main reason for the difference was the fully open curtain walls, which removed the direct effect of outside temperature on the methane level inside the barn. Generally speaking, the methane levels during summer were between 5 and 15 ppm in the inside of the barn and between 5 and 25 ppm at the ridge chimney. Comparison of one-hour averages (Figure 31) shows clear difference between methane levels at the ridge chimney and inside the barn. This difference was not observed as strongly in the wintertime measurements. One-second data (Figure 32) shows that difference is strongest when the methane levels increase above 10 ppm. The concentration at the ridge chimney is more stable, while in the inside of the barn the concentration fluctuates more and sometimes momentarily peaks even above the concentration at the chimney.

During summertime the methane concentration had strong daily fluctuating patter which was not observed during wintertime. The methane level increases always during night while it seems to be at lowest at mid-day. The methane level at least seemingly correlates with the temperature, but as the curtain walls have been completely open, no direct conclusions can be drawn. It is also possible that the cooler summer nights are more suitable for cows and affect thereby the methane production. Feeding times at Arvela barn were 7 – 8 am and 5 – 6 pm, so they don't either directly correlate with the methane formation.

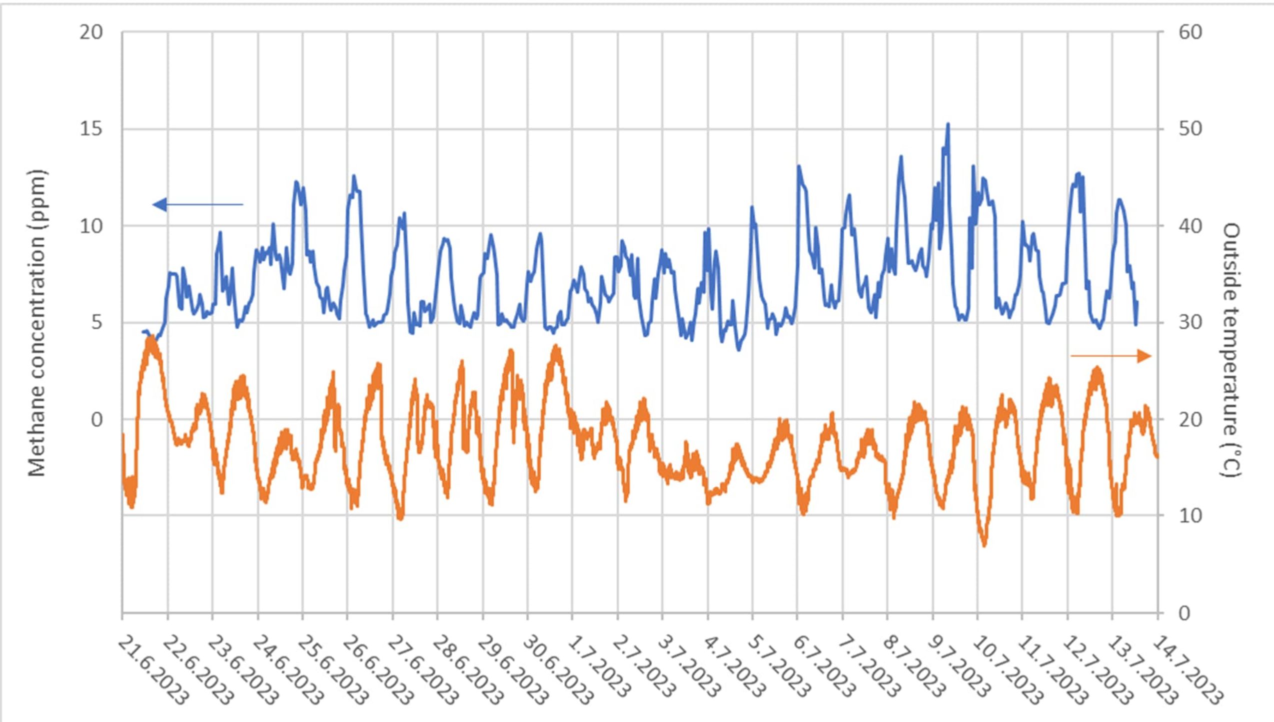


*Figure 29. Summertime long-term methane measurement **inside the barn** compared to outside temperature from the nearest public recording place, Turku Airport [2]. The methane concentration shown here is an average over one hour of measurement.*

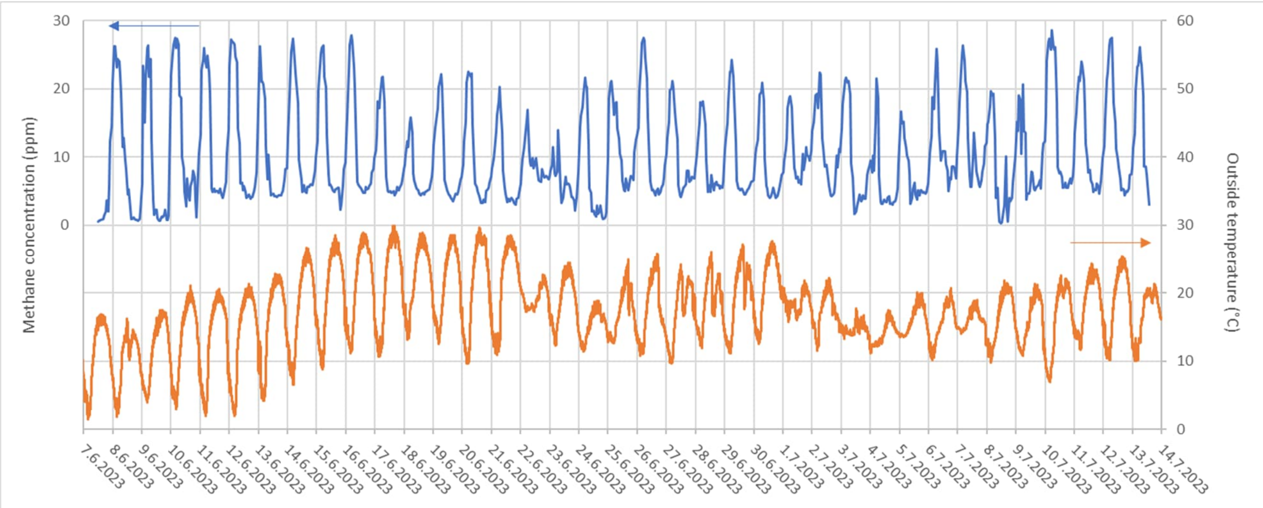


*Figure 30. Summertime long-term methane measurement from the **ridge chimney** compared to outside temperature from the nearest public recording place, Turku Airport [2]. The methane concentration shown here is an average over one hour of measurement.*

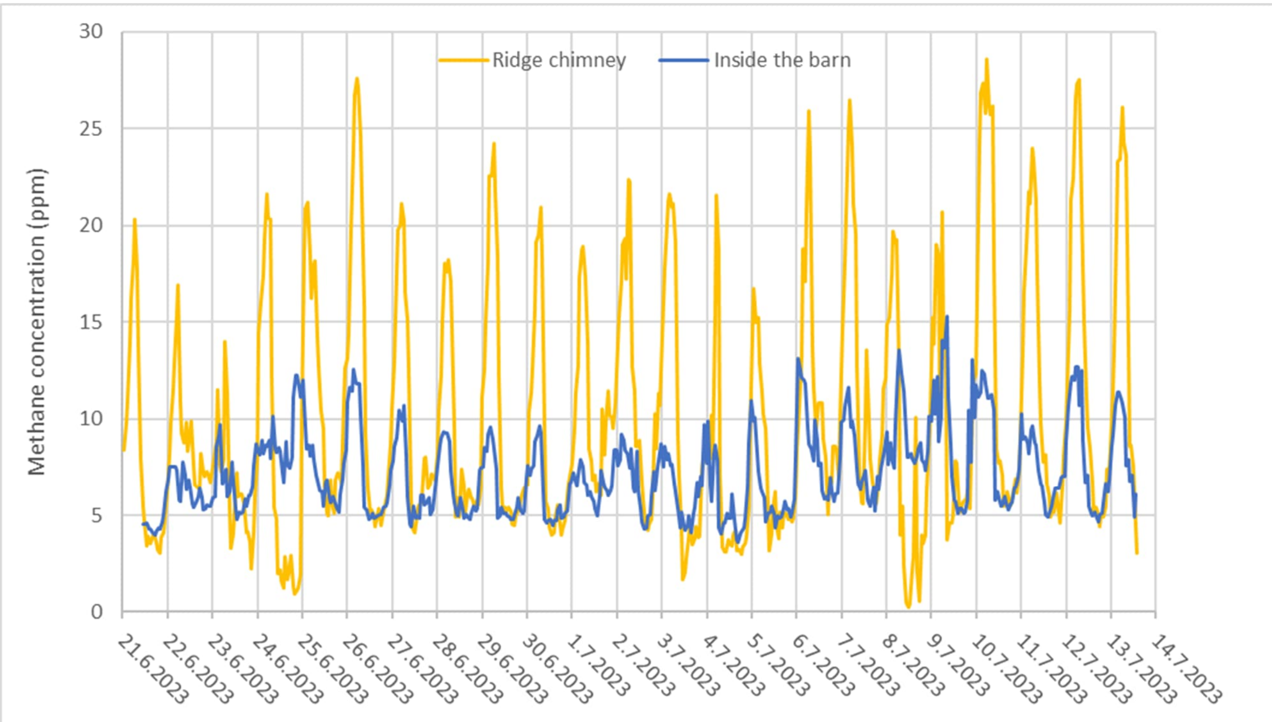


Figure 31. Comparison of summertime long-term methane measurement inside the barn and in the ridge chimney. The methane concentration shown here is an average over one hour of measurement. The comparison is for the duration when both devices were in use at the same time.

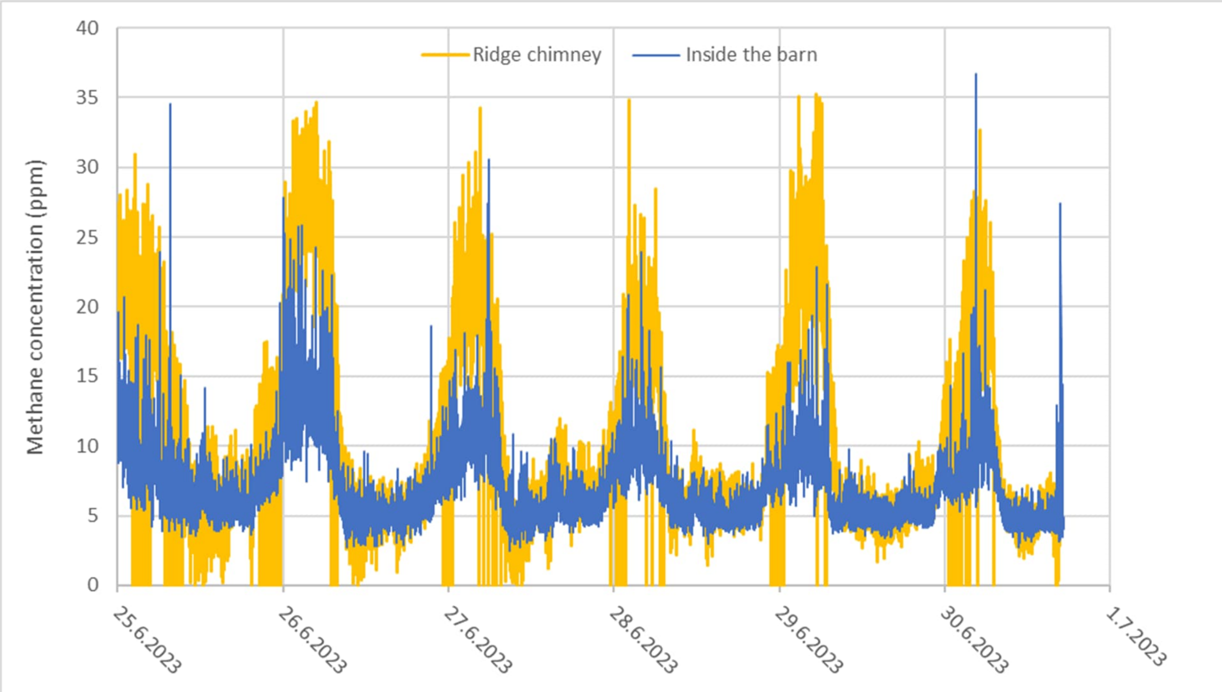


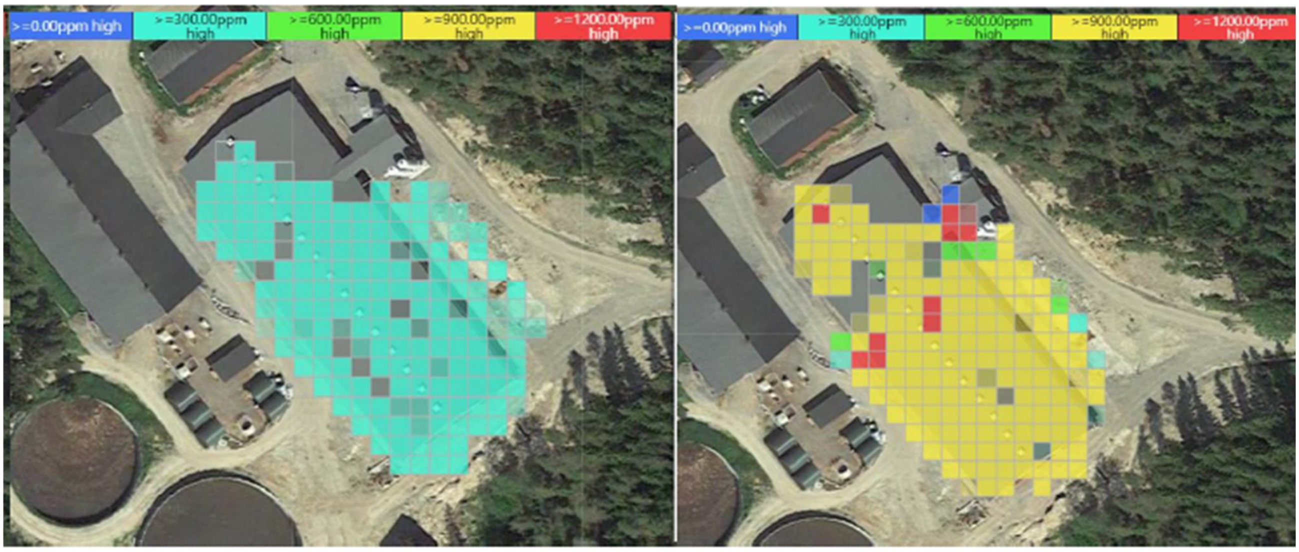
Figure 32. Comparison of summertime one-second data from ridge chimney and inside the barn.

3.4 OTHER IMPURITIES

Other impurities that were measured in the barn were NO_2, H_2S, NH_3 and CO_2. These were only measured during inside and outside area mapping, not during the long-term measurements. The measurements were done January 18th – 20th and 6th of February during winter season, and 7th and 21st of June, and 6th of July during summer season. H_2S and NO_2 were not observed.

CO_2 was observed above background levels in all other measurements expect on 20th of February (Figure 33). During winter season, the measured CO_2 levels inside the barn were typically between 600 – 1200 ppm. The highest point measurements were above 1200 ppm. During winter increased levels of CO_2 were not observed outside the barn. During summer season the CO_2 levels inside the barn were lower, around 390 – 520 ppm and sometimes exceeding 520 ppm. During summertime increased CO_2 levels were also measured outside the barn in similar range as inside the barn. The reason could be the fully open curtain walls which allowed CO_2 to travel with more ease out of the barn. The increased level of CO_2 inside the barn was an expected result as cows naturally produce CO_2. Understanding the CO_2 level is important, as it might increase the risk for carbon formation on catalyst or affect the reaction gas system.

18.1. 19.1.



20.1. 6.2.

Figure 33. CO_2 levels inside the barn during winter season. Light blue presents the background CO_2 level (approximately 400 ppm of CO_2 in atmosphere).

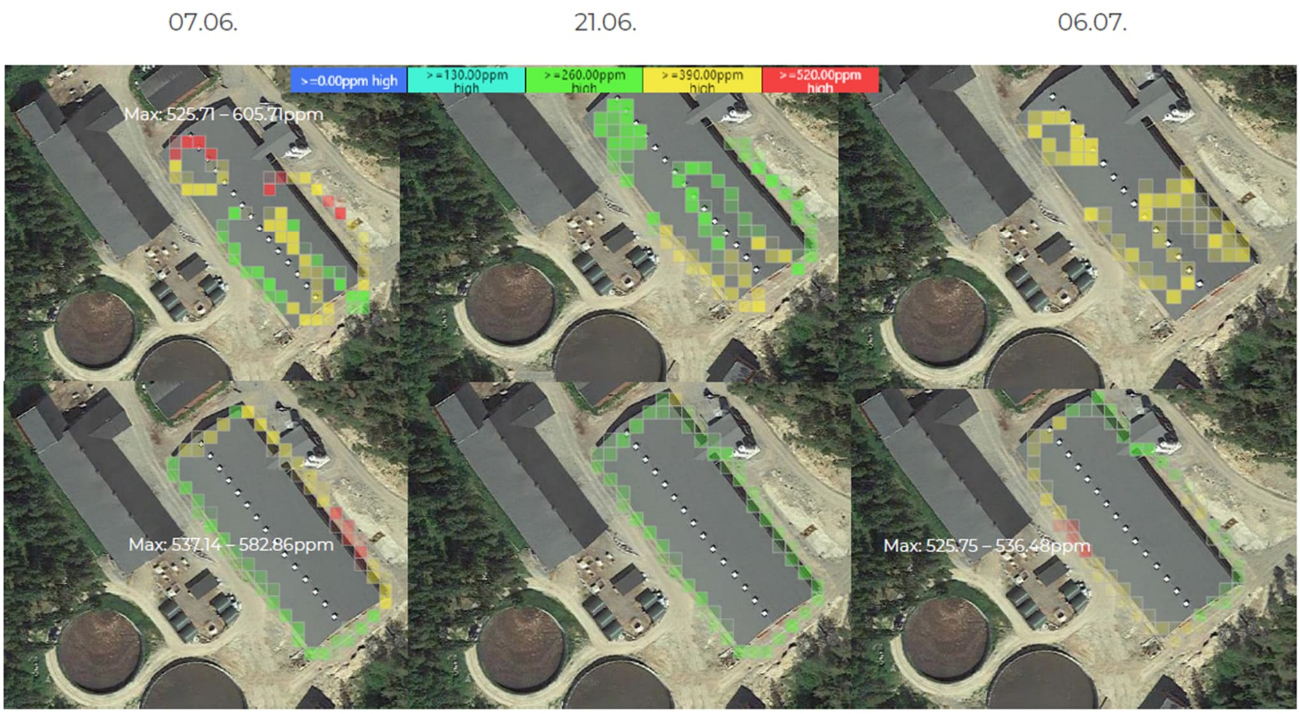
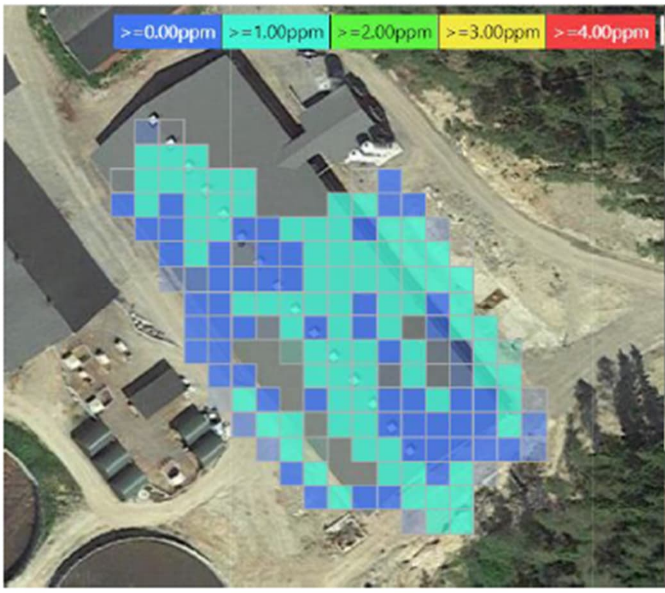
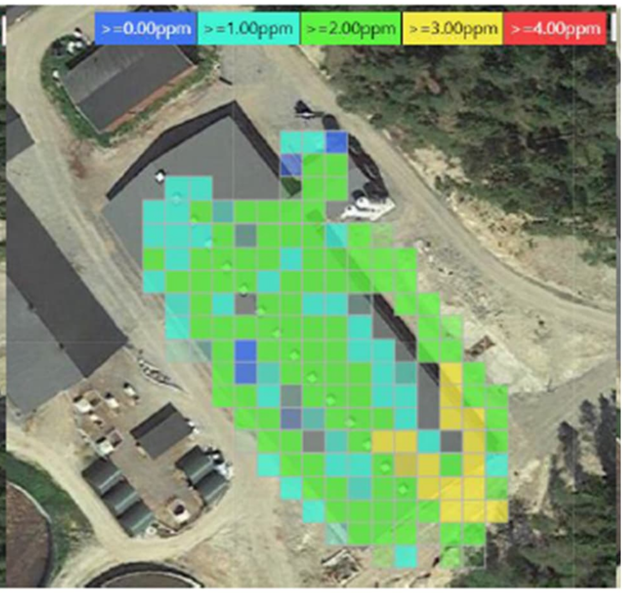


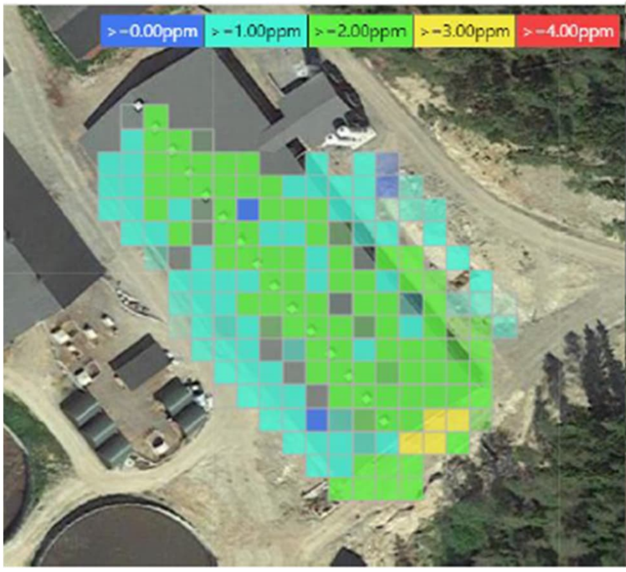
Figure 34. CO_2 levels inside and outside barn during summer season. Light green represents the background level which was measured to be 320 ppm). Top row: inside measurements. Bottom row: outside measurements.

The ammonia levels were generally speaking very low. Maximum observed levels during winter season were around 4 ppm (Figure 35) and 1.2 ppm during summer (Figure 36). For the most of the measurements, the ammonia levels remained just above the detection level. There was some indication during the measurements that the movement of the hydraulic manure scrape on the floor momentarily increased the ammonia levels, which was an expected result. Also on two occasions the area where pregnant cows were housed had higher ammonia concentrations, but whether this is something related to the cows, manure handling or ventilation cannot be determined from this small dataset. Ammonia was also observed directly outside of the barn during summertime. As ammonia is a deactivating compound for some catalytic materials, it is an important finding that the ammonia levels in the barn were very low.





18.1. 19.1.



20.1. 6.2.

Figure 35. NH_3 levels inside the barn during winter season. The area in with red on 6th of February is the location where pregnant cows were housed.

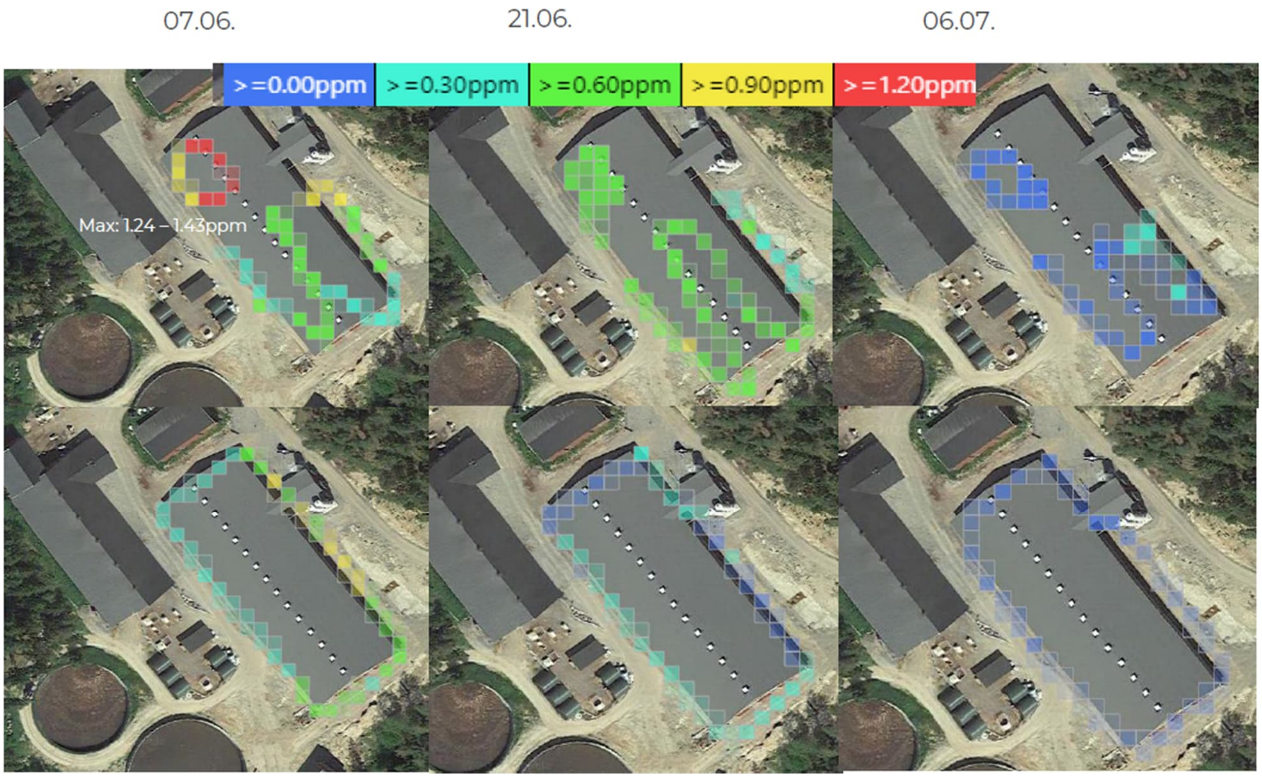


Figure 36. NH_3 levels inside (top row) and outside (bottom row) the barn during summer season. The area in with red on 7th of June is the location where pregnant cows were housed.

3.5 AIR FLOW MEASUREMENTS

Air flow measurements were carried out by VTT at Pöytyä barn during a winter measuring campaign to support modeling work in WP5. Measurements were carried out between March 14 and March 15, 2023. Pöytyä barn has a total of 15 chimneys that are used to exhaust warm air. To determine the average air velocity and assess the possible fluctuations caused by weather conditions, the air flow measurements were done for each chimney and repeated twice a day.

3.5.1 DAY 1

On the time of measurements, 14.3.2023, the outside air temperature varied from +1.4 to +4.3 °C (Figure 37), average air pressure was 980.6 hPa, and overall weather was cloudy and drizzly. The wall curtains were approximately 30 % open during the time of measurements.

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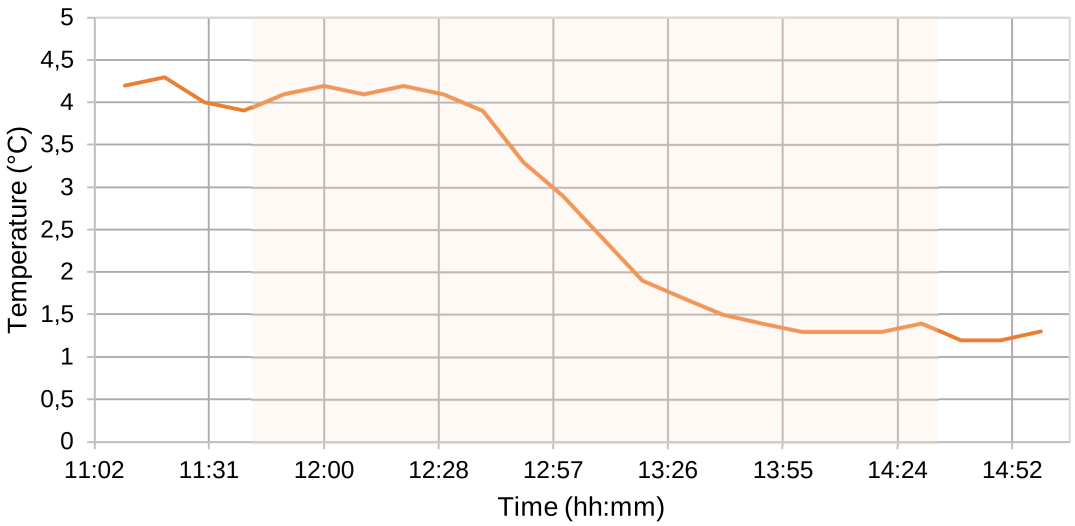

Figure 37. Outside air temperature during 14.3.2023. Measuring time period is illustrated with light orange box. Weather conditions were provided by Meteorological Institute of Turku Airport [2].

Air velocities were measured twice on March 14th, 2023. During the first set of measurements, the average velocity was measured from each ridge chimney moving from north-west end to the south end of the barn, while in the second set of measurements, air velocities were measured from every second chimney coming back from the south to north-west corner. The results of the average air velocities for each chimney during the two measuring periods are shown in Figure 38. The dark blue dots represent data from the first measurement, while the light blue dots represent data from the second measurement. The average air velocity varied between 0.6 – 1.5 m/s per chimney in the two measuring periods. We also noticed some variation between the measured values and the two measurement occasions. This difference was attributed to varying weather conditions, as the two measurements were conducted at different times of the day when the wind speed and outside air temperature varied from each other. Figure 39 displays the two data sets along with additional weather information, including wind and gust speed obtained from the meteorological station at Turku Airport. During the first measurement period, the variation in the measured velocities between chimneys (0.7 – 1.5 m/s) was more significant compared to the second measurement period, where the wind speed was lower and also the variation in velocity (0.6 – 1.0 m/s) was less evident. The average wind velocity was 5.6 m/s, and gust velocity was 8.0 m/s for the first measurement period, while the values were between 2.7 m/s and 3.6 m/s for the second one.

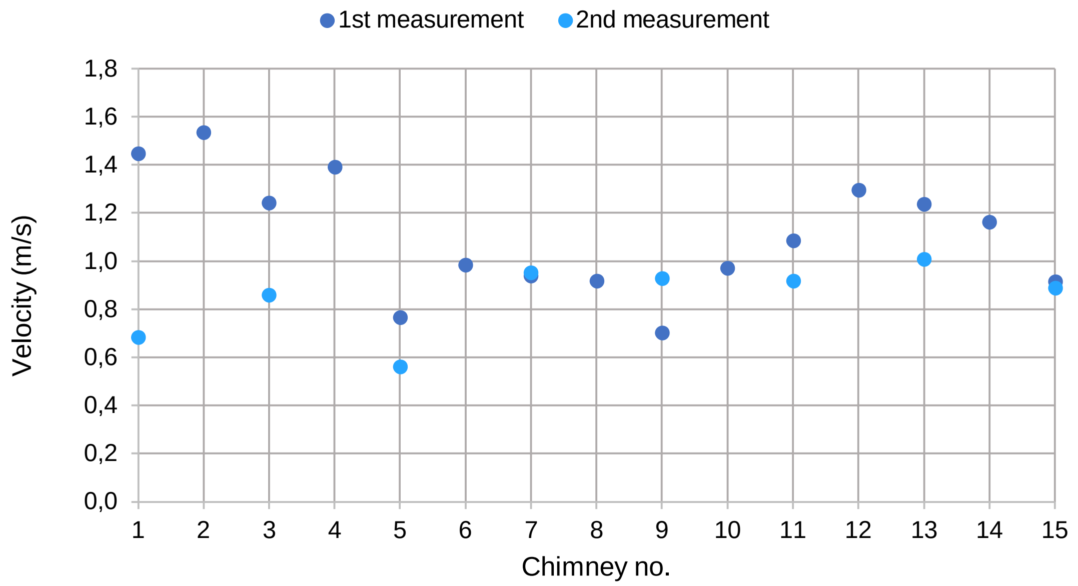

Figure 38. Measured average air velocities for the 15 ridge chimneys on 14.3.2023. Results from the first measurement are marked with dark blue dots and 2nd results are marked with light blue dots.

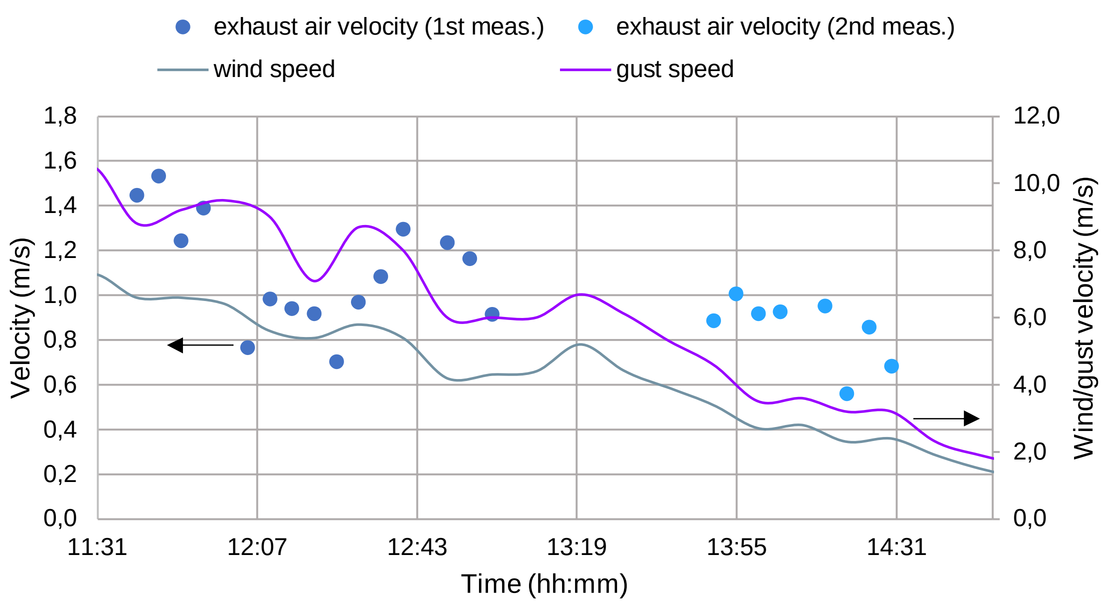

Figure 39. Average air velocities from the 1st measurement (dark blue dots) and 2nd measurement (light blue dots) on 14.3.2023. Figure shows wind speed m/s (blue line) and gust speed m/s (purple line) during the two measuring periods. Weather conditions were provided by Meteorological Institute of Turku Airport [2].

The wind and gust speed also caused a lot of variation in velocity values within the chimneys, i.e., the nine measuring points that were used to calculate the average flow velocity for each chimney. As seen from Figure 40, depending on the wind direction and speed, the velocity per x-y coordinate was drastically affected.

1.52	1.25	0.71
1.60	1.42	0.48
2.46	2.08	1.50

Figure 40. Measured velocities (5 s average, values are in m/s) for the first ridge chimney (north-west corner) at 9 different measuring points. Values were recorded on 14.3.2023 at 11:40. These values were used to report average velocities per one ridge chimney.

3.5.2 DAY 2

On the second day and during the measurements, the outside air temperature varied from +0.7 to +2.2 °C (Figure 41), average air pressure was 997.0 hPa, and sun was shining from the clear sky. The wall curtains were approximately 50 % open during the time of measurements.

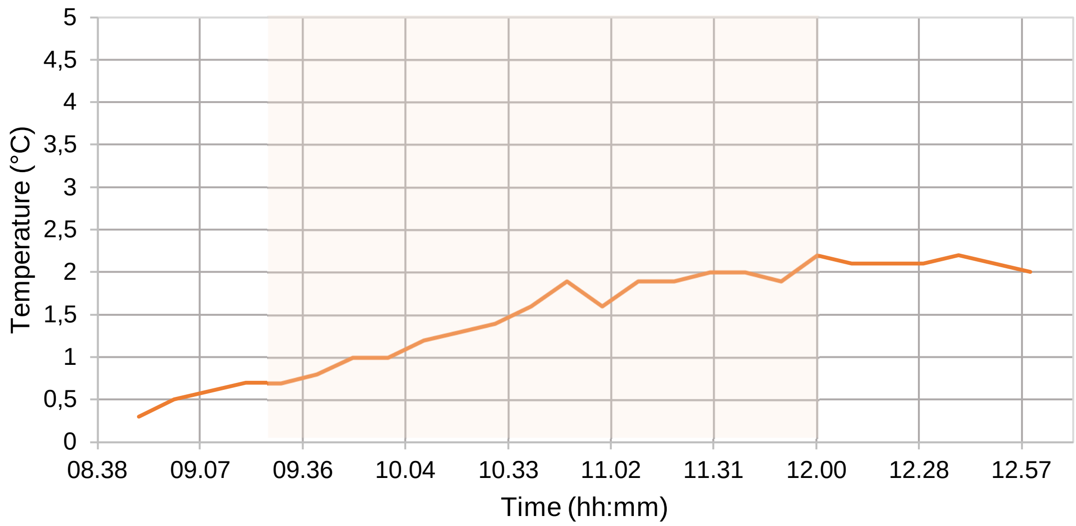

Figure 41. Outside air temperature during 15.3.2023. Measuring time period is illustrated with light orange box. Weather conditions were provided by Meteorological Institute of Turku Airport [2].

Figure 42 displays the average exhaust air velocities measured on March 15th, 2023. The original idea was to perform the measurement similarly to the previous day. Unfortunately, the second set of measurements had to be discontinued due to bad weather conditions as the high gust velocities (up to 12 m/s) caused unacceptable variation in the measured values (0.11–3.06 m/s) and prevented the average velocity to be recorded. As a result, there are only two data points available for the second set of measurements. Figure 43 shows the average velocities for the two datasets, along with the reported wind conditions on March 15th, 2023, obtained from the meteorological station at Turku Airport. Despite the rather high wind speed on the second day, the measured velocities were reasonably stable for the first measuring period. The velocities per chimney varied from 0.5 – 0.8 m/s, which was in similar range compared to the first day.

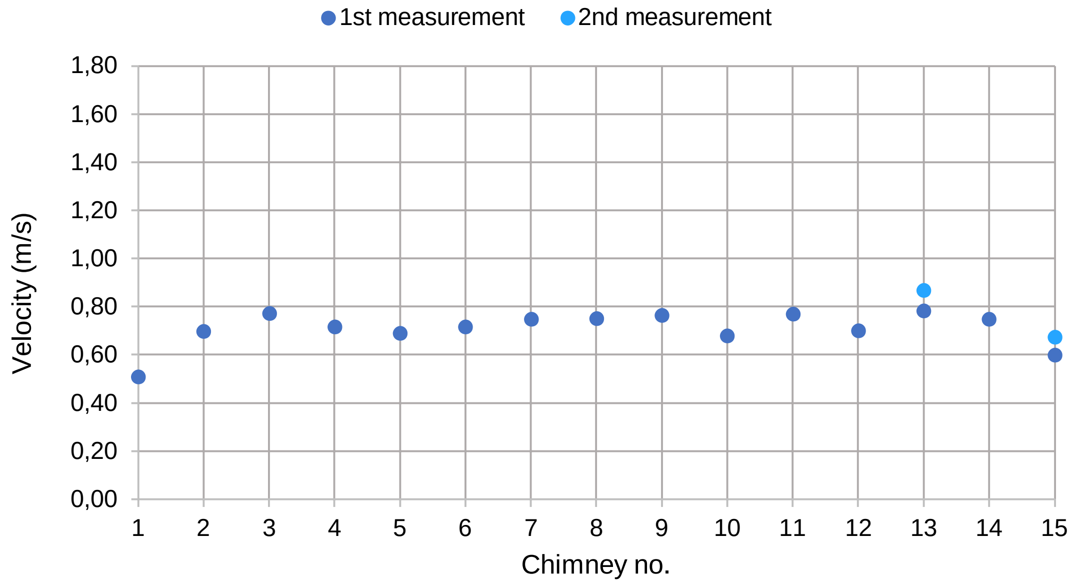

Figure 42. Measured average air velocities from the 15 ridge chimneys on 15.3.2023. Results from the first measurement are marked with dark blue dots and 2nd results are marked with light blue dots.

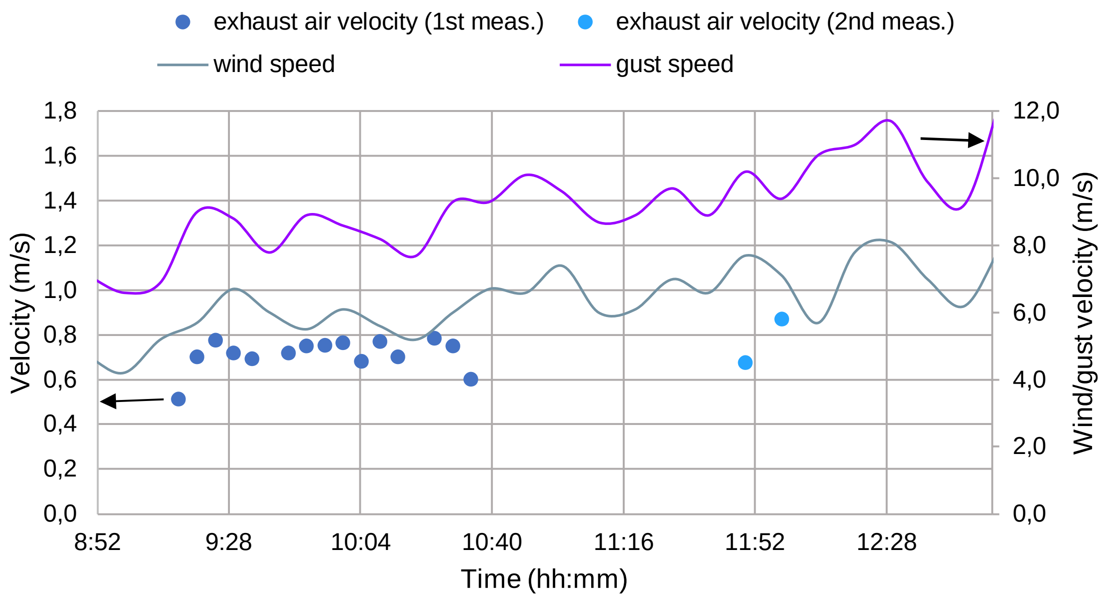

Figure 43. Average air velocities from the 1st measurement (dark blue dots) and 2nd measurement (light blue dots) on 15.3.2023. Figure shows wind speed m/s (blue line) and gust speed m/s (purple line) during measuring period. Weather conditions were provided by Meteorological Institute of Turku Airport [2].

3.5.3 COMPARISON DATA

Table 2 provides a summary of data from two days of measurements, including weather conditions, average air velocities (the mean velocities measured from 15 chimneys), and calculated average flow rates. The Meteorological Institute of Turku Airport provided weather conditions such as air pressure, temperature, and wind conditions. On the 14th of March 2023, the weather was cloudy and drizzly, while on the 15th of March 2023, the sun was shining from a clear sky. The air pressure on the first day was 980.6 hPa, while on the second day, it was 997.0 hPa. The outside air temperatures were 3.9 °C and 1.0 °C for 14th and 15th March respectively, while indoor air temperatures measured from the exhaust chimneys were 4.7 °C and 4.1 °C for the same days respectively. Despite the momentary high gust speeds that interrupted manual measurements, the average wind speed during the measuring period was relatively consistent. On the first day, the average wind speed was 5.6 m/s, and on the second, it was approximately 5.9 m/s.

Using the measurements gathered, we calculated the velocity variation for each day. The velocity was somewhat higher on the 14th of March than on the 15th of March, 0.8 – 1.5 m/s and 0.5 – 0.8 m/s, respectively. The average flow rate was calculated to be 0.91 m/s per chimney, equivalent to a flow rate of 2654 m3/h, based on the two-day data. This corresponds to a total exhausted flow rate from the barn of approximately 39,810 m3/h. Therefore, the space velocity for the Pöytyä barn with a total volume of 21,510 m3 would be 1.9 h-1 under these conditions. The calculated average flow rates and space velocities align with literature values. For naturally ventilated barns, the space velocity typically varies between 1-5 times per hour, depending on weather conditions, during winter. The minimum recommended space velocity for dairy barns is approximately 1.0 h-1, regulated by the number of cows and barn dimensions. [1, 3, 4].

Table 2: Summary data of the ventilation air measurements and prevailing weather conditions between 14.3.2023 – 15.3.2023

	DAY 1	DAY 2
Weather conditions		
	cloudy, drizzly	sunny, clear sky
Air pressure (hPa)	980.6	997.0
Average outside air temperature (°C)	3.9	1.0
Average wind speed (m/s)	5.6	5.9
Average gust speed (m/s)	8.0	8.5
Ventilation measurements		
Average exhaust air temperature (°C)	4.7	4.3
Min velocity (m/s)	0.77	0.51
Max velocity (m/s)	1.53	0.78

Average velocity (m/s)	1.11	0.71
Average flow rate (m^3/h)	3237	2070

3.6 MASS FLOW ESTIMATION

As described in section 2.2.4.4 Aeromon also attempted to carry out a mass flow estimation. This was outside the immediate scope of the study and the calculation model is only at the development stage. The data for the calculation was gathered on 21st of June when the curtain walls were fully open. This naturally leads to situation where methane is escaping from the barn from many locations through the walls in addition to the ridge chimney. The measurements were done on the road behind the barn (Figure 44), which allowed measurements below the wind. The measurements were repeated twice. The calculated mass flow of methane given by the model varied between 0.22 – 0.43 kg/h.

Figure 44. Location for the mass flow measurement.

4 DISCUSSION

The objective of the barn air measurements was to increase understanding of the methane levels inside a modern, open-walled dairy barn. The technology which is developed in the CANMILK project is aimed for the conversion of very dilute methane concentrations. The heart of the concept is in the combined plasma-catalysis reactor, which converts the methane to CO_2. One concept option also includes an adsorber unit before the conversion unit. For the operation of the reactor and possible adsorber the knowledge of methane levels and possible impurities in the barn is highly valuable. Looking from the perspective of the techno-economics and feasibility, the barn air measurement helps to assess the potential methane abatement and how it affects the economics of the unit.

The main results from the measurements can summarised as following:

- During winter season the methane levels were higher (ca. 50 – 150 ppm) as the curtain walls were partially or fully closed.
- During summer season and on warm winter days the curtain walls were fully open and the methane levels were between 5 – 30 ppm.
- Methane production from the cows was estimated to be around 200 ppm. The measured methane levels were always lower than that, although highest momentary peaks reached 175 ppm and above.
- Methane mixed well inside the barn and most of the methane observed inside the barn also reached the ridge chimney.
- During summertime methane had clear formation pattern with highest levels always measured during nighttime.
- H_2S and NO_2 were not observed.
- NH_3 was observed on very low levels up to ca. 4 ppm.
- CO_2 concentration was often increased above background level up to 1200 ppm level which was an expected result.

The fluctuations of the methane levels and the very low levels around 5 ppm should not be problematic for the plasma-catalysis system. However, if the concept utilizes the adsorber and the operation is based on reaching certain output concentration from the adsorber, the fluctuation of methane and especially the low levels can be a challenge. On the other hand, the daily pattern of methane formation during summer could be utilized for adsorbtion/desorption cycle. Adsorbtion during nighttime when highest levels of methane occur and desorption during daytime.

Positive results for the CANMILK concept were the good mixing of methane inside the barn, lack of H_2S and low level of NH_3. Many catalysts planned for the CANMILK concept are noble metals, which are very sensitive for the poisoning which leads to the catalyst deactivation. Therefore, lack of impurities in the barn air is an encouraging result.

The methane monitoring results will be utilized in the modelling of the barn, which will be carried out in Work Package 5. The techno-economic assessment will help to determine what effect the lower-than-expected methane levels have on the feasibility of the whole concept. It should be noted that even thought the Arvela barn was chosen as it represented a modern dairy barn, there is plenty of variation within Europe in what types of dairy barns there currently are and what is the favoured design for any new barns. Therefore, the potential effect of the CANMILK technology is always specific for each barn, but this study at Arvela barn with different opening degrees of the curtain walls gives a good indicator what variation there can be in the methane levels overall.

5 CONCLUSIONS

Methane levels were monitored in a modern dairy barn housing 240 cows. The barn had curtain walls which responded to the outside temperature helping to maintain the inside temperature on a comfortable level for cows. The curtain walls were usually fully open above ca. 0 °C and fully closed when the temperature dropped down to -8 °C. The measurements were carried out during winter and summer to observe the seasonal variations. Three types of measurements were carried out. Inside mapping with a hand-held device covered the entire inside area of the barn at three different heights. In the outside mapping the same hand-held device was carried around the barn, but also attached to a drone and flown over the barn. In the long-term measurements one measuring device was in fixed position inside the barn and other in ridge chimney. The measurement continued at least for three weeks or more during both summer and winter time. During the mappings with hand-held devices also levels of H_2S, CO_2, NH_3 and NO_2 were measured. Otherwise, the measurements focused on methane levels.

The results indicated that the one-hour average methane levels inside the barn were around 50 – 150 ppm during wintertime and 5 – 30 ppm during summertime. Thereby, methane concentration inside the barn was highly affected by the existing weather conditions, as the curtain walls were at least partially close during the winter season. The highest momentary methane concentrations around 175 ppm were measured when the curtain walls were fully closed. This level was very close to the estimated 200 ppm level. Barn air is well mixed meaning that no local points of concentration were detected. During summer season the methane levels always increased at nighttime, but now clear reason for this pattern could be determined from the data alone. Regarding the other impurities, H_2S and NO_2 were not detected, NH_3 only at very low levels and CO_2 up to 1200 ppm level which was expected result.

The data from the measurements will be utilized in the modelling of the barn, which will be carried out in WP5. The data is naturally also used as starting point for the design of the CANMILK unit and helps to plan test matrix for the Proof-of-Concept unit that will be built in WP4.

6 REFERENCES

1 I. Heimonen, J. Heikkinen, J. Laamanen, and T. Kivinen, “Lypsykarjapihaton luonnollinen ilmanvaihto Ismo Heimonen | Jorma Heikkinen | Jarmo Laamanen |,” 2012. [Online]. Available: http://www.vtt.fi/publications/index.jsp.

2 Ilmatieteenlaitos, “Download observations,” 2023. https://en.ilmatieteenlaitos.fi/download-observations.

3 T. Kivinen, K. Mattila, F. Teye, and J. Heikkinen, “MTT 119: Lämpöeristetyn verhoseinäisen lypsykarjapihaton ilmanvaihdon toimivuus,” 2006.

4 T. Kivinen, J. Ahokas, V. Poikalainen, F. Teye, M. Hautala, P. Tamminen, I. Veermäe, and A. Pajumägi, “MTT 155: Kylmäpihattojen toimivuus Suomessa ja Virossa,” 2008.