A Measurement-Driven Approach to Understand Urban Greenhouse Gas Emissions in Nordic Cities

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Abstract

Cities are main drivers for climate change mitigation and emission reduction today. However, in many cases they lack reliable baselines of emissions to validate current developments over time, assess the impact of their projects, and prioritize investments and actions. They also need better data on a small geospatial and temporal scale to really understand local emissions. This paper describes the rationale and the design of the Carbon Track and Trace project (CTT) that aims to develop an automated system for greenhouse gas (GHG) emissions monitoring through a low-cost city-level sensor network. The system is based on a flexible architecture incorporating open source sensor platforms, an Internet-of-Things wireless backbone, and extensive data analytics. We describe concept, architecture, and deployment as well as initial results.

1 Introduction

Cities are the largest consumers of energy, and account for 80 percent of all greenhouse gas emissions. By 2050, it is expected that over 70 percent of the world population will live in cities [3]. With increasing urbanization, cities need to rise to the challenge of reducing their climate impact. A necessary prerequisite is that they can accurately measure and monitor their greenhouse gas emissions, mainly CO_2. Over 1400 cities around the globe already regularly report their greenhouse gas (GHG) emissions through the carbon*n* Climate Registry and the Covenant of Mayors initiative[1], all of which rely to a greater or lesser extent upon modelling, statistical downscaling, and calculations techniques. It was previously demonstrated that this current practice of estimating or down-scaling city-level emissions inventories is plagued by many issues [5, 8]: suspect data quality, lack of spatial granularity down to a county or city level, incomplete or non-existent uncertainty and confidence intervals, and an inability to support targeted investments in mitigation measures.

Nordic cities are strong in developing low-carbon sustainable solutions. However, corresponding city data at sufficient quality is not always available. For instance,

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[1] `http://carbonn.org/`, `http://www.covenantofmayors.eu/`

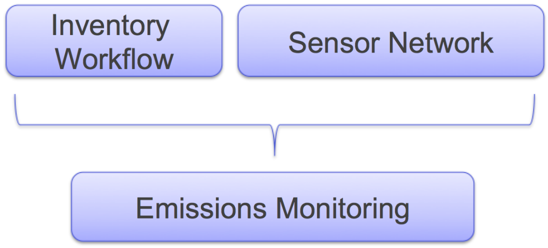

Figure 1: CTT approach of GHG monitoring: combining complementary approaches

the production of regional statistical data was stopped in Norway by the national statistics office due to severe quality concerns. This significant gap has left Norwegian cities in the dark about their exact city-level since 2009. Moreover, city-level emissions inventories are both expensive and time-consuming to build. As an added complexity, they are associated with high uncertainties [22]. Finally, most cities in Europe do not currently possess the capacity to measure actual emissions within their urban space. This is particularly problematic for the building and transport sectors that comprise a significant proportion of total GHG emissions. Even for countries such as Norway that have a 'cleaner' energy profile based more strongly on renewables of hydropower, emissions accounting is a challenging undertaking for Norwegian municipalities [13]. Additionally, cities are adopting highly ambitious climate goals, for example Trondheim at 70%-90% reductions of GHG by 2030 from a 1991 baseline [1], in line with national goals [2].

This represents a strong need and opportunity for a new approach that complements existing yearly statistics-based GHG reporting with a high-granularity measurement approach within cities to get real-time local insights and allow for faster impact assessment and feedback loops in policy development. While conventional air quality measurement stations are very expensive, recent progress on low-cost and open-source sensor hardware [12, 7] enables new approaches.

The Carbon Track and Trace (CTT)[2] approach we describe here combines top-down estimates with bottom-up measurements and enables the possibility for cities to develop real-time, city- and street-level understanding of GHG emissions. CTT is based on building an Internet of Things (IoT) network of low-cost sensors coupled to a data analytics platform that allows for the analysis and visualisation of real-time and historical GHG emissions for a city.

The project forms a part of larger Smart Sustainable Cities and environmental monitoring [11, 16] approaches, especially by setting up an IoT measurement network testbed to build baseline measurement for future projects.

In previous project phases we built an understanding of the field and analyzed gaps in current practices of municipalities to track and report GHG emissions [5, 8] as well as more detailed workflow analyses, including data sourcing and quality issues [6]. This led to the current approach of moving away from only yearly reports and of using sensor-based measurements to fill the information gap. Fig. 1 shows this approach of CTT to complement existing efforts of yearly emission inventories with more real-time measurements through a sensor network to arrive at much improved emission and GHG monitoring for cities. This paper concerns the technical aspects of building up and utilizing the sensor network. In the current phase, the project

[2]http://carbontrackandtrace.com/

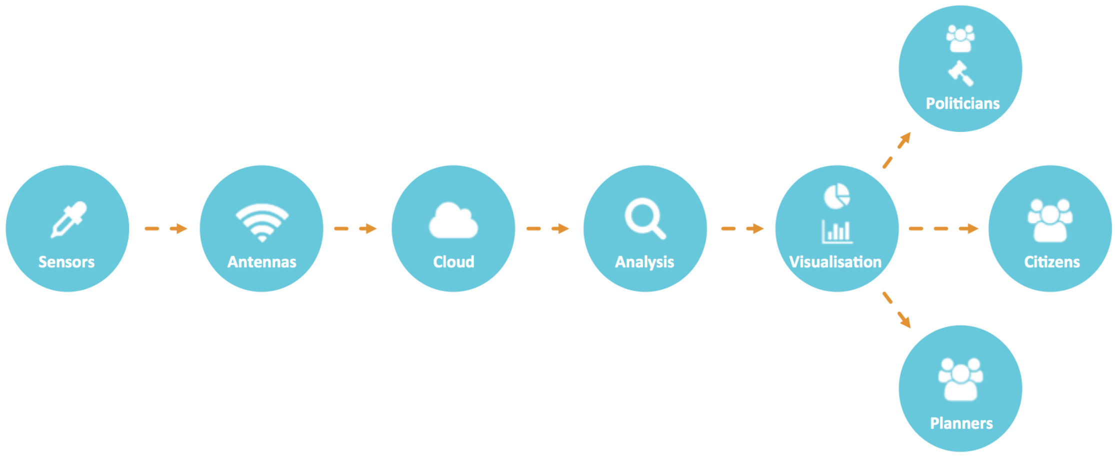

Figure 2: Overall system concept and architecture

is setting up pilot installations of sensor networks in Trondheim, Norway and Vejle, Denmark in close collaboration with these municipalities.

The project is set up to answer a number of relevant research questions and to initiate further research and development: The general utility of on-the-ground measurements for cities and citizens; how to complement conventional high-cost high-accuracy measurement stations with a low-cost, lower-accuracy sensor network with a more comprehensive number of point measurements of lower accuracy [12] and related challenges of absolute versus relative measurements; the selection of the best air diffusion or other modeling approaches for emission mapping in collaboration with our partners [24, 7]; the operation of emission and air quality measurement in high-latitude Nordic countries regarding temperatures and emission levels; the integration and deployment of a communications network in actual Nordic field conditions [16] in a city, including bandwidth and range/coverage of the radio components [9]; combination with external data sets such as weather, traffic, demographic, socio-economic, energy flow, satellite and others [20]; links to existing municipal planning support and decision support systems; and how to link mitigation measures in a city to specific climate and economic impacts [21], through the sensor network in an actionable way.

In the following, we discuss the project's system design, sensor and network development and deployment, data analysis and integration as well as future steps, initial results, and outlook.

2 System Design

The idea of CTT is to enable city officials, decisions makers, citizens, and other stakeholders to access emission measurements throughout a city. To achieve this goal, we define a general concept and overall architecture of the system as outlined in Fig. 2. It shows the system components and the simplified dataflow, starting from individual sensors through gateway antennas to a cloud data storage into an analytics backend that provides insight and visualizations to a range of stakeholders in various degrees of abstraction.

The architecture is kept as flexible as possible to be able to exchange components easily with clear interfaces between them. This facilitates collaboration and development within the project for separation of concerns. Another important aspect is that it allows later integration for additional cities where different infrastructures may already exist. For example, the wireless IoT backbone used in the project can be scaled out to drive a city's IoT projects, but on the other hand, in a city with existing IoT backbone, the project should be able to integrate easily without the need for its dedicated network. The same holds for the data storage, which may instead use a city's existing open data portal. With this in mind, detailed hardware and software/protocol components can be exchanged with limited effort.

A first prototype that we describe here sets up the whole chain from sensor to simple data interfaces, with the express understanding that this is a work in progress that needs refinements within many components of the architecture. The project objectives call for distributed greenhouse gas measurements throughout a city. An easy way to achieve this without too much overhead in infrastructure is to set up a wireless sensor network for easier deployment [23] of sensors throughout the city. This is in line with current approaches towards environmental monitoring with sensor networks [11], which is getting easier due to increased availability of low-cost sensor components. One objective of the project is to test the viability of such an approach especially in terms of data quality and trade-offs between high-accuracy and low-cost approaches [12, 7].

Apart from these technical aspects, we are also following approaches towards the socio-technical integration [18] of the project in terms of general requirements and integration into other city systems as well as collaboration with larger international standards for GHG reporting. In the following sections, we will discuss selected components in more detail, with a focus on sensor and gateway selection and deployment, sensor network development and testing, as well as data analysis.

Sensor Platform

CTT itself does not develop hardware, but builds upon existing sensors and sensor platforms. Therefore we first develop our requirements towards both the raw sensors and the computing and communication platforms that they will be attached to:

- Usability in a range of outdoor environments and weather conditions,
- Installation possible in remote locations; possibility of installation without additional infrastructure such as cabling, electricity, etc.; possible self-sustained operation,
- Compatibility with low-power, wide-range communication protocols with a stable development base and also direct cabling or Wi-Fi options,
- Be well matched with at least one type of CO_2 sensor (and possible additional air quality and pollutant sensors),
- Open-source with respect to software and possibly hardware, and low cost.

The system should be adaptable by the dimension and environment of city and to different sensor deployment densities, as well as the regional climate the city is located in. The open source requirement is based on a general focus on openness in innovation in the project, that aims to develop open and transparent tools for emissions monitoring. Additionally, it allows to more easily adapt available systems,

Figure 3: Sensor deployment example: Attachment of basic CO_2 sensor setup next to an official measurement station at a Trondheim major traffic artery.

which are increasingly available off-the-shelf, and it can also more easily fulfil the low-cost requirement.

Based on these requirements, we are currently testing two sensor technology platforms, namely, Libelium's Plug & Sense! Smart Environment Pro (PSSEP)[3] and Sodaq's Autonomo (SA)[4]. Both platforms are programmed in C/C++, but differ in programming IDEs and included libraries. The PSSEP encapsulates its electronics inside of an IP65 mounting enclosure, meaning it is dust proof can sustain heavy rain. Sensors are plugged in through waterproof sockets. This allows us to deploy it outdoors in Nordic weather conditions (cf. Fig. 3 and 4). While very high or low temperatures may be an issue that needs to be tested thoroughly, we have been able to deploy a default system in Trondheim from the late winter starting in March 2016. Available libraries tailored to the available sensors allow fast integration, since voltage measurements from the sensors have to be translated to actual measurement values, also taking additional measurements such as temperature into account. Out of a range of communication protocols, we chose LoRaWAN as a low-power wide-area radio protocol to cover a city with a minimum of gateway antennas, as discussed in Section 2. Finally, we install the platform with a rechargeable battery and an accompanying solar panel, enabling self-sustained operation. In comparison, the SA is not encapsulated but comes only as an electronic board, with additional communication and sensor components. This allows us cheap and easy prototyping and testing of ideas and solutions in the lab, while the PSSEP with its closer to plug-and-play features allows easier and faster deployment.

Deployment

Due to the main focus of CTT, all sensor nodes are equipped with a CO_2 sensor as the initial minimal deployment as seen in Fig. 3. In our newer deployments (cf Fig. 4), all of the sensor nodes are also equipped with pollutant sensors in the form of an NO_2 sensor and combined temperature, pressure, humidity sensors (for

[3] `http://www.libelium.com/products/plug-sense/`

[4] `http://support.sodaq.com/sodaq-one/autonomo/getting-started-autonomo/`

Figure 4: Sensor deployment on traffic lights in Vejle city center, showing full deployment on a mounting plate with platform, solar panel, and downward facing sensors for CO_2; NO_X; combined Temperature, Pressure, Humidity; and combined PM_1, $PM_{2.5}$ and PM_{10} (the separate box on the left)

Figure 5: Deployment of LoRaWAN antenna gateway outdoors on the roof of the Student Society building in Trondheim (left) and elevated indoors in a clock tower in Vejle (right).

improved calibration of gas sensors), with some nodes also equipped with a particle matter (PM) sensor for dust of different sizes. This will allow us to correlate CO_2 measurements with NO_2 that is generated through fossil fuel burning and may deliver insights into vehicular emission contributions. Furthermore, as often CO_2 is not measured by official stations, this still gives us an indirect comparison to those datasets. The deployable sensor package is fairly small and manageable. Thus it can easily be moved during the pilot phase to identify better locations [10] or support for instance rotation-based calibration protocols. Nodes, sensors, and solar panels are fixed on a metal plate which in turn can be attached to a wall or a lamp post.

Locations for sensor deployments are decided in close collaboration with the municipalities. There are many factors which affect the decision of where to place the sensor nodes. An initial deployment consists of around 10 sensors for a city of the size of Trondheim with a ramp-up depending on initial results. A default location choice is that of official measuring stations. By placing parts of our deployment next

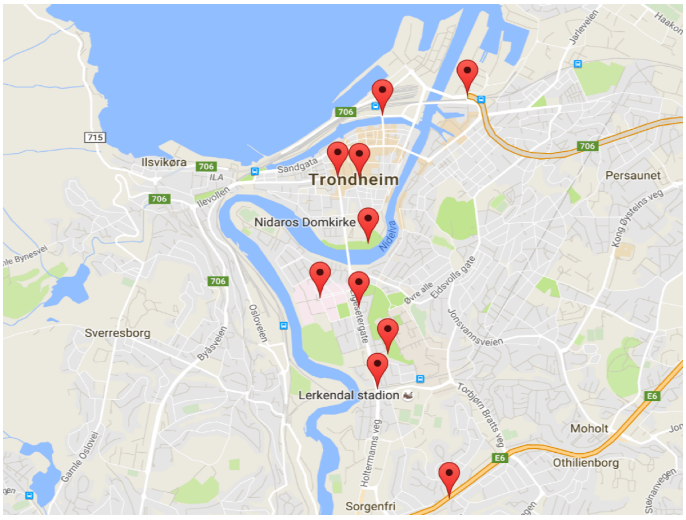

Figure 6: Map of the sensor deployment locations for the pilot phase in Trondheim with 10 sensors.

to them, the sensors can be easier calibrated and verified. Other factors include exposure to traffic and coverage of the city's geographical area. In the case of Trondheim, the initial focus for the pilot is on the "Knowledge Axis", stretching from the harbour through the city center to the Southern industrial area as shown in Fig. 6. Future deployment will spread out from this area. Deployment also considers the locations of the IoT gateways, which are running LoRaWAN [15], a low-power wide-area network (LPWAN) for wide coverage with minimal installation. In turn, the gateway antennas are to be deployed in central and elevated locations to cover the city efficiently (cf. Fig. 8). These consist of a receiver and an antenna as seen in Fig. 5 that can be operated in varying conditions.

Sensor Network

To make it's way from the sensors to the cloud, the data travels through the wireless sensor network illustrated in Fig. 7. The sensor devices **(1)**, described in the previous section, send their measurements periodically every 6 minutes via the low-power LoRaWAN protocol, minimizing energy use on the sensors. The LoRaWAN gateway **(2)** forwards the data packets through standard TCP/IP to the servers of The Things Network (TTN, chosen for ease of pilot development)[5] **(3)**. Each sensor node has a unique address registered with TTN. Our servers run a data aggregation software **(4)**, called *dataport*. It fetches data from TTN using the MQTT protocol [17], an event-based sensor messaging protocol, converts it from our compact binary representation to a more descriptive one (including units), and forwards it to data storage for further analysis and archival **(5)**. The dataport also analyzes the incoming network metadata, and generates alarms and reports **(6)**. It detects for instance when packets (expected every 6 minutes) are missing and observes the battery level of the sensors, so that malfunctions and decaying network health can be detected and fixed. The dataport also generates a report about the state of the network. This report includes information about which of the LoRaWAN gateways forward data of which sensors. This provides insights into

[5] `https://www.thethingsnetwork.org`

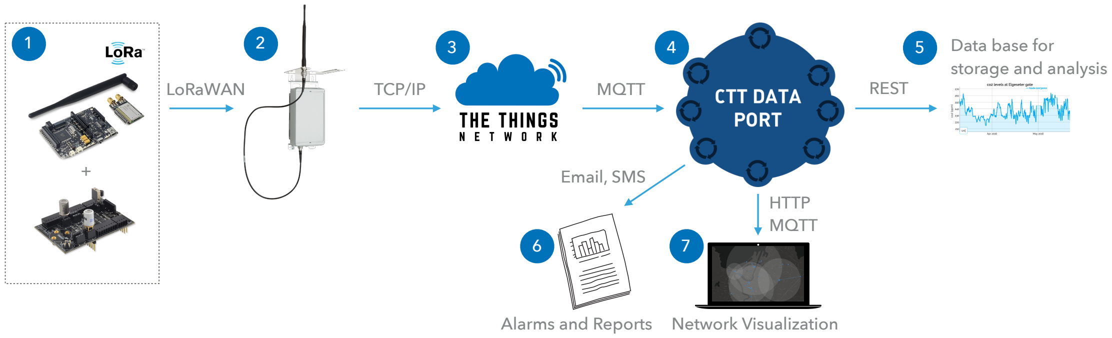

Figure 7: Network structure from sensor to server using LoRaWAN and MQTT. Adapted from [9].

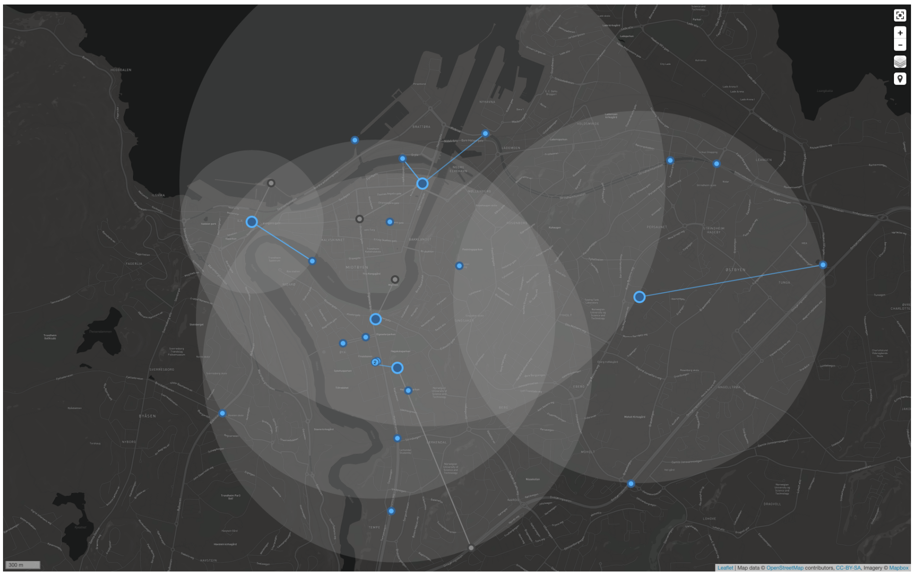

Figure 8: Visualization of an initial network of two installed gateways and two nodes with additional simulated gateways and sensor nodes, dataflow and coverage

which gateways are utilized and gives clues as where to place additional gateways when the network is extended. The dataport has a Web interface, so that browsers **(7)** can visualize and observe the CTT network. It shows a map with an overlay of the sensors and gateways, as shown in Fig. 8. With each received transmission, the website is updated via MQTT over websockets and thus gives a live view of the sensor network.

The range of LoRaWAN depends on various factors, such as payload size, data rate and the topology of the area [19]. With the highest data rate, TTN allows for a payload of 111 bytes in total 292 messages per day, or roughly a message every 5 minutes [9]. Compressing the payload to 54 bytes opens up the lowest data rates. They have the benefit of increased range, but since the transmission takes more time, the data can only be sent 12 times a day, or every 2 hours. Also, theoretical range limits of LoRaWAN can usually not be reached inside built up cities (and may drop to 2–3 km). Therefore, an important goal is finding the optimal parameters for CTT data: How much precision is needed, how many readings per hour make sense, and how does this influence the network design of sensors and gateways; this will be further evaluated through the project.

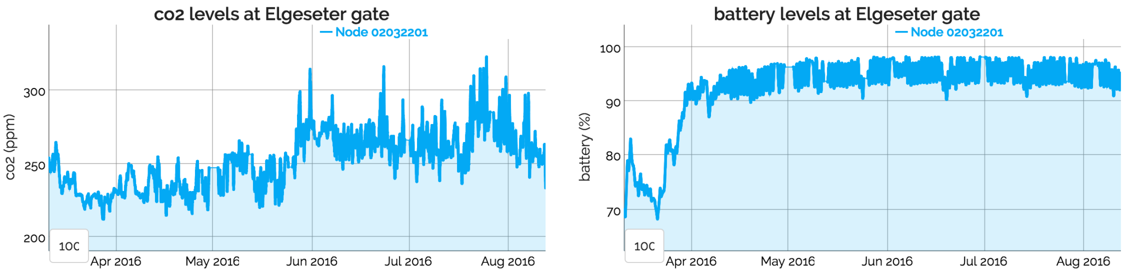

Figure 9: Initial Trondheim sensor stream for CO_2 and battery level measurements captured over half a year in 2016 to date (raw data, uncalibrated)

Data Analytics

Logically situated after the sensor network development, data analytics is a major aspect of CTT to transform the raw data into visualizations and insights for the various stakeholders (Fig. 1). This phase of the project is currently being developed. As discussed in Section 2, we use a staged data storage with an intermittent IoT storage before data is stored in our analytics servers. The Dataport described above is an intermediate service that allows to monitor and observe the current network status and data packages from a growing network as they come in (Fig. 8). The server-side data storage is used to capture and store data long-term to be able to run long-term data analysis on emissions and GHG [4, 24] and to potentially improve used models with ongoing data from multiple years once it has been captured.

Data visualizations with the ongoing deployment will be available for each sensor package in the network and all of its constituent sensor data streams. As an example, Fig. 9 shows an initial sensorfeed for the first sensor that we have deployed to test the long-term robustness of the sensor platform and its self-sustainability (cf. Fig. 3). Other sensors in Trondheim (cf. Fig. 6) and Vejle were deployed later and cover less time. As an initial result, the data already shows the relative dynamics of the concentration within the year and we can also identify weekly and daily patterns such as weekends and rush hours. A few outages in the data and other glitches can be expected in the network setting. This is one issue to be addressed by data cleaning and processing. Another is to calibrate and regularly recalibrate the network based on calibration protocols, manual measurements, and the data from official stations.

The more complex part is to develop city-scale emission models that can take into account the sensor data and environmental influences to be able to map emissions for the whole city area by estimating values for the full city grid. This is an iterative process also linked to data fusion techniques [20], which can take additional data sources into account, for example yearly inventories, satellite measurements of CO_2, and others. Initial work is promising, also in using satellite data for recurring calibration. A special challenge is the variance in measurement accuracy, spatial and temporal resolution, and data availability, which needs multi-scale analysis. The integration of results into decision support system for the municipalities and also the complementing of yearly emission inventories with within-year measurements is an open issue that we follow up with an external partner.

3 Discussion and Future Work

There are challenging research questions in each part of the project. Implementation of the initial pilot installation and prototype system is well underway and basic functionality is in place. The initial project results are promising and we can already share some interesting results. We can especially show that the sensor deployment and networking structure and protocols work in two cities and that measurement data is coming in. The prototype status allows us to continue ongoing sensor evaluation and system development, especially on the analytics side. The data fusion and comparison to other sources is very exciting and is also showing initial results which are useful for the municipalities. One challenging aspect is that this sort of data collection and analysis has not been done before for CO_2 data on this city level. However, for a broader scale and more detailed analyses, existing models and analytics can evolve with the growing data collection. While prediction of energy use is an established topic [14], a similar prediction on emissions and air quality on a city level is rather new [25], and also opens up interesting research venues only now possible with a wider sensor coverage.

In terms of sustainability and durability, it is encouraging to see is that the sensor works since early March autonomously on a solar panel (Fig. 9). The battery level after deployment quickly reaches over 70%. While the energy gain is also at least in part due to street lighting, this open a reliable deployment option. Thus we are confident that even with the 15x20 cm solar panel the sensor packages should make it through the winter even in worse conditions, which will be tested further in the following seasons. This means that they do not need complex installation and can be deployed mostly anywhere in a city without much considerations about infrastructure. It also makes them neutral in terms of energy use, easing a large-scale deployment. For more remote installations, larger panels or electrical connections would still be necessary.

A further step is scaling out from Nordic countries to other EU countries as well as also internationally and to developing countries. The reason for this is bound to the larger goal of GHG reduction. Even if we are able to achieve meaningful reductions in the Nordics, it is still a very limited impact worldwide. The only way to drastically scale up the impact beyond this is to get to cities internationally. From our initial experiences with China and India, we also derived the additional pollutant sensor configuration with PM sensors, as PM is a higher concern than just CO_2 in some places even though it may often be tightly coupled. This would also allow to evaluate beyond the specific Nordic characteristics of lower emission levels to expand to different air quality characteristics as well as to other environmental and temperature factors.

4 Conclusion

We have presented the CTT approach to municipal greenhouse gas monitoring and an initial validation of the data flow of the approach. We described the overall approach of a low-cost Internet of Things sensor network for measurement of CO_2 and air quality indicators as a way to give cities more fine-grained and accurate data than would otherwise be available from standard sources such as energy companies, fuel sales, and national statistics. CTT can help in closing the gap between few high-quality measurements and the need of officials and citizens to have more detailed insights into emissions and greenhouse gases on a local level. Furthermore, cities will be able to accurately monitor specific impacts of policy changes on drastically reduced timescales (for example effects of signal timing, changes in road tolls, or increased investment in public transport).

There is a strong drive towards low-cost sensors networks [23] in many application domains, not least for air quality. With the infrastructure in place, we are also setting up a testbed for more general IoT for cities approaches. Additionally, the project ties in strongly to our related ongoing and future smart cities work.

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