Air Quality Sensing in Denmark

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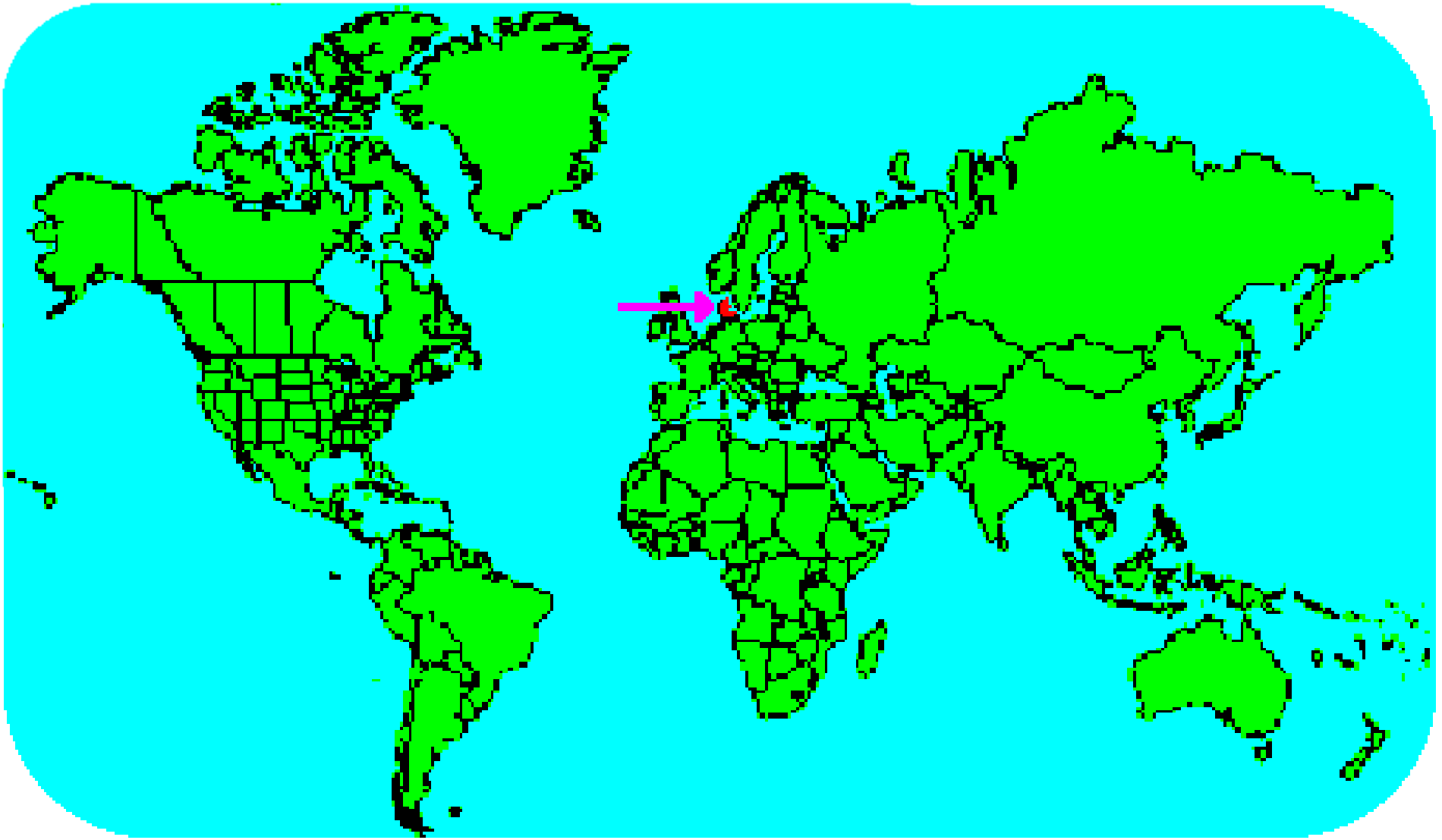
Network Startup Resource Center

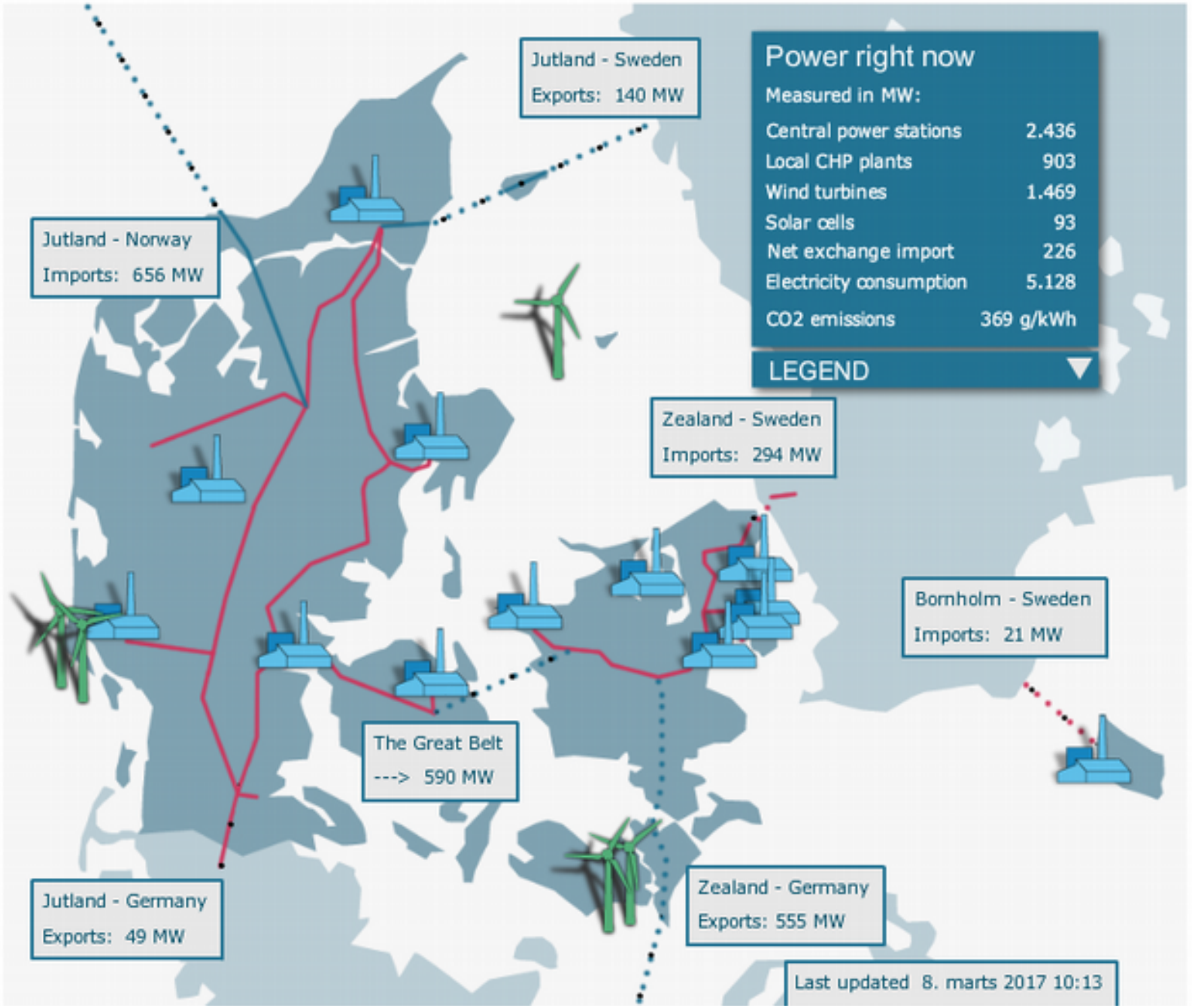
ICTP March 2017
ITU.dk
NSRC.org

Meet Denmark

Meet Denmark



Meet Denmark

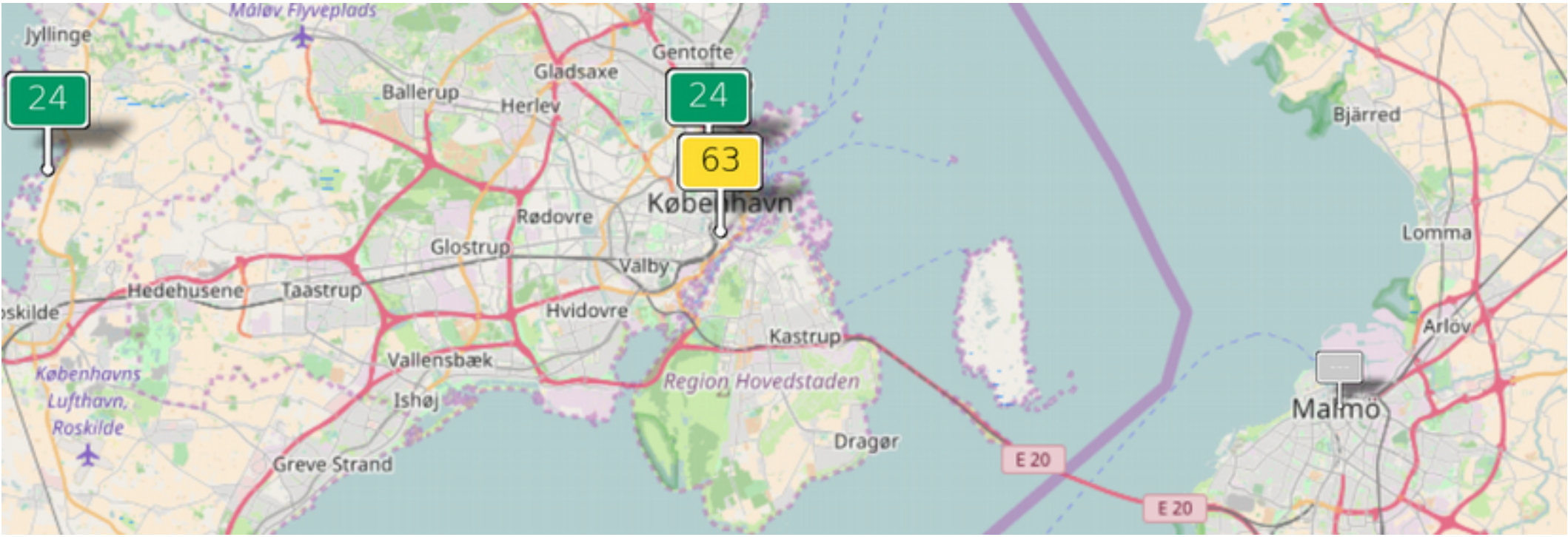


Meet Denmark

Meet Denmark

Meet Denmark

But things are not always green ...



But things are not always green ...

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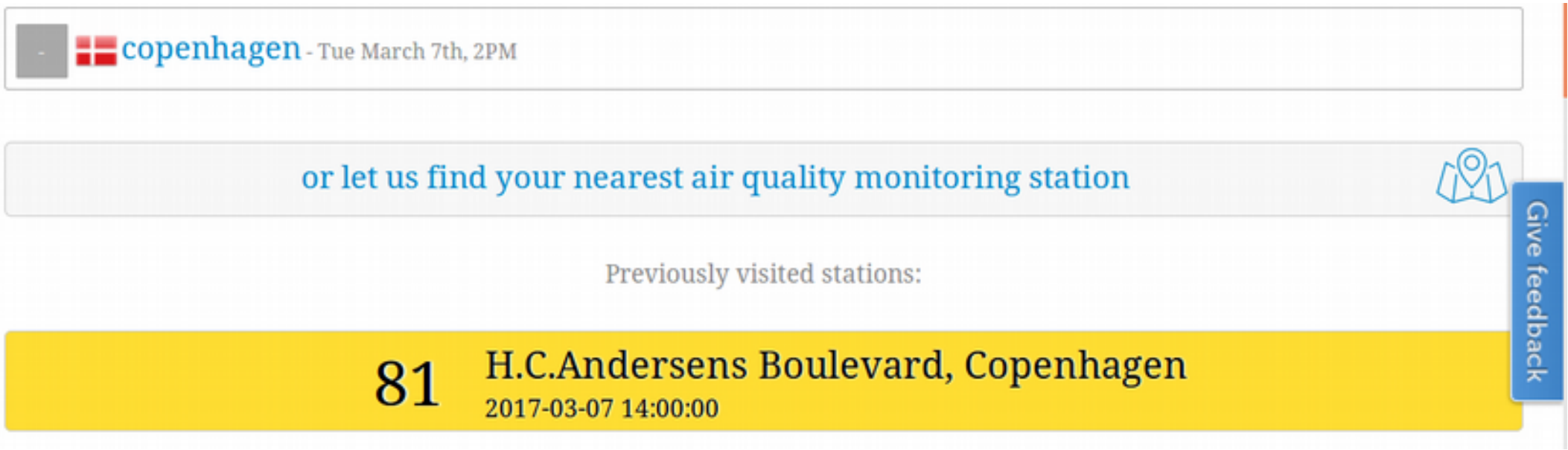
Source for international AQI : http://aqicn.org/

But things are not always green ...

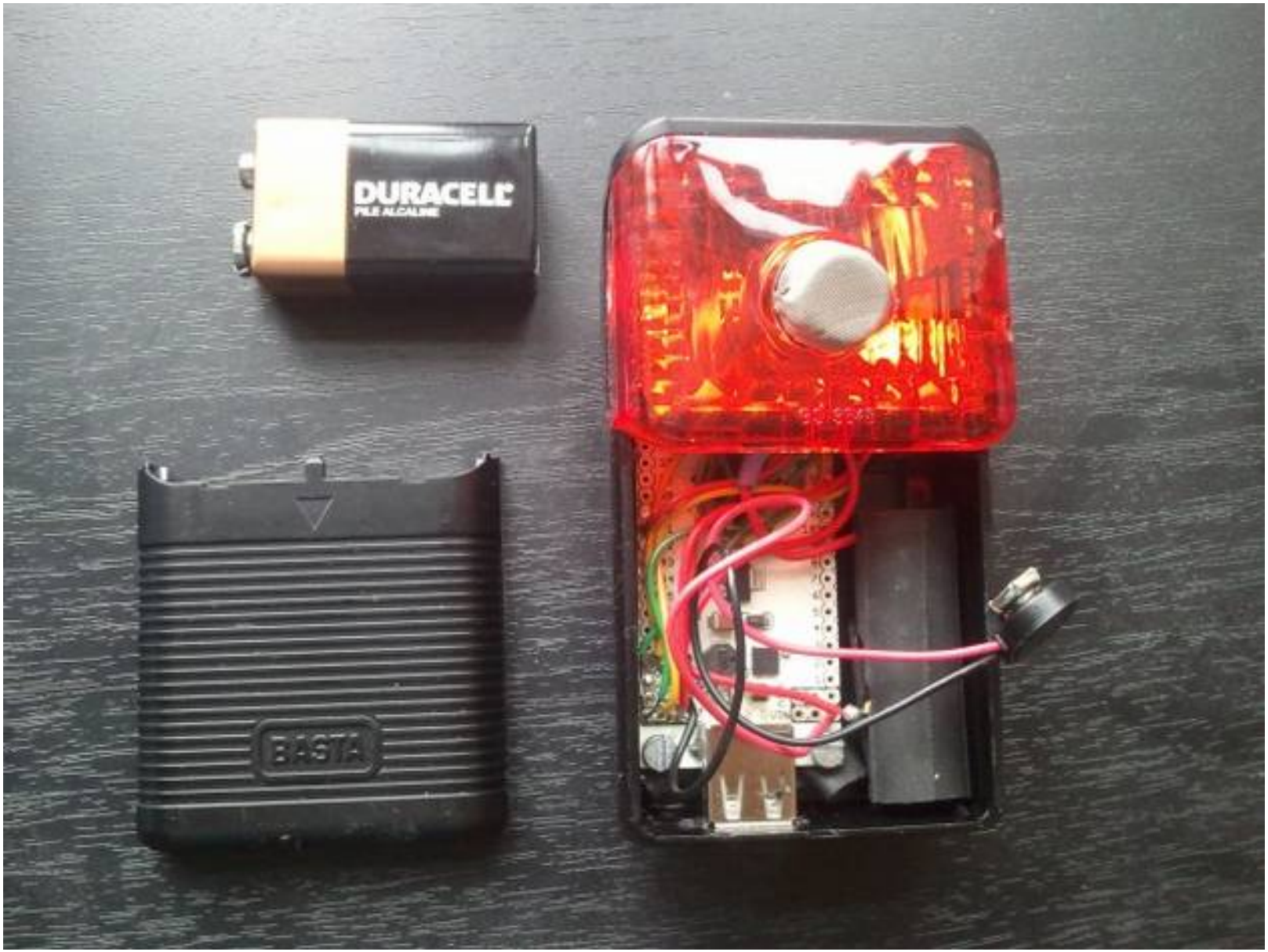


Back in 2011, at IT University ...

Project NoxDroid, http://noxdroid.org

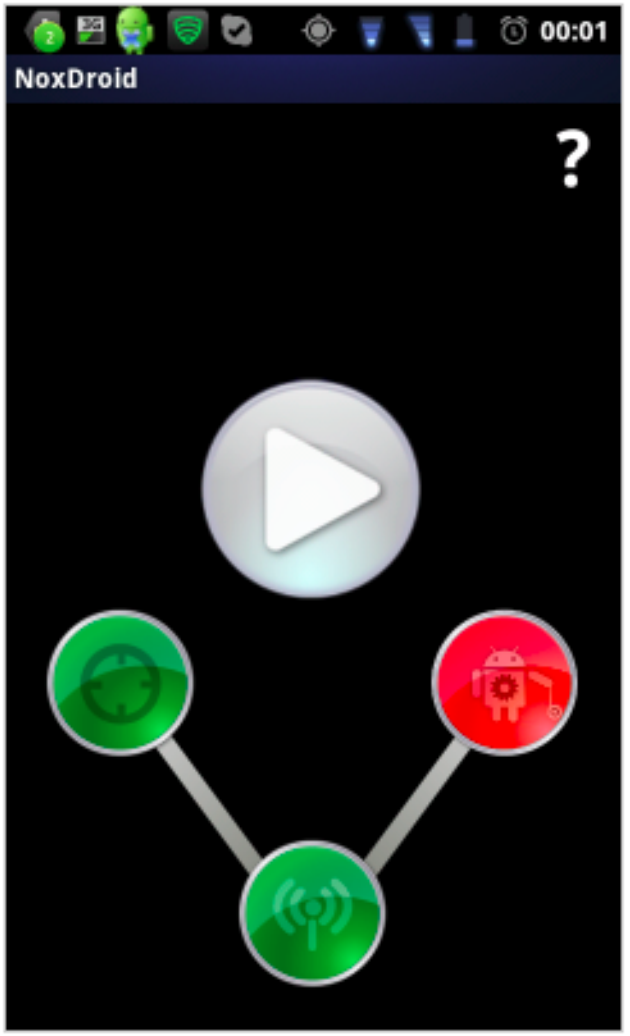
NOxDroid

Bike lights as air sensors

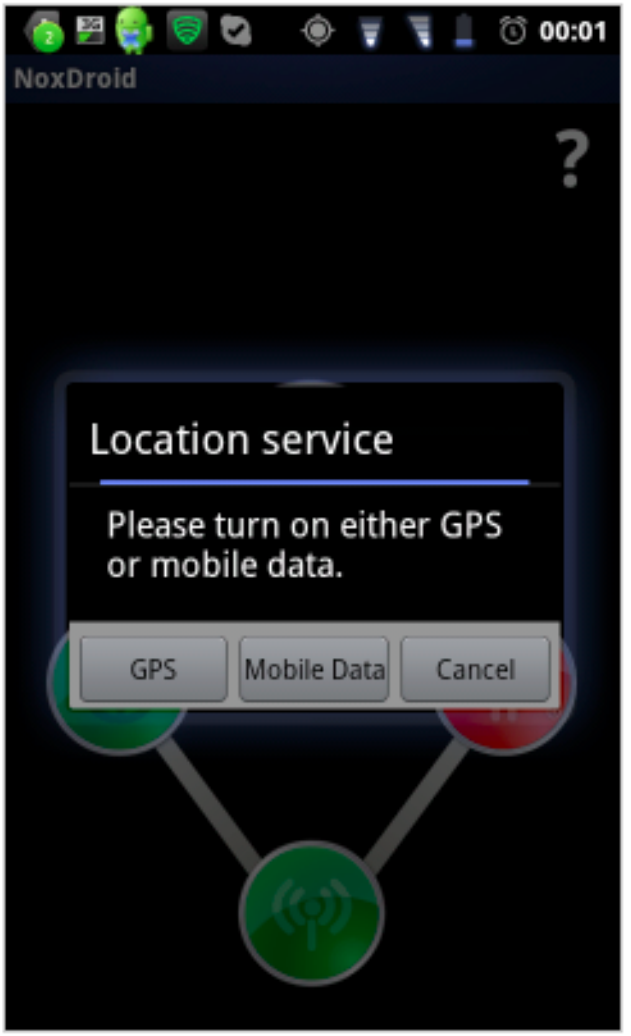


NOxDroid

Sensors, Arduino/IOIO, cable, Bluetooth, Mobile phone, GPS/time ==> map



Main screen



After pressing the GPS icon

NOxDroid

Live tracks

All worked well, but … a question:

What does it mean?

1/ What does the sensor measure? And what else?

2/ How precise?

3/ What is the threshold sensitivity?

4/ What gases are good indicators for Air Quality?

We could do the IT/networks parts easily,

But **we needed to talk to air quality experts.**

Introducing the Air Quality Index

$$I = \frac{I_{high} - I_{low}}{C_{high} - C_{low}}(C - C_{low}) + I_{low}$$

where:

I = the (Air Quality) index,
C = the pollutant concentration,
C_{low} = the concentration breakpoint that is ≤ C,
C_{high} = the concentration breakpoint that is ≥ C,
I_{low} = the index breakpoint corresponding to C_{low},
I_{high} = the index breakpoint corresponding to C_{high}.

EPA's table of breakpoints is:[35][36][37]

O_3 (ppb)	**O_3 (ppb)**	**$PM_{2.5}$ (µg/m³)**	**PM_{10} (µg/m³)**	**CO (ppm)**	**SO_2 (ppb)**	**NO_2 (ppb)**	**AQI**	**AQI**
C_{low} - C_{high} (avg)	*C_{low} - C_{high} (avg)*	*C_{low}- C_{high} (avg)*	*C_{low} - C_{high} (avg)*	*C_{low} - C_{high} (avg)*	*C_{low} - C_{high} (avg)*	*C_{low} - C_{high} (avg)*	*I_{low} - I_{high}*	**Category**
0-54 (8-hr)	-	0.0-12.0 (24-hr)	0-54 (24-hr)	0.0-4.4 (8-hr)	0-35 (1-hr)	0-53 (1-hr)	0-50	Good
55-70 (8-hr)	-	12.1-35.4 (24-hr)	55-154 (24-hr)	4.5-9.4 (8-hr)	36-75 (1-hr)	54-100 (1-hr)	51-100	Moderate
71-85 (8-hr)	125-164 (1-hr)	35.5-55.4 (24-hr)	155-254 (24-hr)	9.5-12.4 (8-hr)	76-185 (1-hr)	101-360 (1-hr)	101-150	Unhealthy for Sensitive Groups
86-105 (8-hr)	165-204 (1-hr)	55.5-150.4 (24-hr)	255-354 (24-hr)	12.5-15.4 (8-hr)	186-304 (1-hr)	361-649 (1-hr)	151-200	Unhealthy
106-200 (8-hr)	205-404 (1-hr)	150.5-250.4 (24-hr)	355-424 (24-hr)	15.5-30.4 (8-hr)	305-604 (24-hr)	650-1249 (1-hr)	201-300	Very Unhealthy
-	405-504 (1-hr)	250.5-350.4 (24-hr)	425-504 (24-hr)	30.5-40.4 (8-hr)	605-804 (24-hr)	1250-1649 (1-hr)	301-400	Hazardous
-	505-604 (1-hr)	350.5-500.4 (24-hr)	505-604 (24-hr)	40.5-50.4 (8-hr)	805-1004 (24-hr)	1650-2049 (1-hr)	401-500	

Who is monitoring?

Department of Environmental Science,
Aarhus University

http://envs.au.dk/en/knowledge/air/

Including knowledge base, real time data, modeling, and lots more

Copenhagen monitoring station, video
https://vimeo.com/39794264
NO2, PM model data
http://lpdv-en.spatialsuite.dk/spatialmap?
Copenhagen real time data
http://www2.dmu.dk/atmosphericenvironment/byer/forside.htm

Who is monitoring?

Department of Environmental Science

- Home
- About the Department
- Research
- Science-based advisory Activities at ENVS
  - Environmental Chemistry
  - Adaptation to Climate Change
  - Air pollution
    - Air quality at your street
    - Air pollution forecast
    - Monitoring
    - Emission inventories
    - Air pollution models
    - Collaboration networks
    - Publications - air
    - Air pollution, links
  - Sustainable Energy and Environment
  - Resource Flows in the Environment
  - Risk Assessment
  - Emission Inventories
  - Public Sector Consultancy Committee
  - Business cooperation
- Education
- Current affairs
- Contact

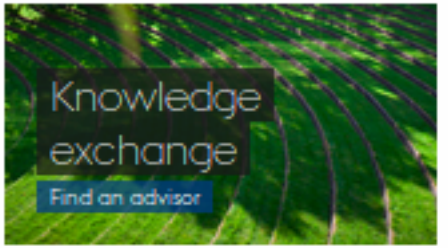
Air pollution

Direct adress to the current web page envs.au.dk/air

Use the menu on the left to find results of air pollution monitoring, inventories of Danish emisssion to the air, information on air pollution models and much more.

A remarkable new service launched in 2016 is "Air Quality at your Street" (opens in new window). An interactive map shows air pollution in Denmark in general and in detail, even to the level of each single address (the service is currently in Danish only).

Photo: Lise Balsby, Aarhus University



For staff only | For PhD students

Employees

- List of employees at Department of Environmental Science

Introduction

Air pollution has a substantial impact on health, Nature and climate. Issues currently in focus in Denmark are population exposure to particle pollution, and nitrogen deposition to sensitive parts of our countryside and to marine areas. On a worldwide level, the most serious problem is the emission of CO_2 (carbon dioxide) and other greenhouse gases that can contribute to global warming.

Aarhus University's activities within air pollution

The topic of Air Pollution is a "Research flagship" at Aarhus University, meaning that it is a high priority area, and that internationally recognized research of high quality is conducted.

The research involves studies of the physical, chemical and biological processes in the atmosphere governing inorganic, organic and biological environmental constituent. It further includes how these constituents affects health, environment and climate in different parts of the world, but mainly in Denmark, Europe and the Arctic environment.

Focus is particularly on the subject of air quality and health, including research on the effect of airborne particles on health. Thus, "Atmospheric pollution and impacts on human health" is defined as a so-called "Strategic Growth Area" at the Department of Environmental Science.

Aarhus University (AU) conducts field studies of air pollution and climate parameters in Denmark as well as internationally in close cooperation with other research groups. Work with mathematical models that can

Environmental Sciences

Background: Cost Action EuNetAir

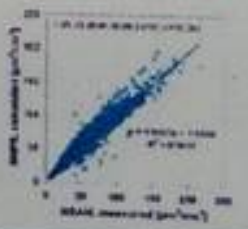
cost

EuNetAir

New Sensing Technologies for Air Quality Monitoring

Challenges addressed by Action TD1105

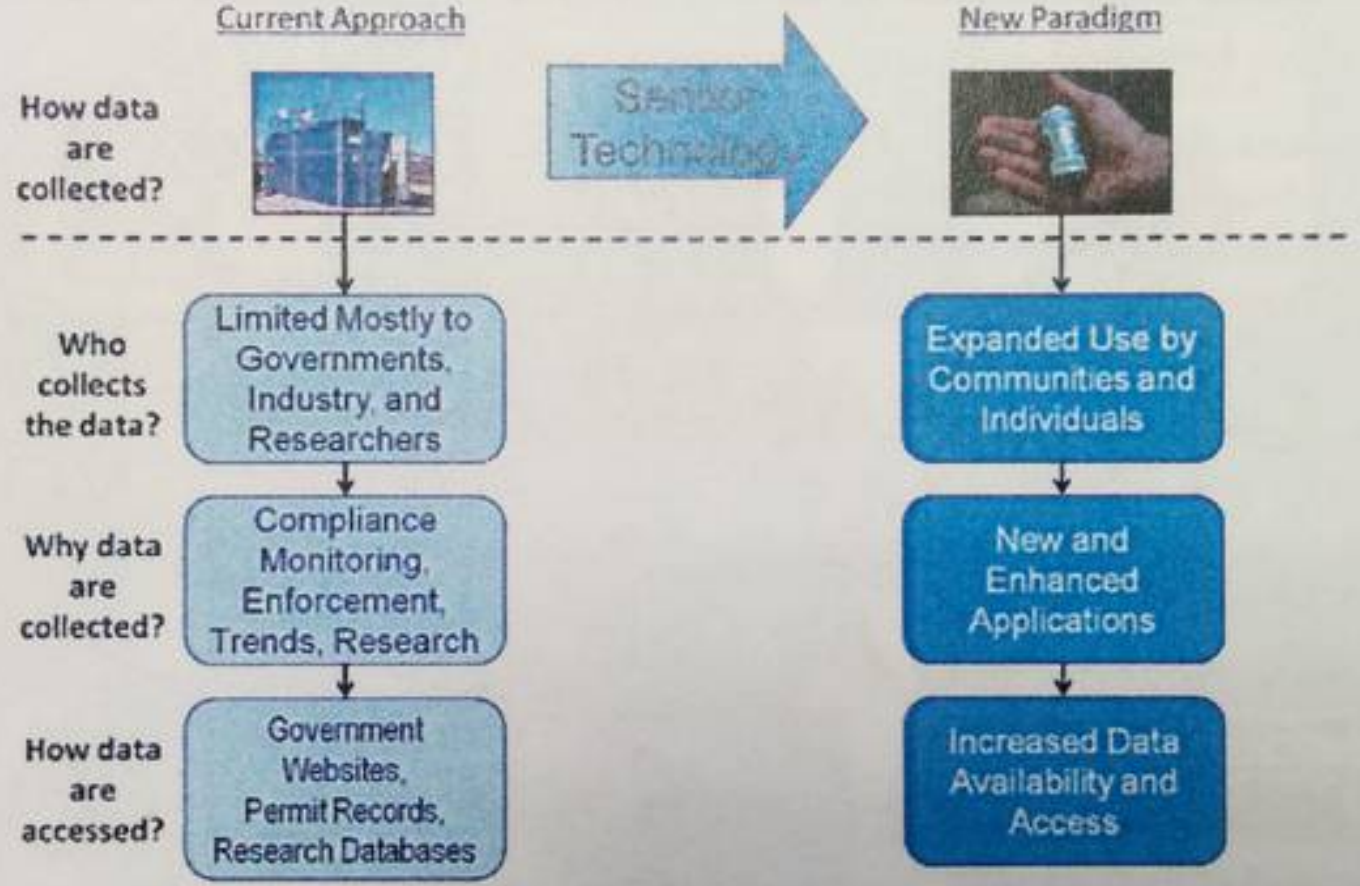
- **Nanomaterials for AQC sensors**
- **Low-cost Gas Sensors**
- **Low-power Sensor-Systems**
- **Wireless Technology (*Environmental Sensors Network*)**
- **Air Quality Modelling**
- **Environmental Measurements**
- **Standards and Protocols**



Source: M. Penza (ENEA), EuNetAir Chairman

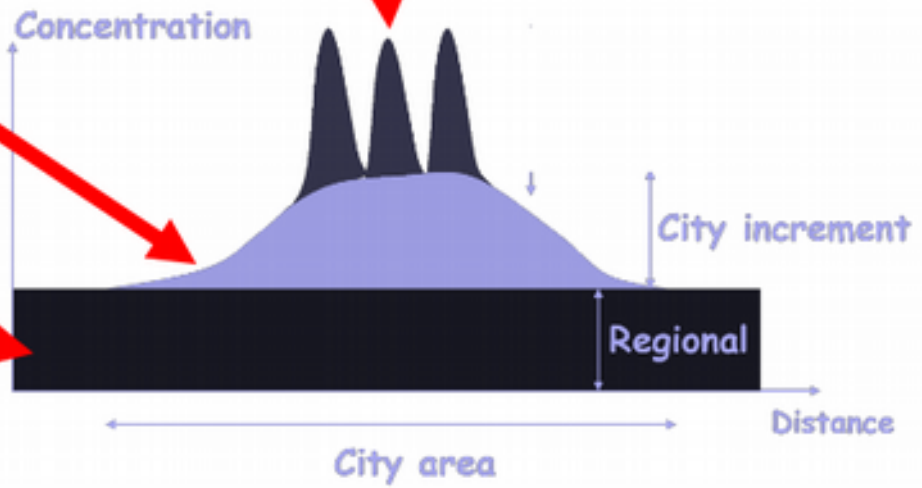
Environmental Sciences

Changing Paradigm of Air Pollution Monitoring

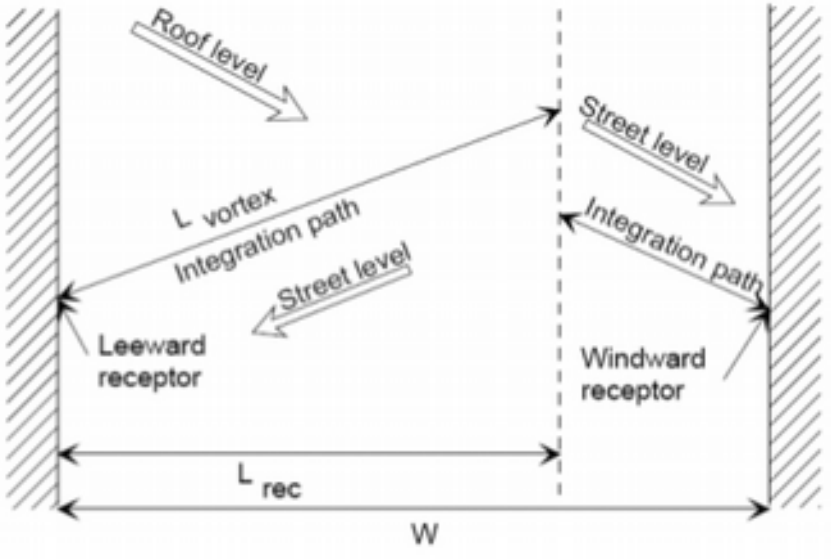


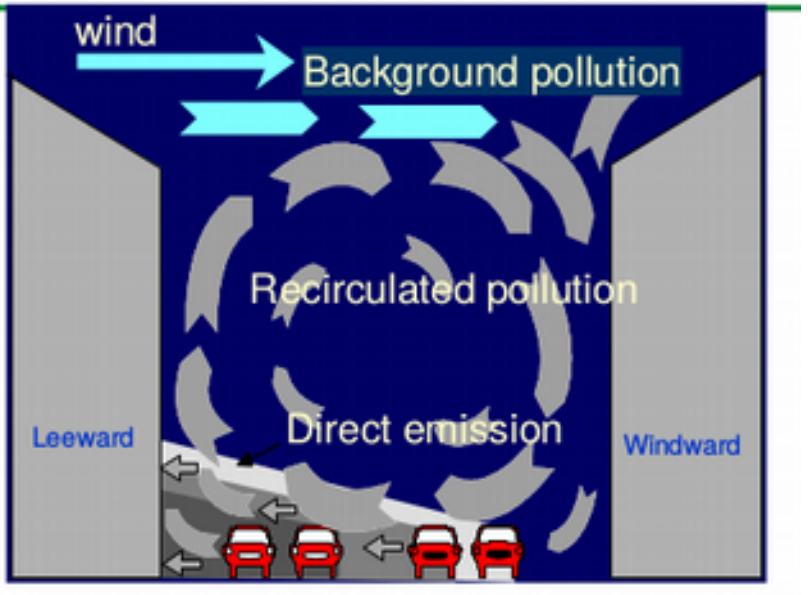
Source: E.G. Snyder et al. (U.S. Environmental Protection Agency): The Changing Paradigm of Air Pollution Monitoring, Environ. Sci. Technol., 2013, 47 (20), pp 11369–11377

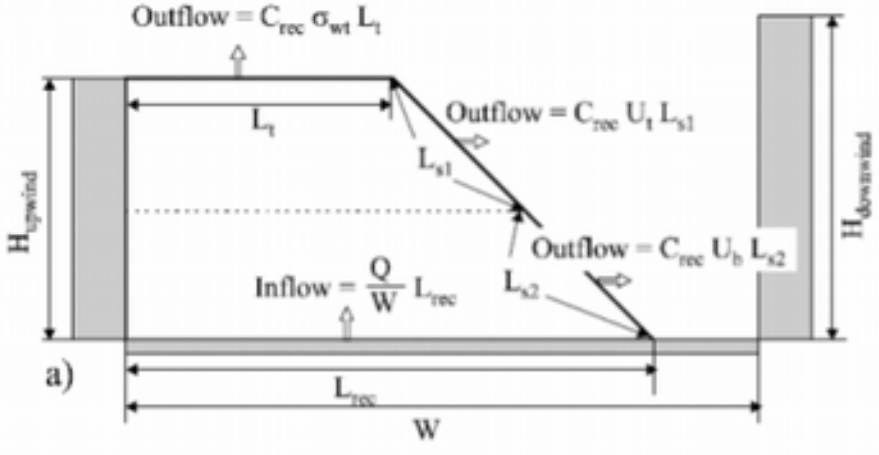
Regional – Background - Street

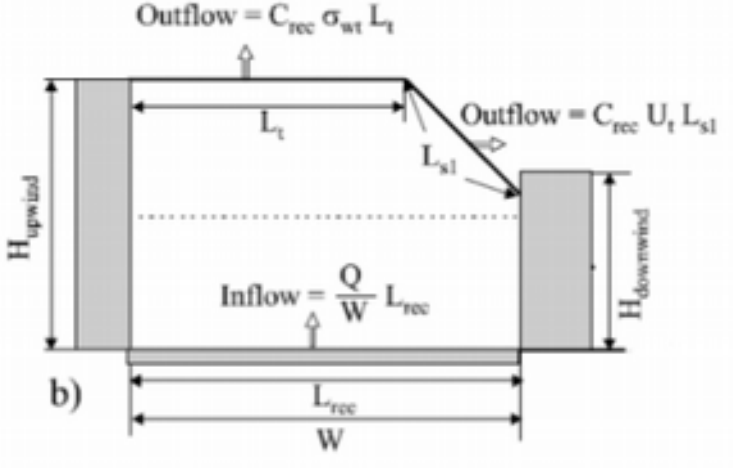


Urban Modeling



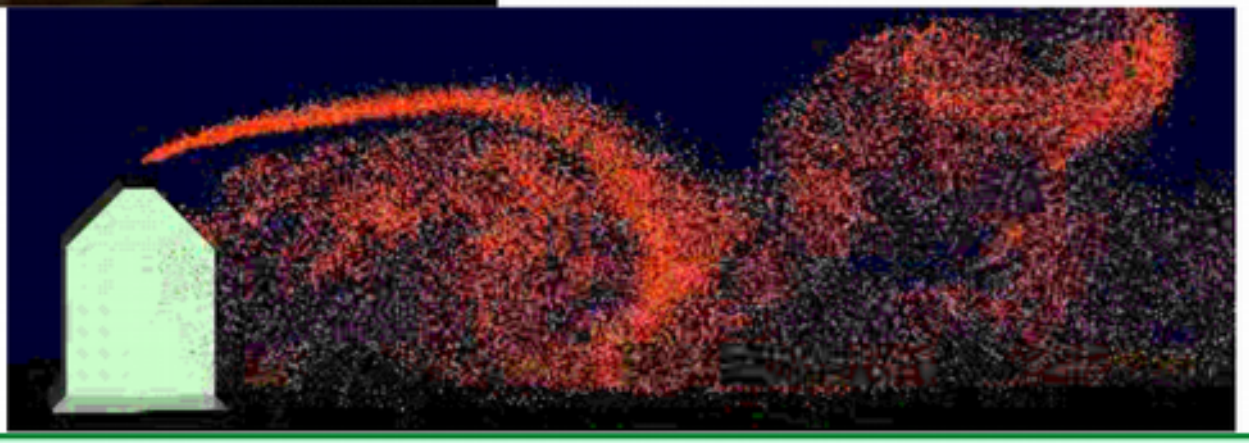






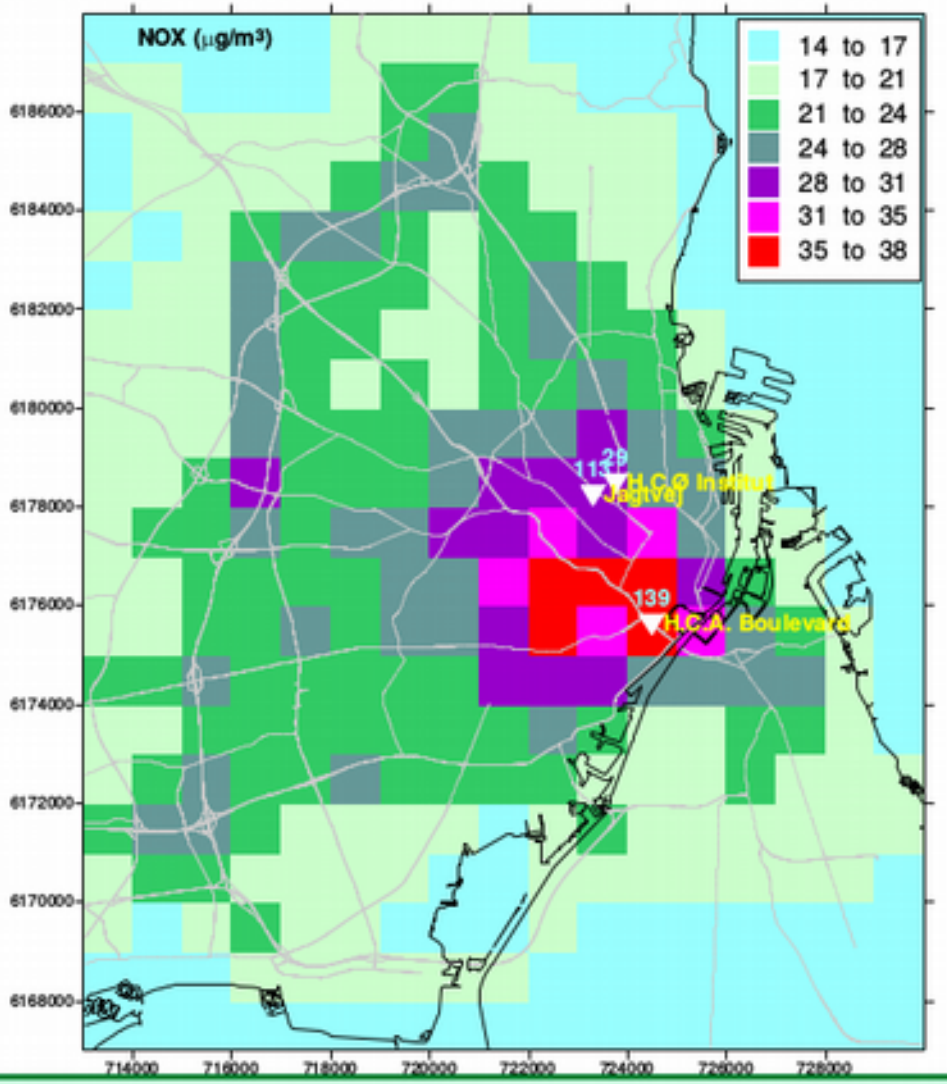
Physical Modeling

Physical modelling – wind tunnels



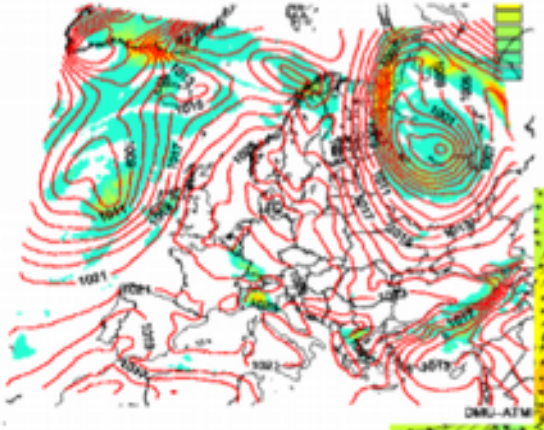
Urban Background Model

Urban Air Pollution computed with the Urban Background model (UBM)



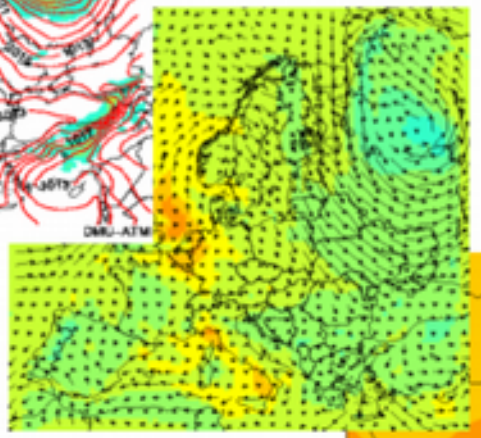
From large scale to detail

Coupled models in the THOR system

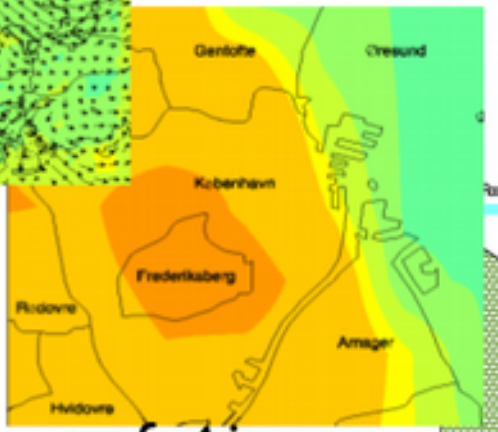


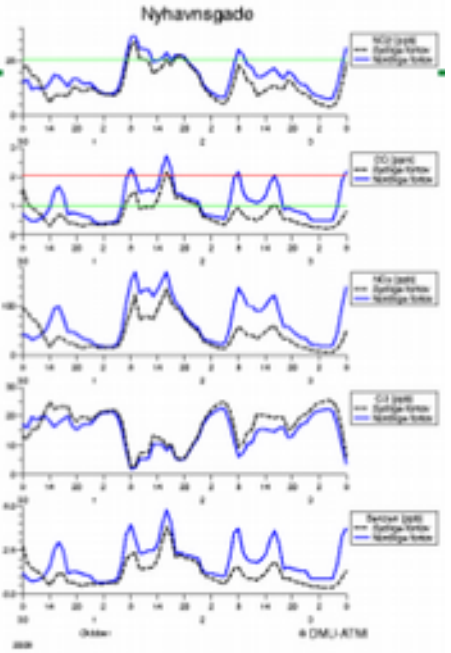
Weather

Long-range transport



Urban scale





Street level

Performs 3-days prognoses of Air Quality 4 times a day

What we learned

1/ **Do NO2, O3** and maybe PM

(but PM is difficult:

relatively easy to measure,

very difficult to interprete)

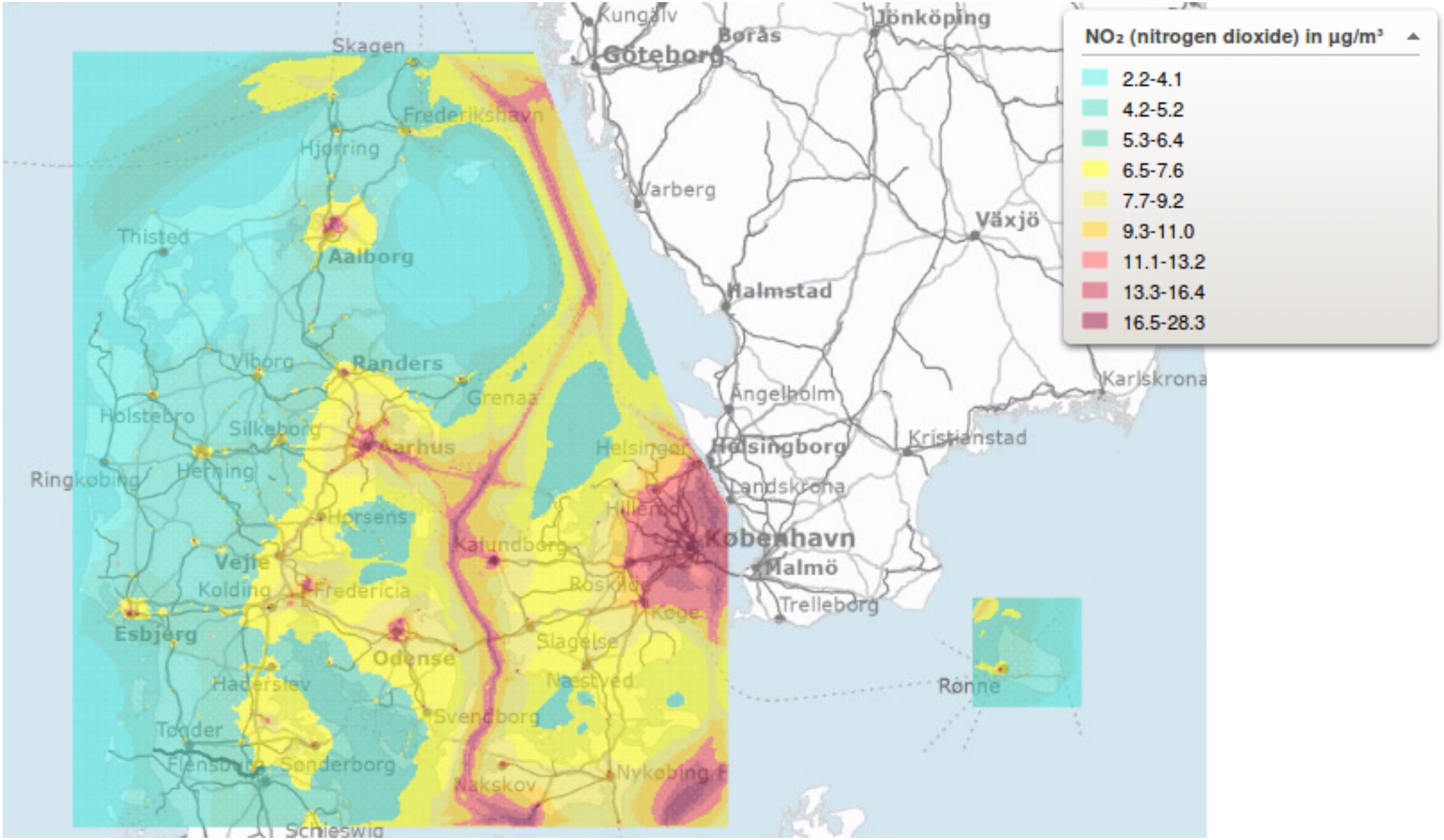
2/ Study the sensors in detail!

So we left the things we know (apps, arduinos networks) aside for a while

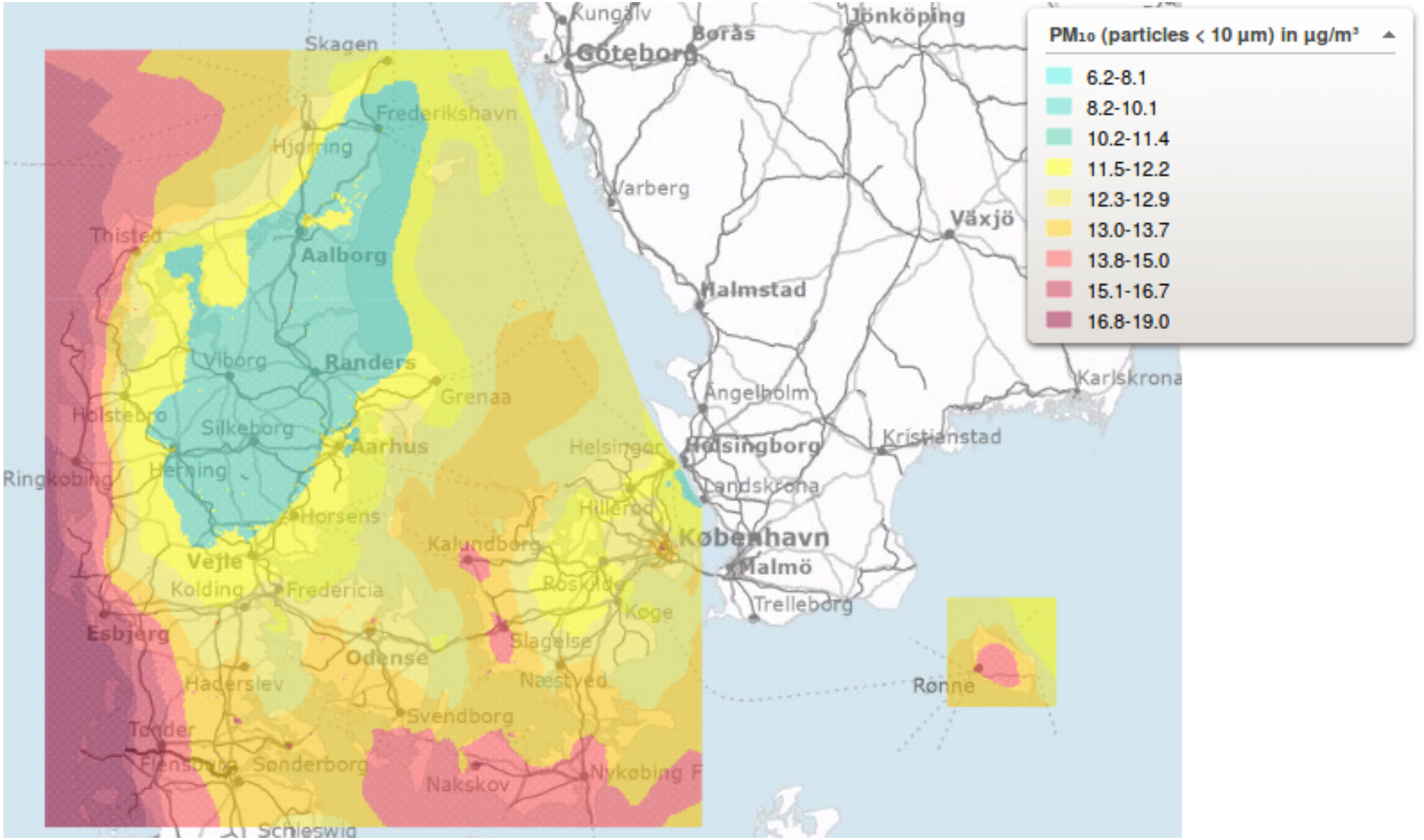
and looked at **sensors**.

But before that, a quick look at PM vs. NO2:

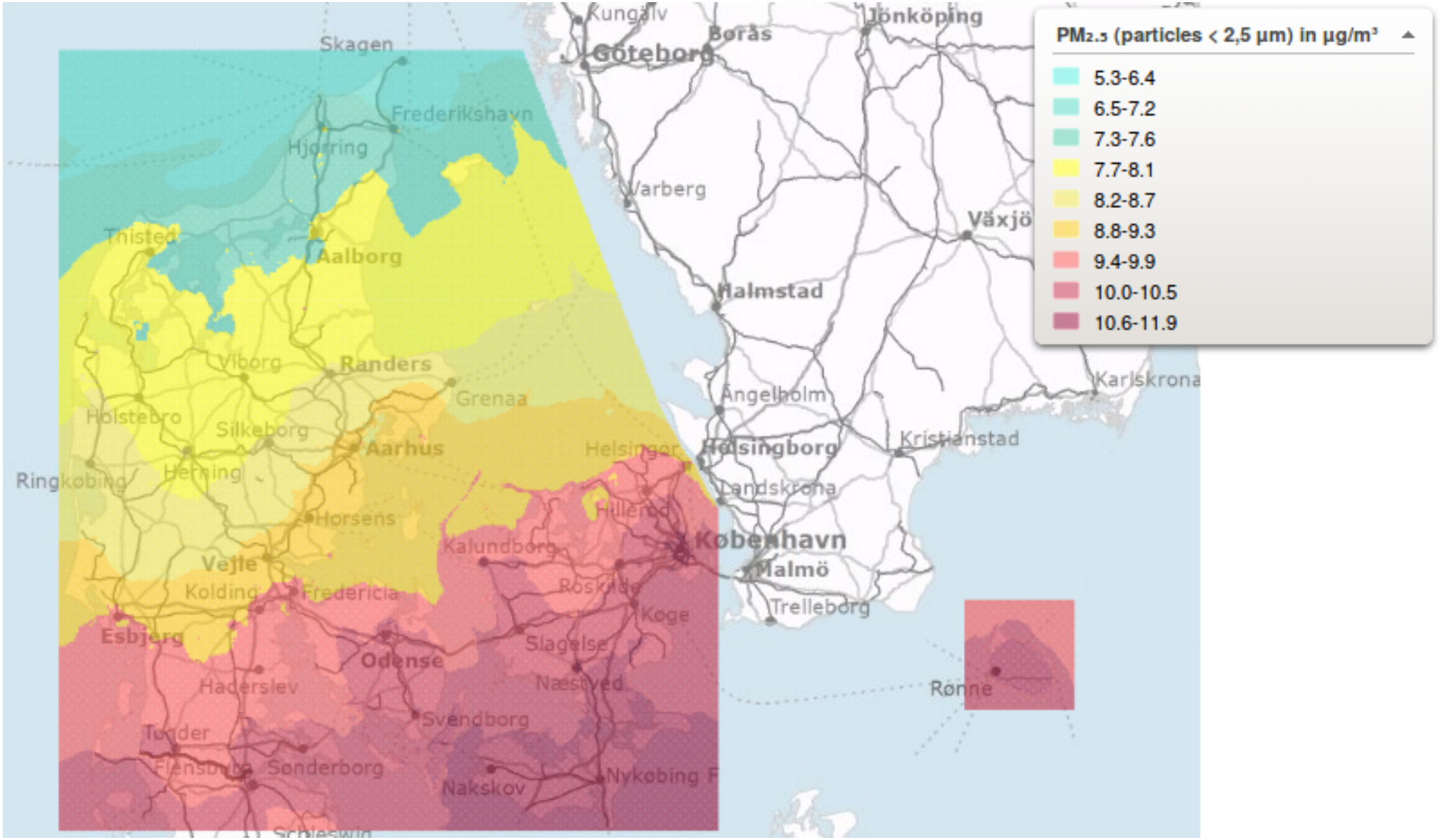
Public data / Models / NO2



Public data / Models / PM10

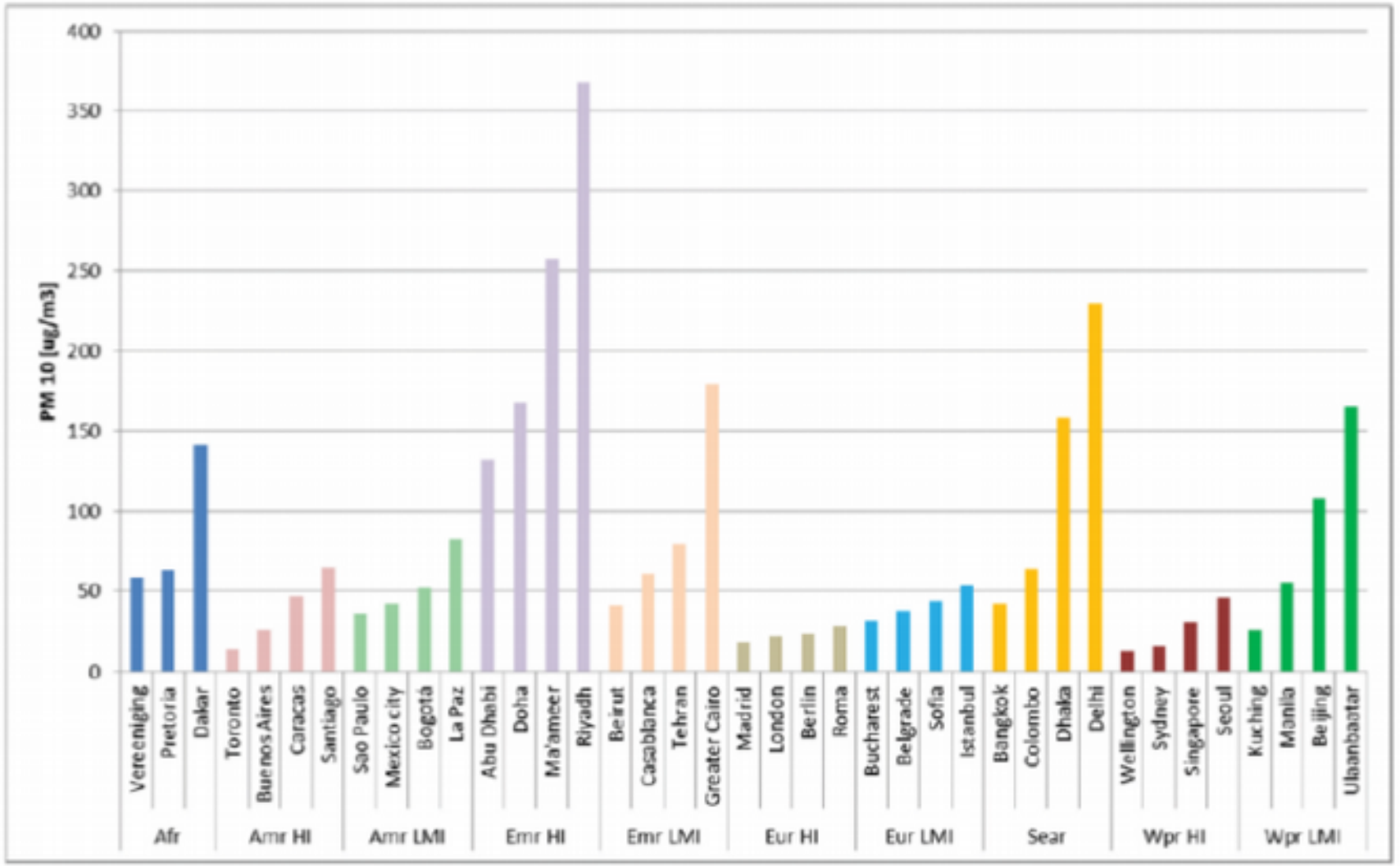


Public data / Models / PM2.5



About Particulate Matter (PM)

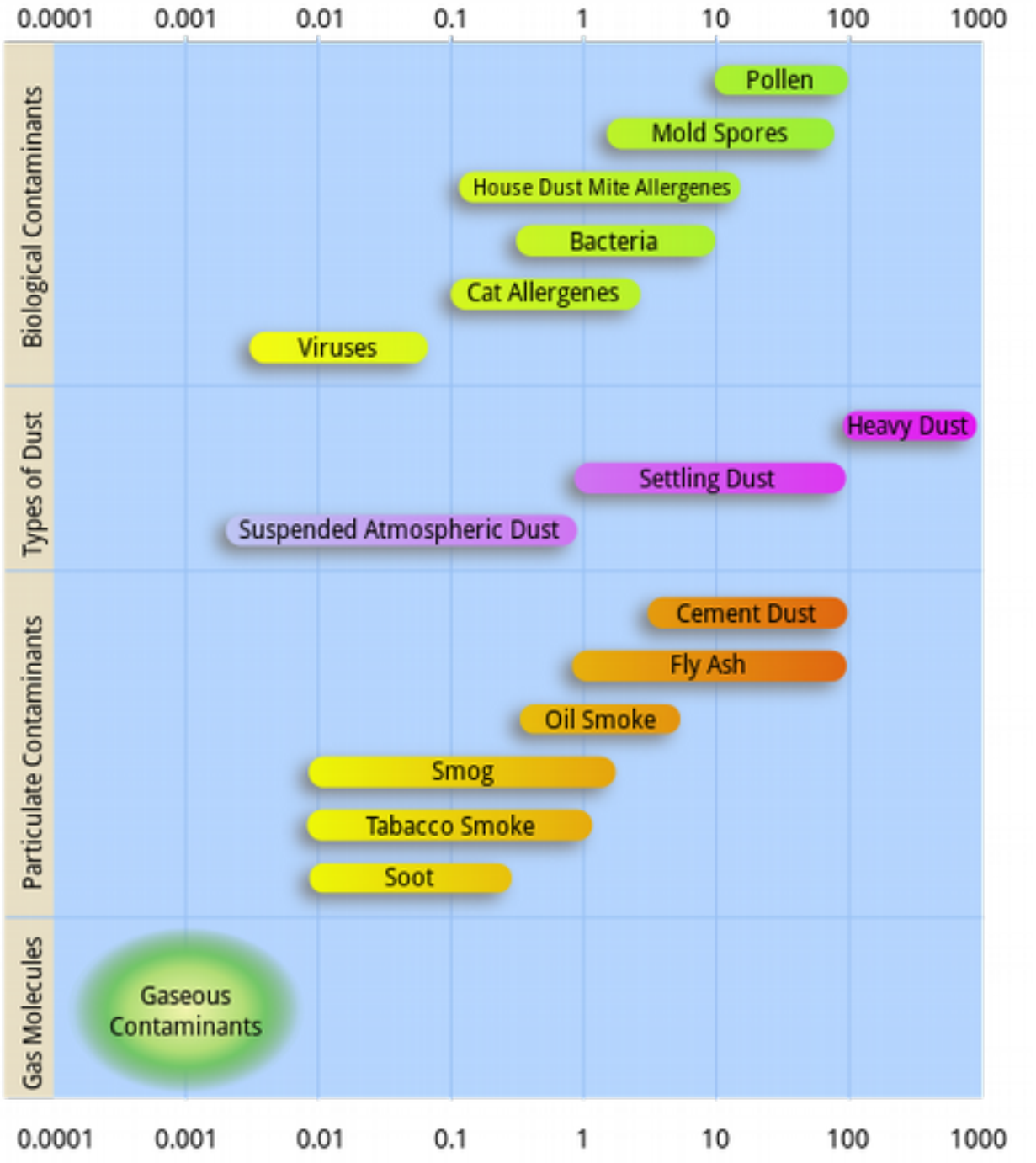
Figure 3: *PM_{10} levels for selected[2] cities by region, for the last available year in the period 2011-2015.*



PM_{10}: Fine particulate matter of 10 microns or less; Afr: Africa; Amr: America; Emr: Eastern Mediterranean; Eur: Europe; Sear: South-East Asia; Wpr: Western Pacific; LMI: Low- and middle-income; HI: high-income.

http://www.who.int/phe/health_topics/outdoorair/databases/cities/en/

About Particulate Matter (PM)



So ...

… we looked at **sensors**

used in citizen science …

And it did not

look so good ...

Overview table

Gas/Pollutant	Sensor	Range	Sensitivity	Typical range in C/ph	Needed resolution f % precision	Usable?
CO	Figaro TGS2442	10 – 1000 ppm	None in needed range	0.1 - 1 mg/m3 0.1 - 1 ppm	10 ppb	no
	Figaro TGS2600	1-100 ppm	None in needed range	0.1 - 1 mg/m3 0.1 - 1 ppm	10 ppb	no
	AS-MLC	0.5 - 500 ppm	Almost none in needed range	0.1 - 1 mg/m3 0.1 - 1 ppm	10 ppb	no
	Zhengzhou Winsen ME4-CO	0-1000 ppm	65 ppm 2-20 uA	0.1 - 1 mg/m3 0.1 - 1 ppm	10 ppb	no
	MQ-135	10-1000 ppm		0.1 - 1 mg/m3 0.1 - 1 ppm	10 ppb	
	CMM30-02	0 ~ 800ppm	? claims "Linear analog output proportional to gas concentration"	0.1 - 1 mg/m3 0.1 - 1 ppm	10 ppb	Maybe
	MQ-9 Grove	10-1000ppmCO		0.1 - 1 mg/m3 0.1 - 1 ppm	10 ppb	no
	MICS-4514 Combined CO and NO2 Sensor	1-1000 ppm CO		0.1 - 1 mg/m3 0.1 - 1 ppm	10 ppb	no
	TGS10-AN	0-100 ppm				Yes?
	ECO-Sens (2e) LXH version CO	0-200 ppm				Yes?
SO2						
O3	MQ-131	10-1000 ppm		0 ... 50 ppm		partly
NOx	MICS-4514 Combined CO and NO2 Sensor	0.05-5 ppm		0 .... 0.2 mg/m3 0 ... 0.1 ppm		maybe
PM	Sharp GP2Y1010AU0F	0-0.7 mg/m3	0.5 V/ 0.1 mg/m3	0 ... 0.1 mg/m3	0.001 mg/m3	Possibly, with 0-10 bit ADC at Uref=1V

But wait: Wisdom of the Crowd?

“The wisdom of the crowd is the collective opinion of a group of individuals rather than that of a single expert.

A large group's aggregated answers to questions involving quantity estimation, general world knowledge, and spatial reasoning has generally been found to be as good as, and often better than, the answer given by any of the individuals within the group.”

Sensors of the Crowd?

“Maybe your individual sensor is not good enough, but surely, if you have many …?”

We will get back to that ...

Sensors for air, gases

1/ Pellistors
2/ Electrochemical
3/ Semiconductor cells
4/ Field Effect devices
5/ Mass sensitive devices
6/ Optical (mostly for PM)

Our criteria: the 3 S

Sensitivity
Selectivity
Stability

Our enemies:

Watts & $$$s

Sensors for air, gases

1/ Pellistors
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Our criteria: **the 3 S**

Sensitivity
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Our enemies:

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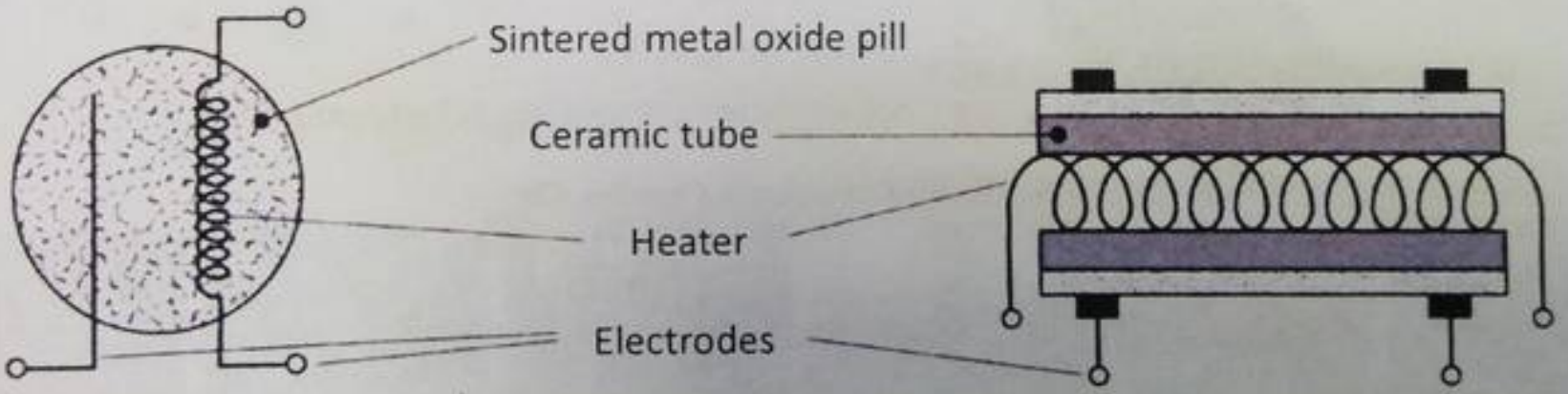
Semiconductor sensors

Semiconductor gas sensors I: function principle

- Gas adsorption/-reaction changes electrical properties (impedance) of the semiconducting gas sensitive layer
  (however, often only the "ohmic" resistance is evaluated)
- Gas sensitive materials:
  - Metal oxides (i.e. SnO_2, Ga_2O_3, WO_3, In_2O_3, ZnO) with additional catalysts
  - organic semiconductors (Phthalocyanine, polypyrroles)
- Manufactured at first as pressed composites, see below
- Today, screen printing is most widely used



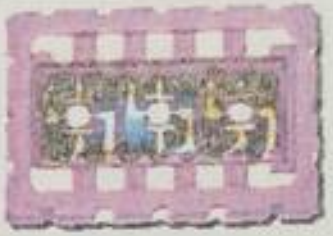
Source: Figaro, Inc.

Semiconductor sensors

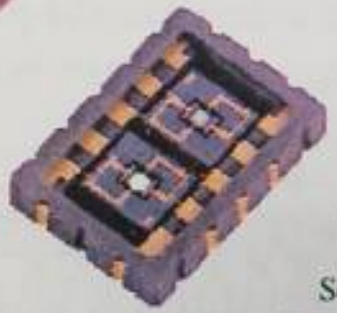
Semiconductor gas sensors III: MEMS sensors

Metal oxide semiconductor sensor in MEMS technology

- Micro hotplate: reduced power and time constant
- Gas-sensitive layer deposited via screen-printing, drop dispension or PLD (pulsed laser deposition)



Dual Gas Sensor



Primary application today

- Automotive Cabin Air Quality

Future applications?

- Fire detection
- Indoor Air Quality
- Smartphone integration (cf. chapter 11)

Source: SGX Sensortech, Corcelles, CH

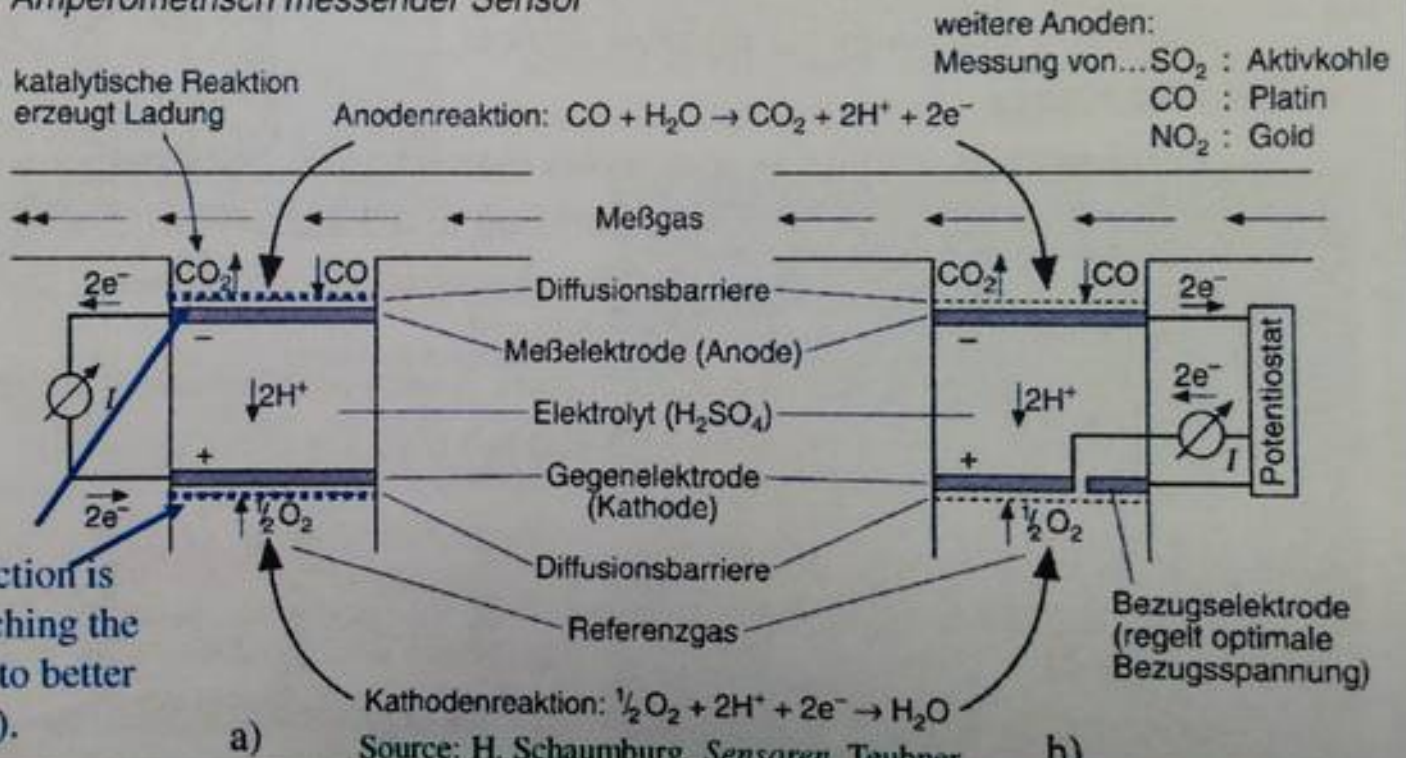
Electrochemical sensors

Electrochemical cells I: function principle

- Gas molecules are ionized at the measurement electrode, an electrolyte in the sen-sor allows ions to reach the counter electrode, the resulting current is measured.
- Selectivity can be influenced by selection of the electrolyte, measurement electrode material and the electrical potential.

Amperometrisch messender Sensor

Source: Alphasense



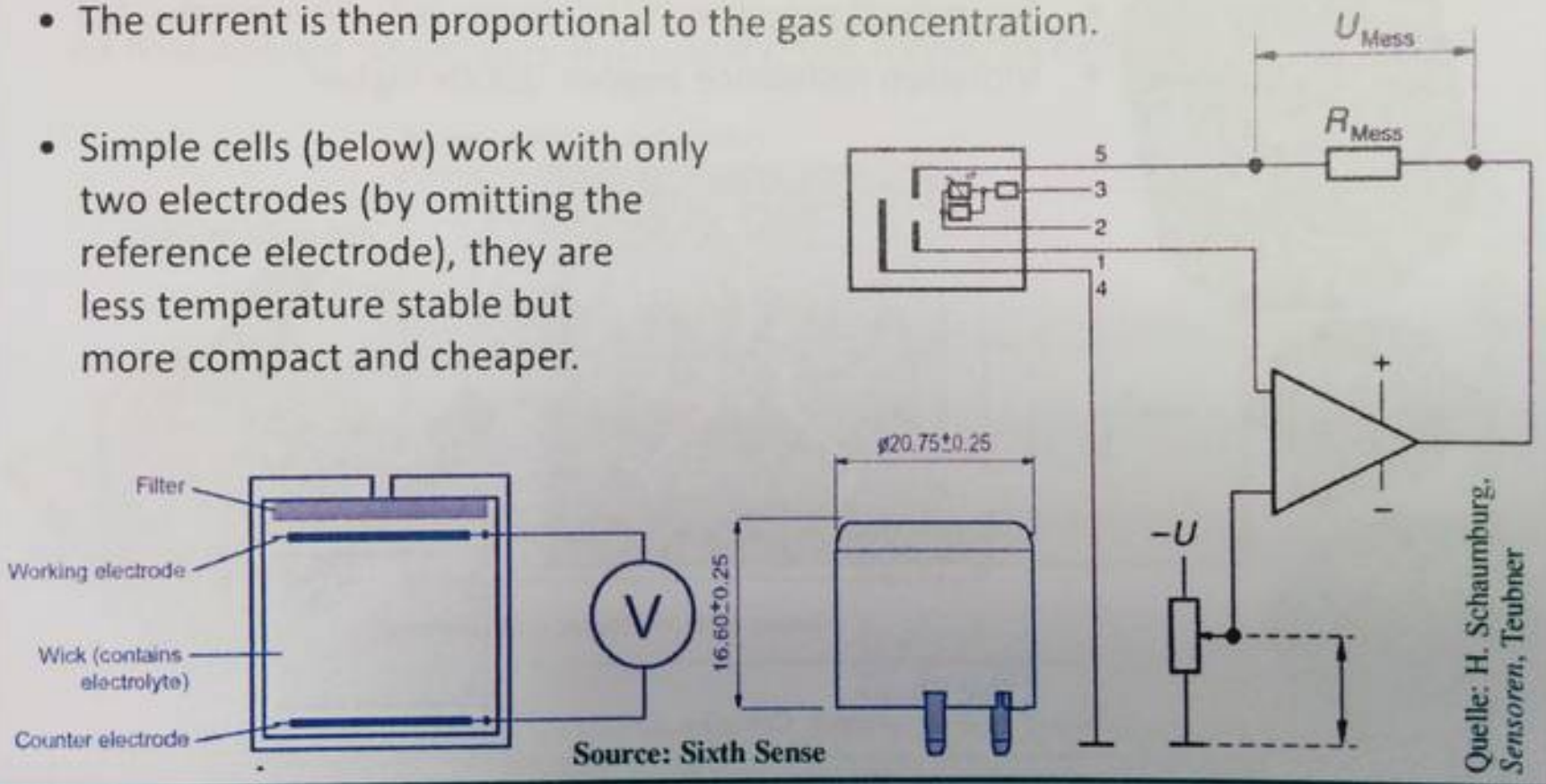
Diffusion limited gas access, i.e. reaction is limited by gas reaching the electrode (leading to better long term stability).

Source: H. Schaumburg, *Sensoren*, Teubner

Electrochemical sensors

Electrochemical cells II: electrical circuit

- A potentiostat keeps the voltage between measurement and counter electrode stable, the reference electrode is used to supply a defined reference potential.
- The current is then proportional to the gas concentration.
- Simple cells (below) work with only two electrodes (by omitting the reference electrode), they are less temperature stable but more compact and cheaper.



Electrochemical sensors

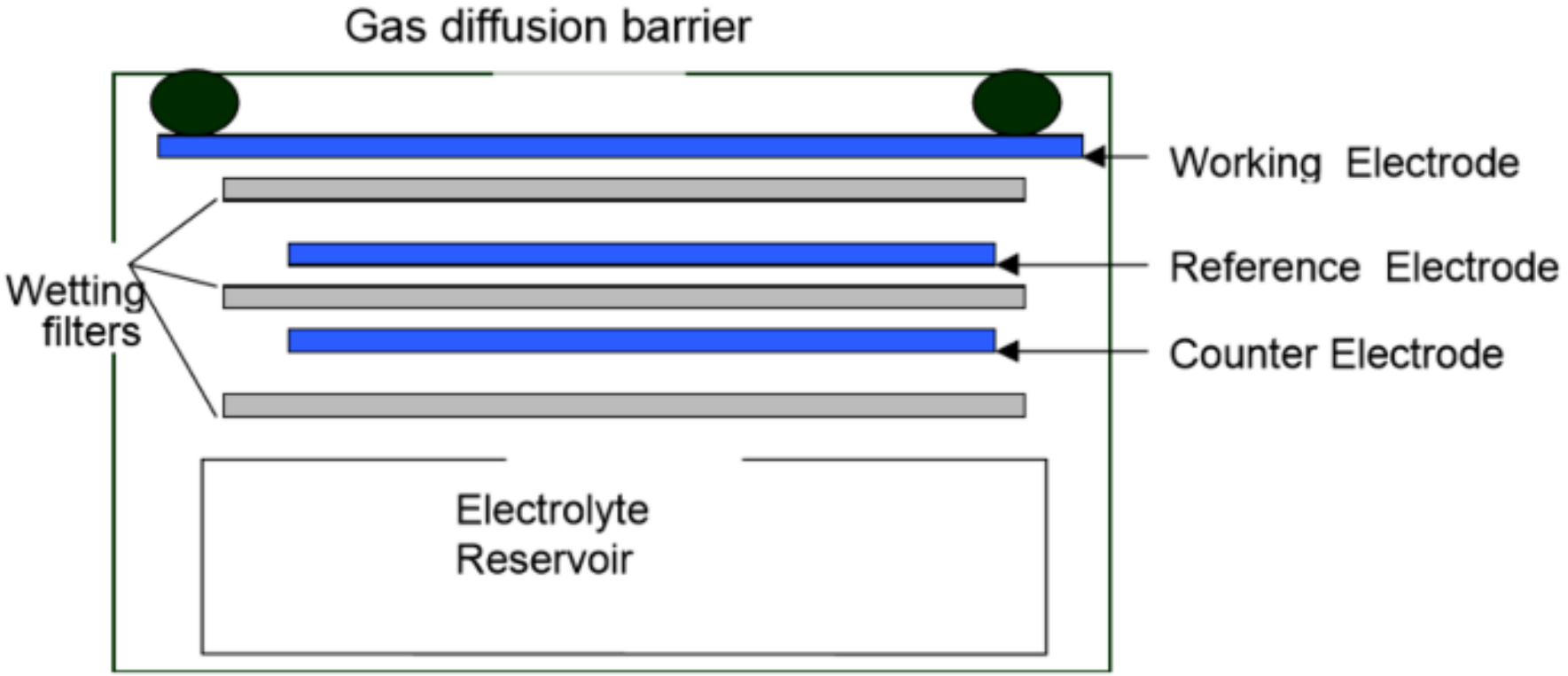


Figure D.3: A schematic diagram of a 3-electrode toxic gas sensor. The Alphasense 4-electrode sensors have an additional auxiliary electrode within the cell. From Alphasense Ltd. (2015f)

Sensors for Nitrogen dioxide NO2

(Low to moderate price!)

SGX Sensortech Limited
http://www.sgxsensortech.com/sensor-selector/
MICS-4514, -2710 MEMS MO

Spec Sensors
https://www.spec-sensors.com

Alphasense (Electrochemical)

A look at citizen science projects

e.g. the AirQualityEgg

A community-led air quality sensing network that gives people a way to participate in the conversation about air quality.

Created by

#Sensemakers

927 backers pledged $144,592 to help bring this project to life.

A look at citizen science projects

What are others using?

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Important: I will say critical things about it here –
NOT to be disrespectful, but to illustrate our shared challenges!
Read more: http://citizensense.net/air-quality-egg/

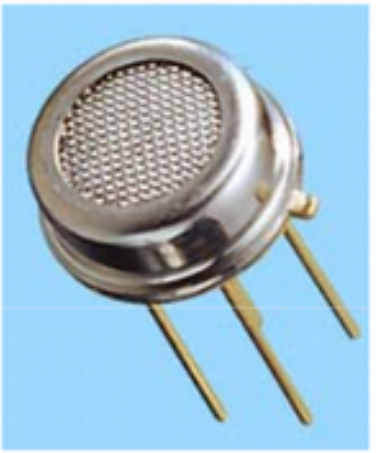
Inside the AirQualityEgg

“The standard AQ Egg has four built-in sensors - Temperature, Humidity, Carbon Monoxide, and Nitrogen Dioxide. Additional sensors can be added to the AQ Egg. These add-ons include an ozone sensor (MiCS 2610/2611 sensor), particulate matter sensor (Shinyei PPD42), and a VOC sensor (MiCS 5521 sensor).”

MICS-2710

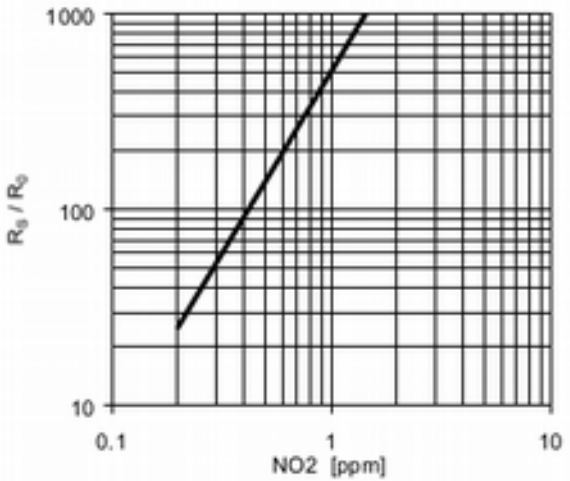
MiCS 2710 datasheet

MiCS-2710
NO_2 Sensor



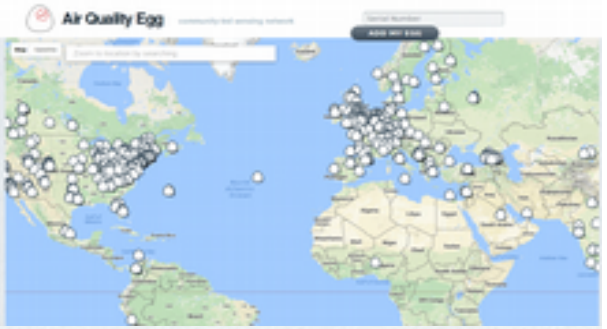
SENSOR RESPONSE

The sensor response to NO_2 in air is represented in Fig. 1.



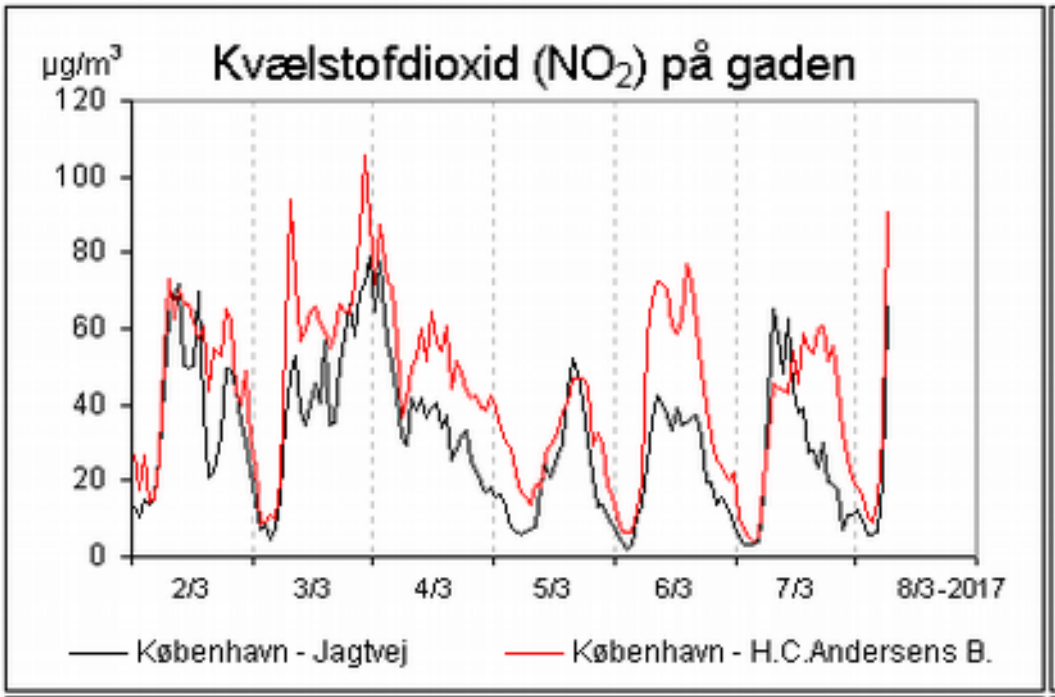
The sensor resistance R_S is normalised to the resistance under air (R_0).

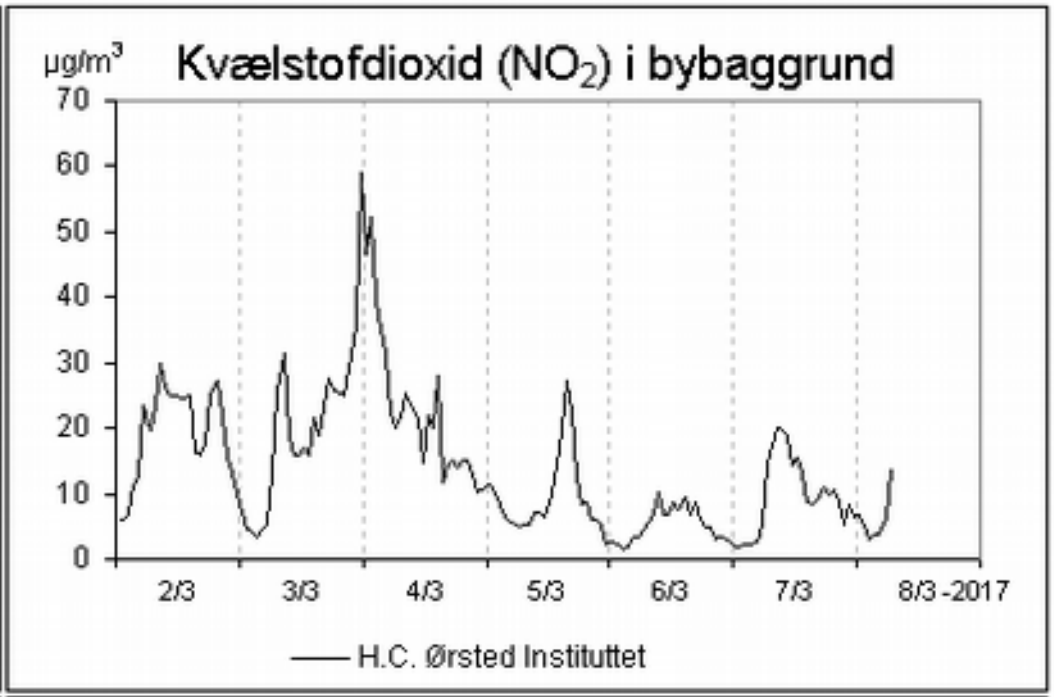
AQE outputs

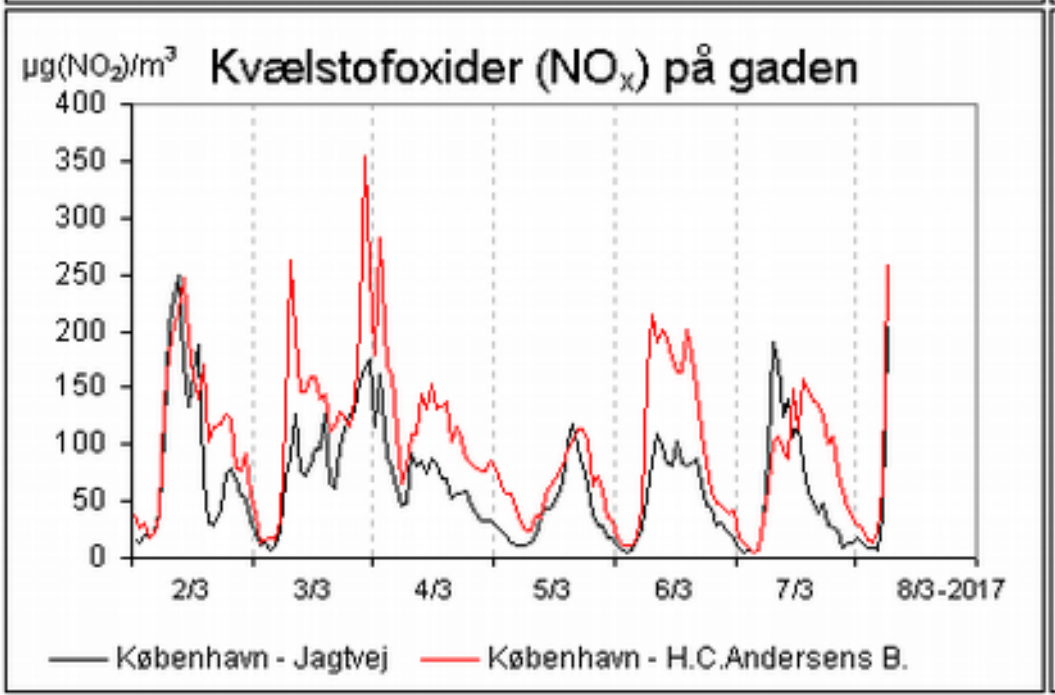


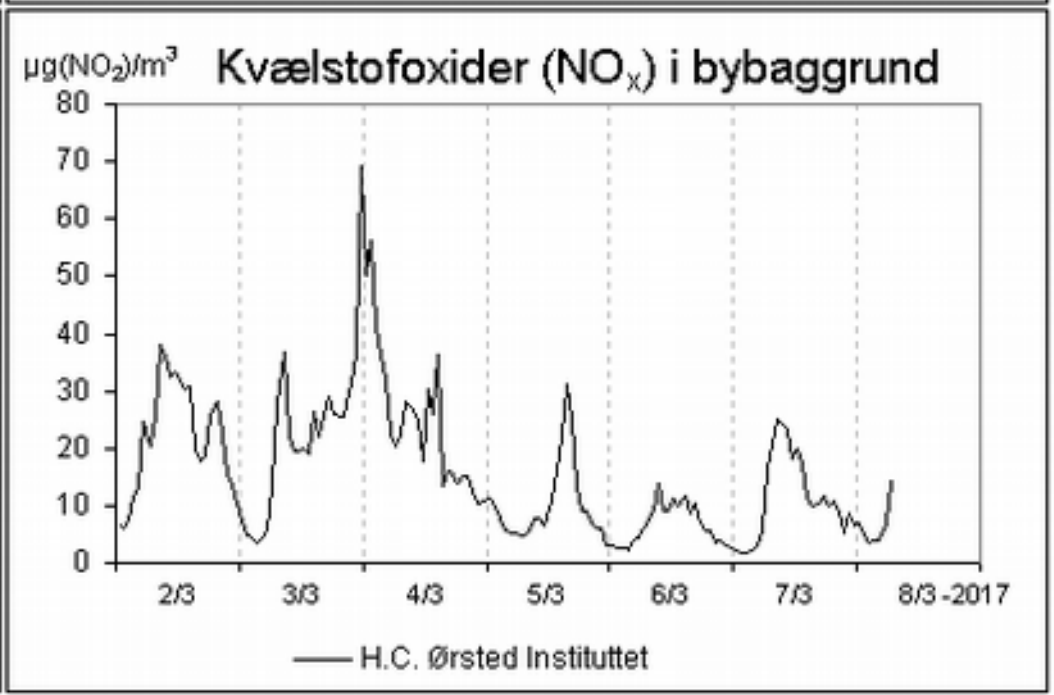
NO2 NITROGEN DIOXIDE	CO CARBON MONOXIDE	Temperature	Humidity
Not available yet.	Not available yet.	Not available yet.	Not available yet.
2459	12032	24	51
3	2279	32	35
732	-208625	28	53
326	122536	24	30

NO2 – what range is interesting?









Conversion: grams and ppm/ppb

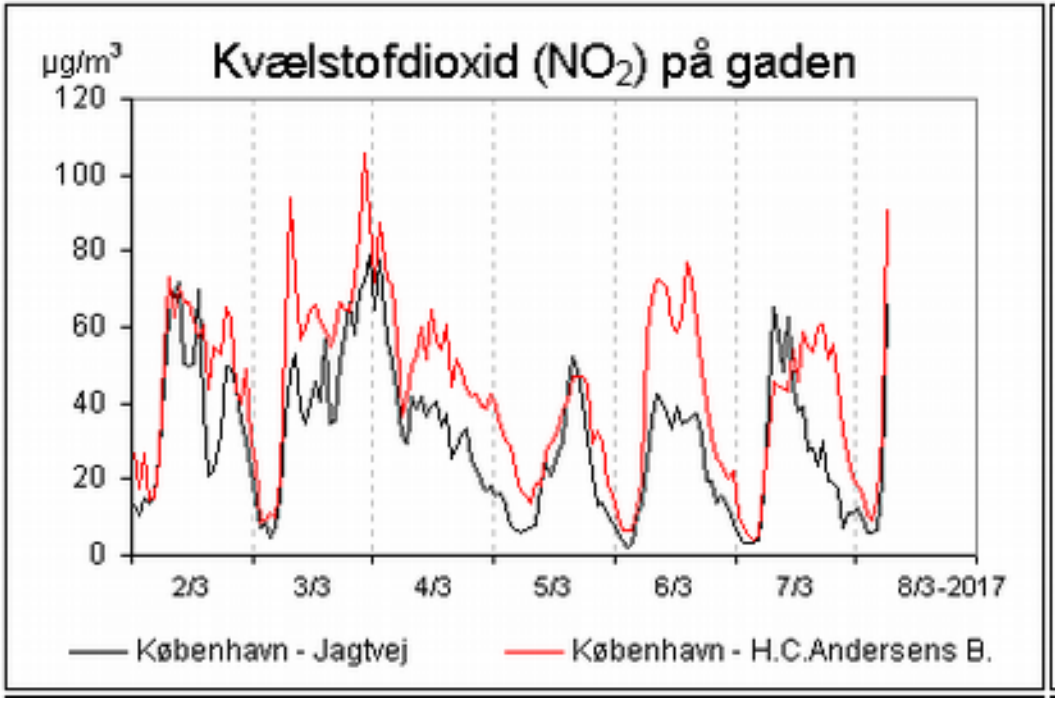
$$\text{Concentration } (mg/m^3 \text{ or } \mu g/L) = \text{Concentration (ppm)} \times \frac{\text{Molecular mass (g/mol)}}{\text{Molar volume (L)}}$$

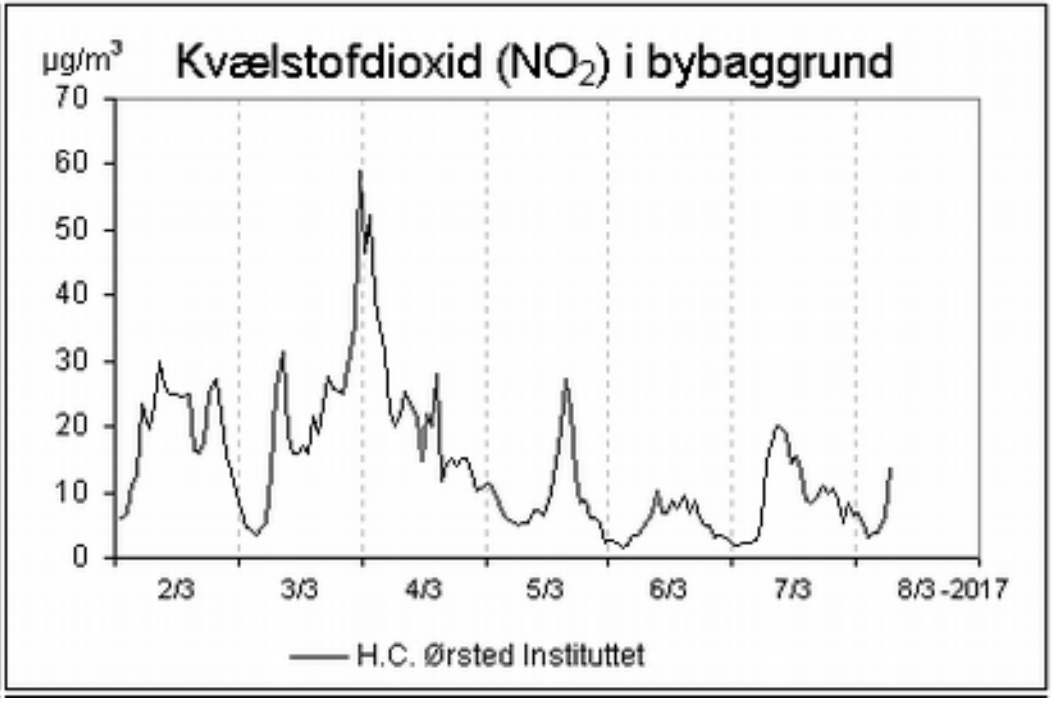
$$\text{Concentration } (\mu g/m^3 \text{ or } ng/L) = \text{Concentration (ppb)} \times \frac{\text{Molecular mass (g/mol)}}{\text{Molar volume (L)}}$$

Molar mass of NO2: 46 (1 x 14 + 2 x 16)
Molar Volume: approx 24 L

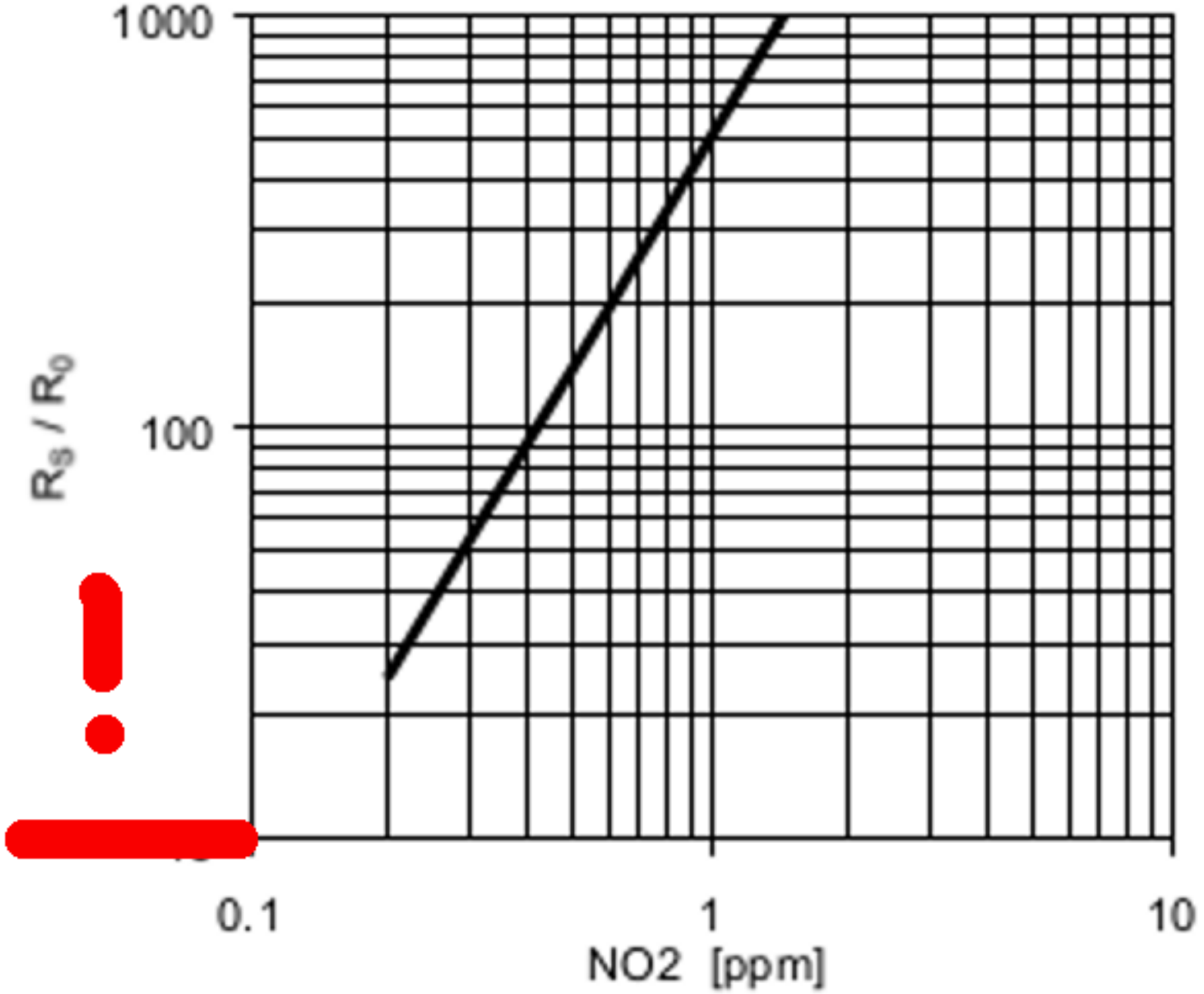
==> 1 ug = 0.5 ppb
1 mg = 0.5 ppm

NO2 – what range is interesting?





NO2 – what range is interesting?



We have a challenge ...

Low cost sensors often have

/ sufficient sensitivity, but not at low concentrations (they may be OK for extremes, but not for typical days and our models)

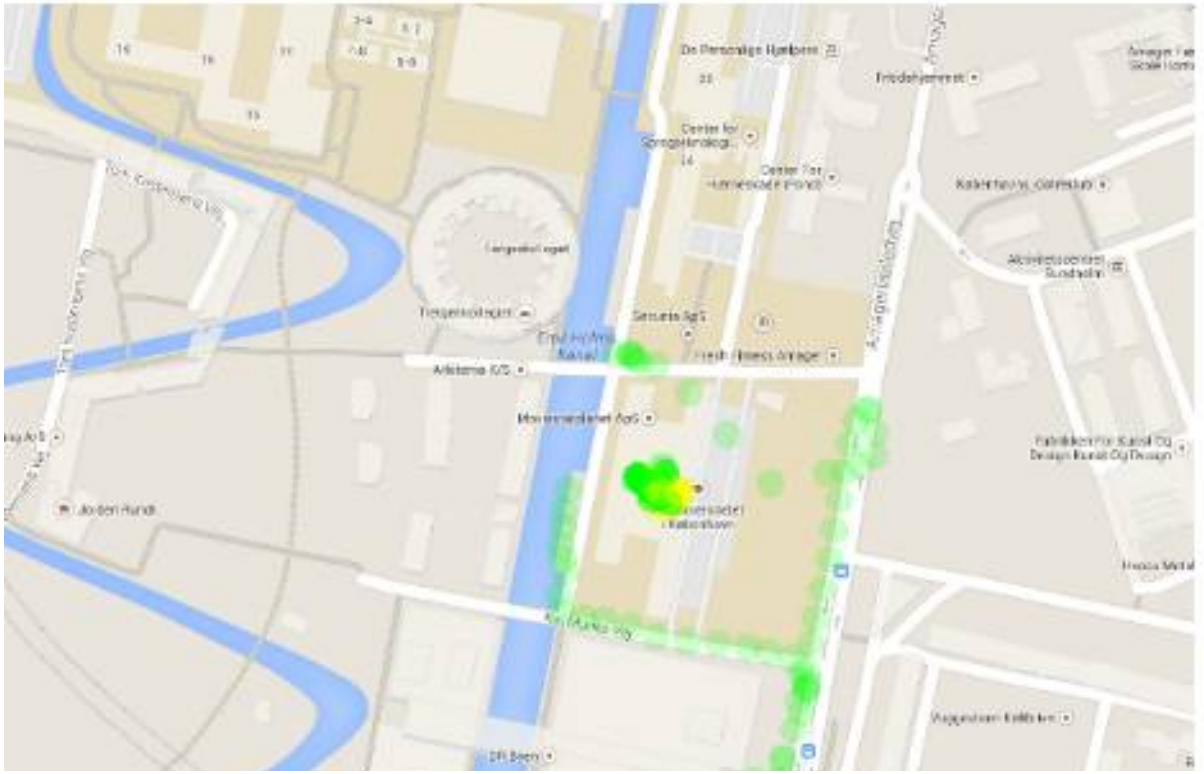
/ cross-sensitivity

/ stability shortcomings

We need to re-think our approach.

Back to our project

bAIR
the air bike



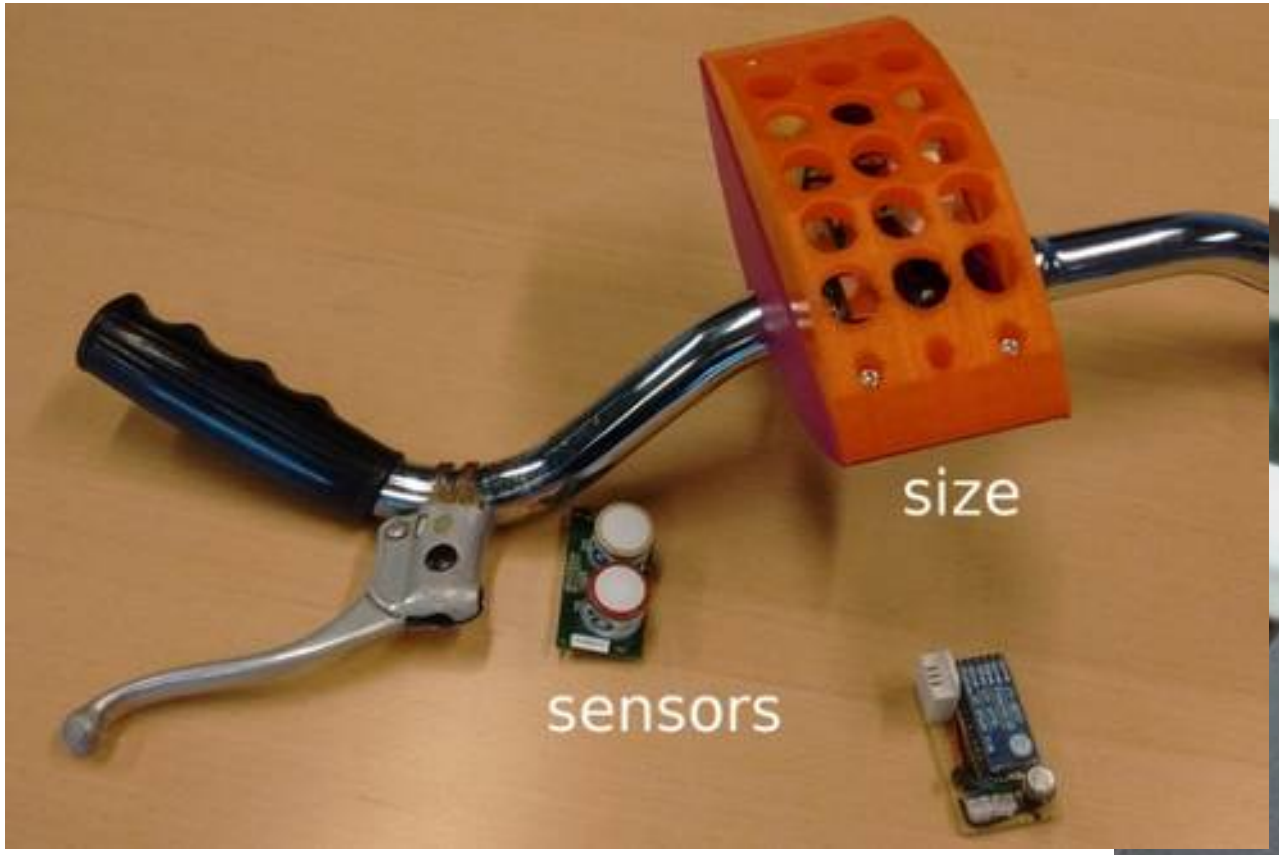
Air Qual. - RI
TGS 2600

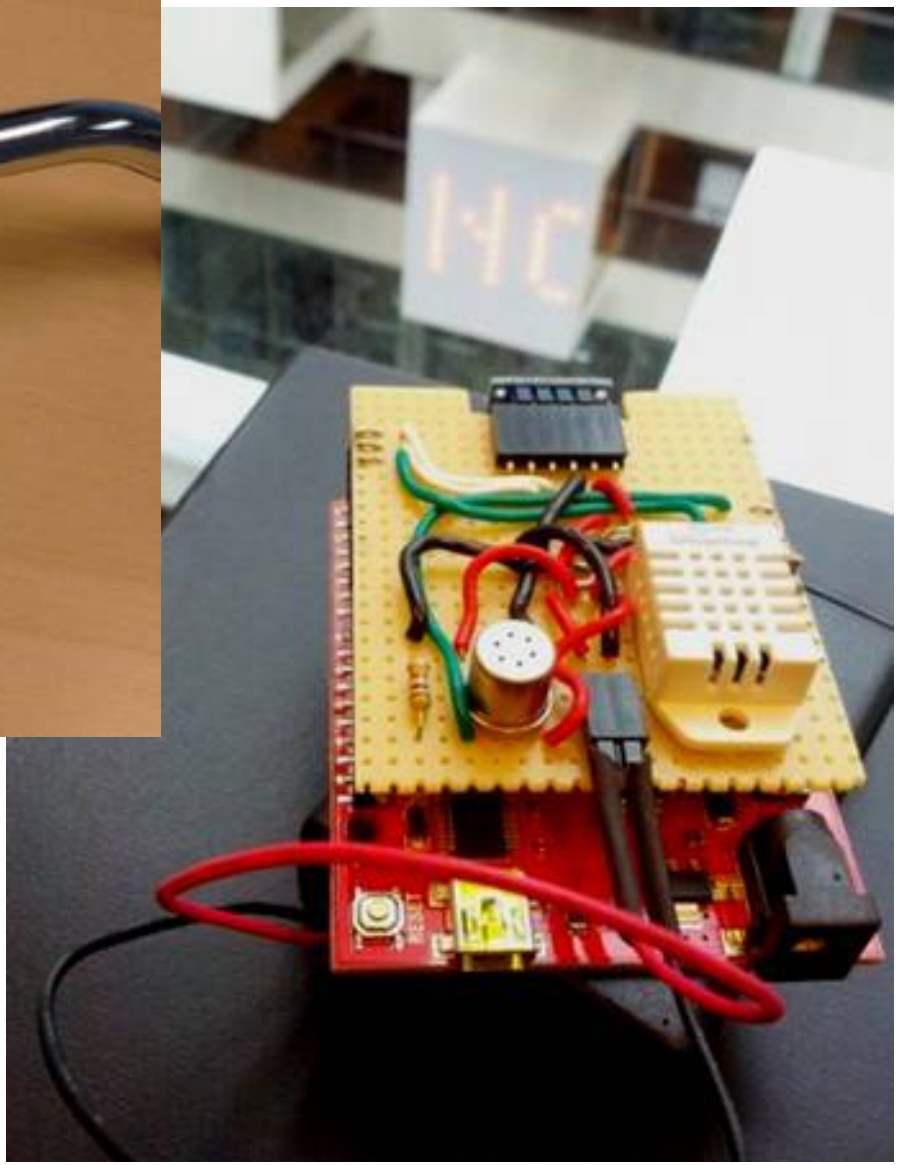
Avg	Peak
437	439

25
Air humidity - RI
RHT03

Avg	Peak
34	43

Back to our project





bAIR – next generation

From $10 to ~$100

Alphasense electrochemical sensors
NO2 – O3

Arduino-based system
16-bit ADC
Temp/humidity

Storage on SD card – currently no network
(network is easy – sensors are hard! :))

We reach 5 ppb precision theoretically
(limited by the very small output voltage)

Current work

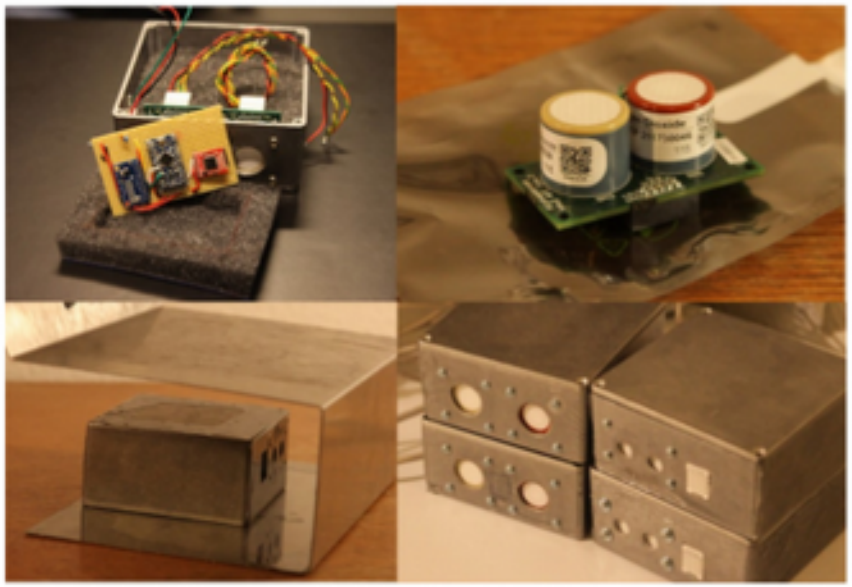
Christian Kjær Jensen

AARHUS UNIVERSITY

DTU Technical University of Denmark

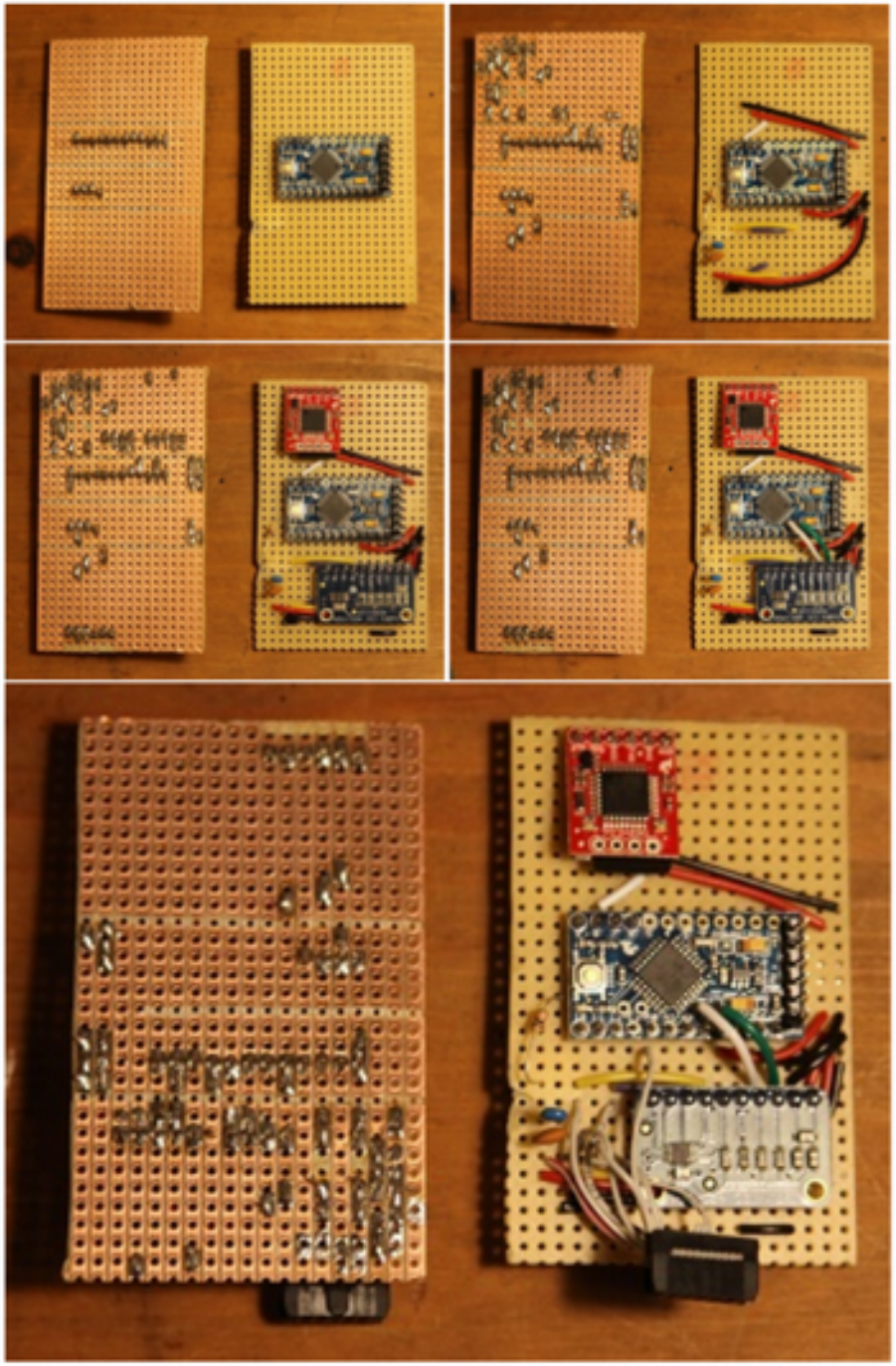
PIT LAB
PERVASIVE INTERACTION TECHNOLOGY LABORATORY

IT UNIVERSITY OF COPENHAGEN



Assessing the applicability of low-cost electrochemical gas sensors for urban air quality monitoring

Current work



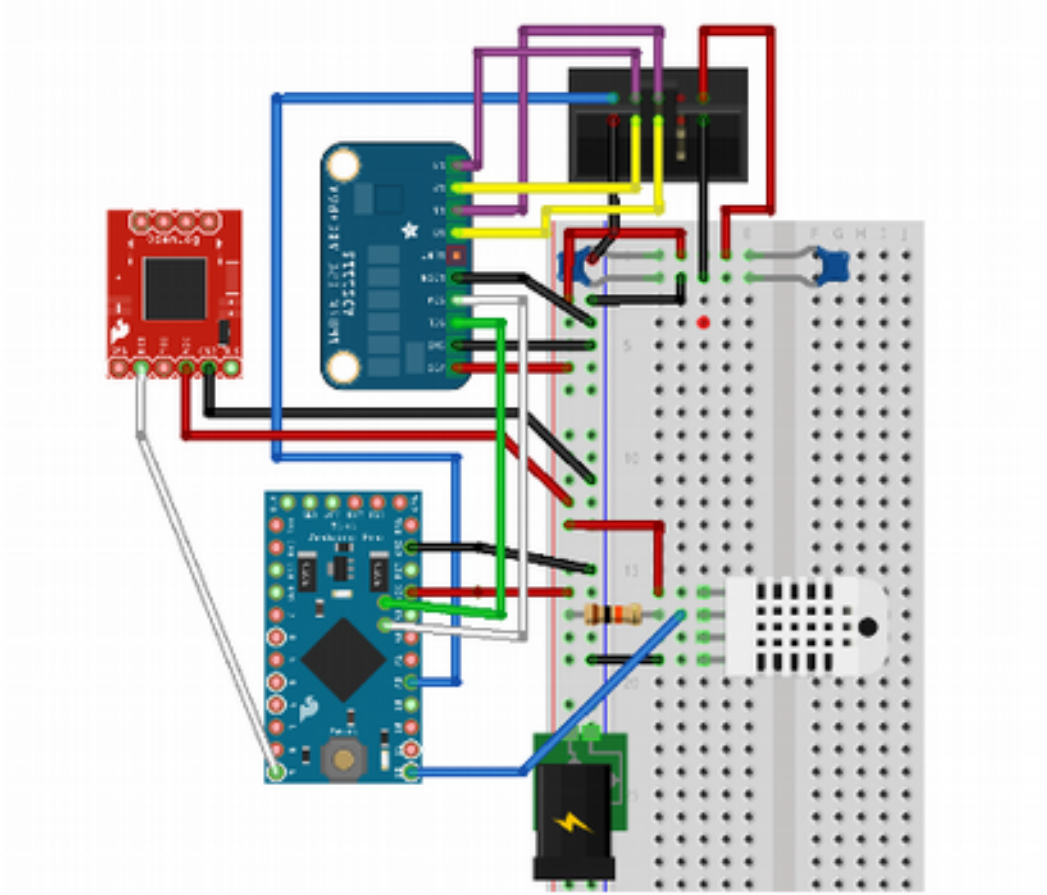


Figure F.3: A visual representation of the components and connections of the sensor node of A type. Made with open source software Fritzing (`www.fritzing.org`)

Alphasense sensors

Alphasense A4 (2-way) Air Quality Sensor Module
Calibration Certificate

Customer	IT UNI of COPENHAGEN
Order No	
Zero Cal Date	04-01-16
AFE Serial No	10-00015
Test PSU voltage	
AFE Type	☒ 810-0021-xx (2xA4)

Circuit Type		SN1	SN2
☒	-00	NO_2/O_3	NO_2/O_3
☐	-01	NO_2/O_3	NO
☐	-02	NO_2/O_3	$CO/SO_2/H_2S$
☐	-03	NO	$CO/SO_2/H_2S$
☐	-04	$CO/SO_2/H_2S$	$CO/SO_2/H_2S$

	SN1	SN2
Sensor Type	NO2 A42F	OX A421
Serial Number	211730533	213570061
WE Electronic Zero (mV)	290	413
WE Sensor Zero (mV)*	-18	1
TOTAL WE Zero (mV)	272	414
AE Electronic Zero (mV)	284	416
AE Sensor Zero (mV)*	-11	-2
TOTAL AE Zero (mV)	273	414
Sensitivity (nA/ppb)*	-.271	-.417
Sensitivity NO_2 (nA/ppb)*	-.271	-.362
PCB gain (mV/nA)	-.73	-.73
Sensitivity (mV/ppb)	.197	.304
Sensitivity NO_2 (mV/ppb)	.197	.300

* at 101kPa, 23 (±2)°C, 40 (±15) %RH

Current work

Deployment
next to routine
monitoring station

Current work

Current work

Calibration

3.7.2 Model 2

Model 2 introduces a linear dependency in the zero offsets on temperature and humidity:

$$Y = \frac{WE - WE_0(a_1T + b_1RH) - (AE - AE_0(a_2T + b_2RH))}{S_T} \tag{3.21}$$

where

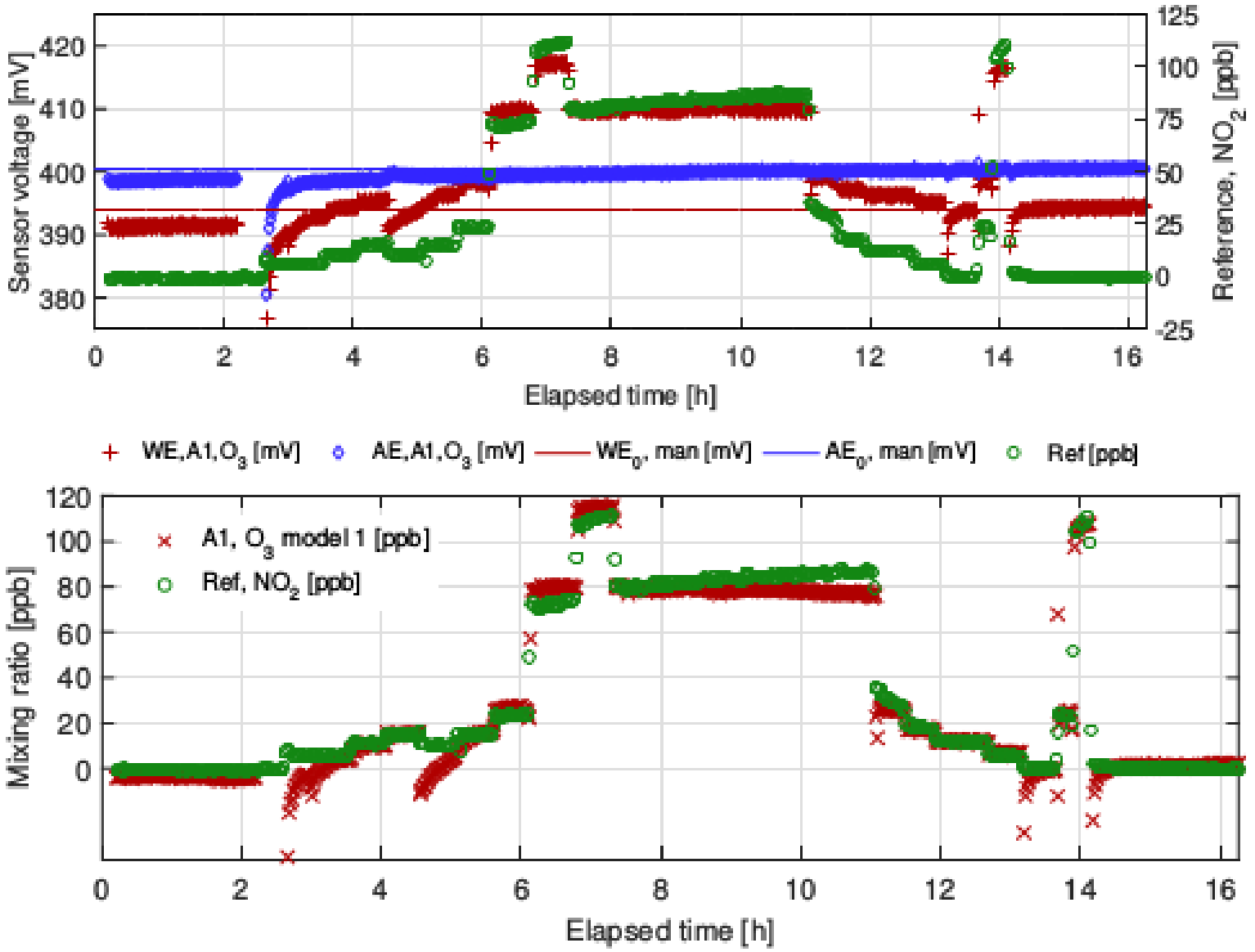
a_1, a_2, b_1 and b_2 are four parameters obtained from the calibration

T is temperature [K]

RH is the relative humidity [%]

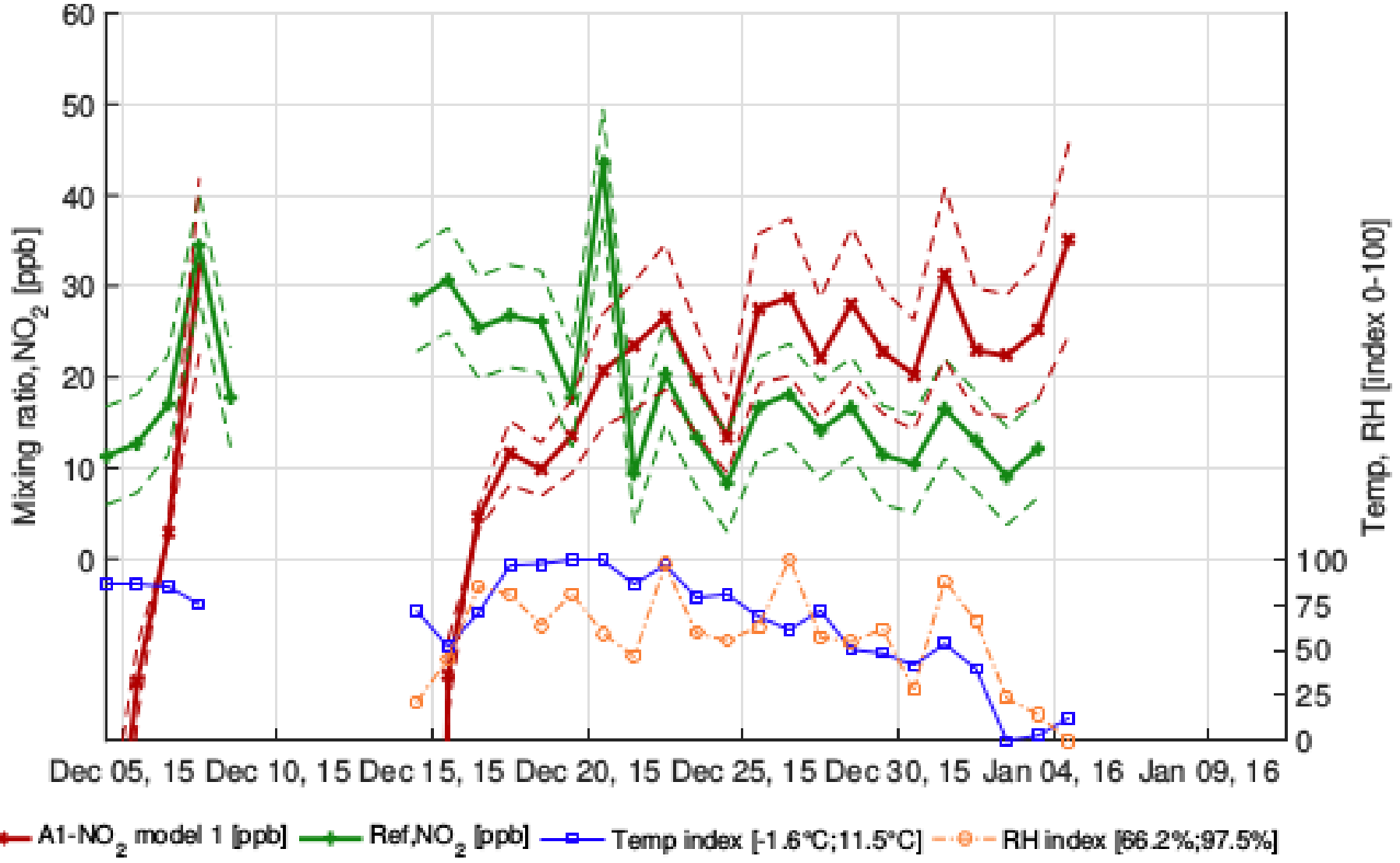
Current work

Calibration



Current work

Calibration



Results

Promising -

We left “low cost” and moved to “reasonable cost”

We can measure NO2 between 0 – 50 ppb with 5 ppb precision and reasonable stability

With proper calibration (!),
we are in good agreement with “expensive science”

What’s next for us?

Mobility
Put sensors on bikes again,

Network
connect via mobile, LoRa (!), WiFi

Data
Machine Learning and Sensor Calibration

Sensors
Add PM to our nodes

Educate
Work with schools and institutions

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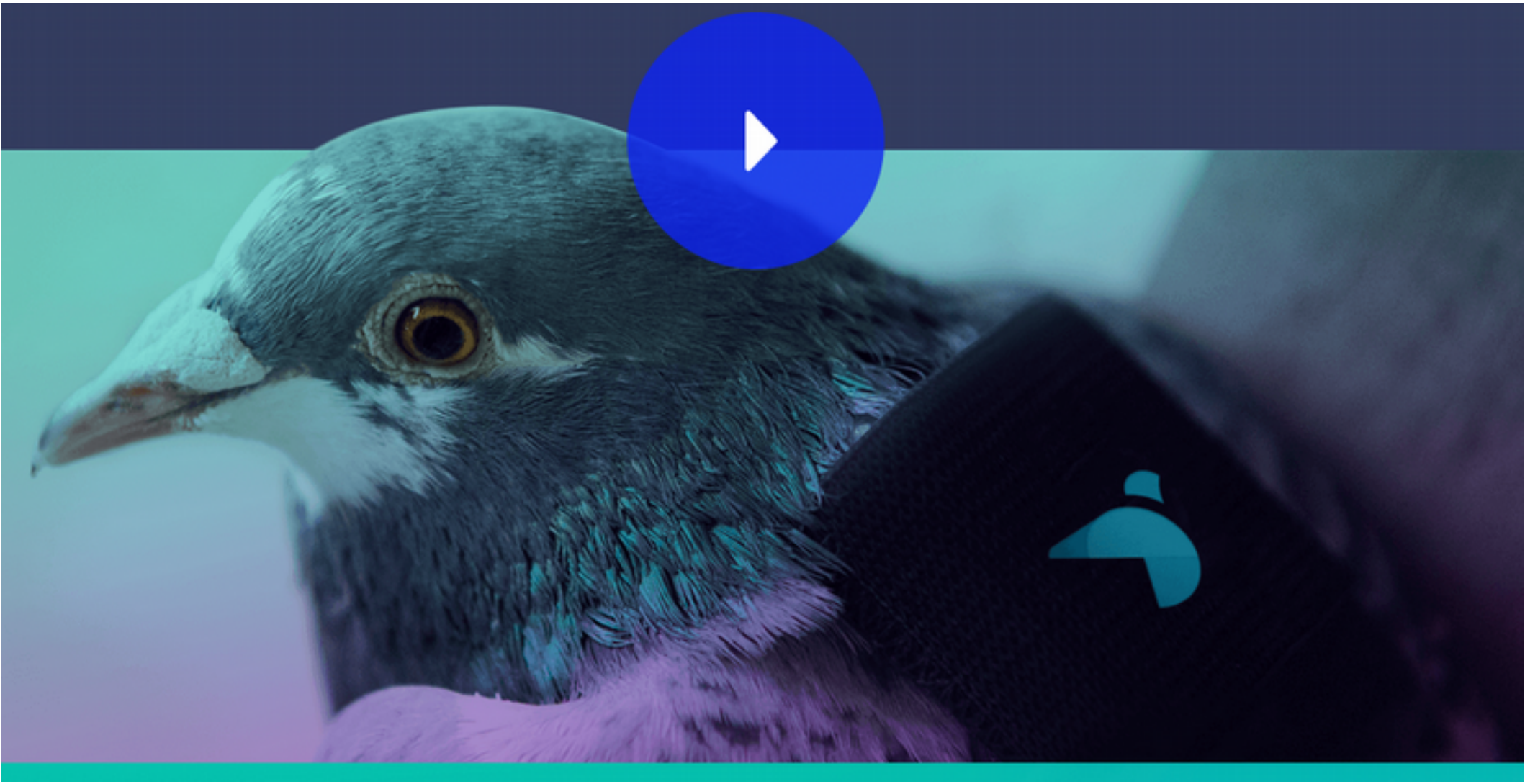
Many other “new sensing” projects

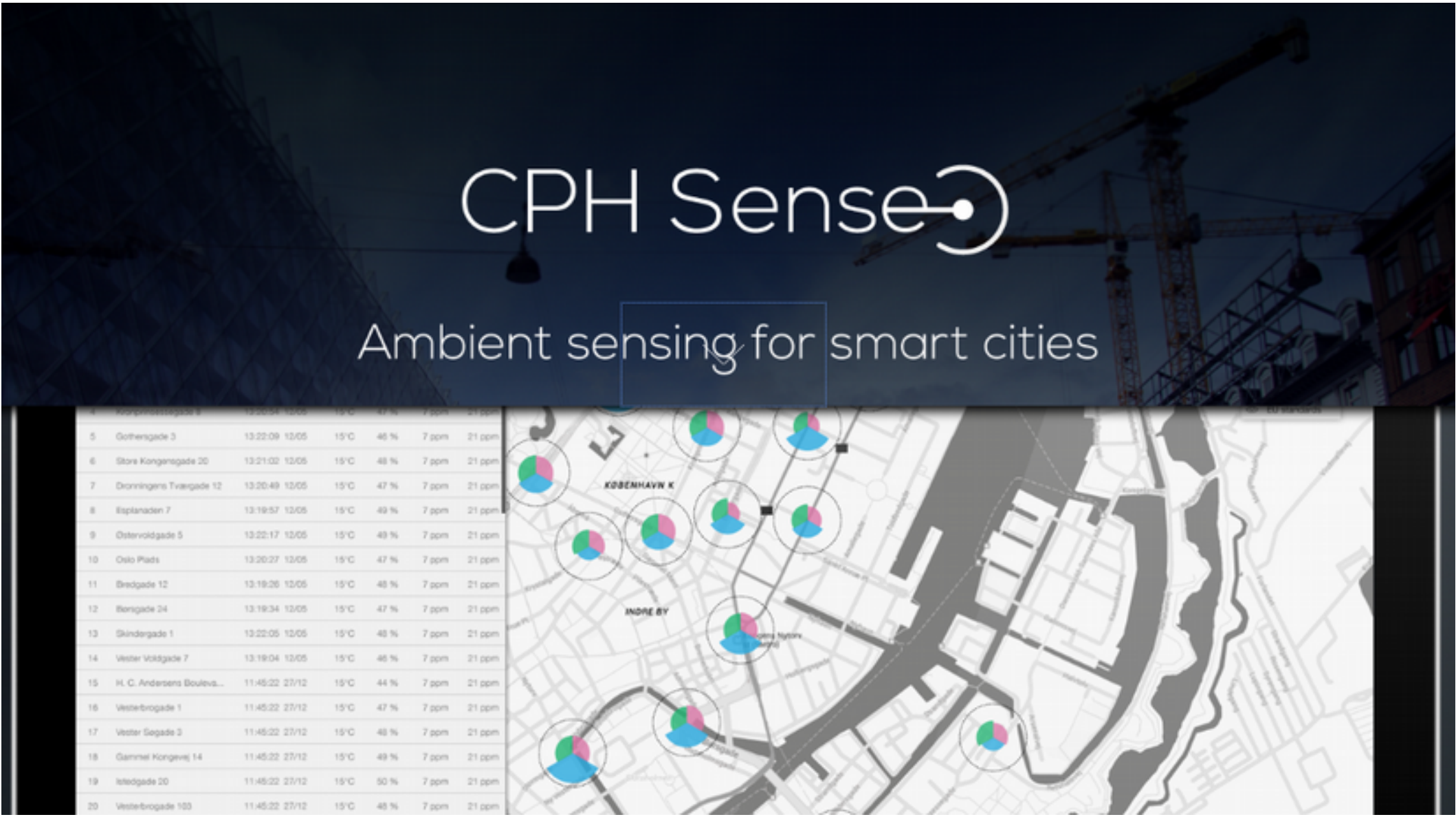
International & national



pigeonairpatrol / plume labs

Many other “new sensing” projects

Denmark CPHsense / Leapcraft



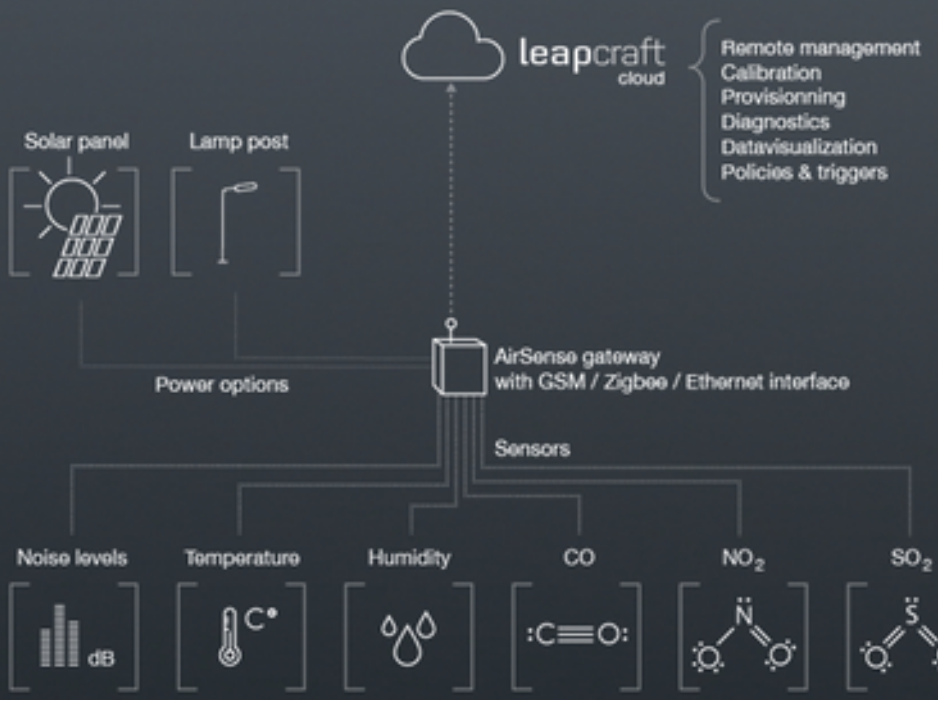
Many other “new sensing” projects

Denmark CPHsense / Leapcraft

The CPH Sense architecture

CPH Sense is an enterprise grade fully scalable solution.

Our system is design to integrate a range of industrial gas sensors like NO2, NO, CO, CO2, SO2 etc along with PM1, PM2.5 and PM10 particle which are connected via our extensible hardware gateway. Our data model is highly scalable and offers an IP based control, monitoring and calibration system. We take the stress out of managing remote deployments so that you can focus on outcomes rather than technology. We are currently working on a low cost Noise (dB sensor), PM2.5 and PM10 sensor integration.



Many other “new sensing” projects

Safecast: PM

SAFECAST AIR QUALITY MONITORING STATION

$1,000.00 USD

KIT

Assembly required (needs soldering)

QUANTITY

− 1 +

ADD TO CART

Description | FAQ | Product Manual | Support | Parts | Warranties | Testers | Purchase Order | Lesson Plans

We are offering a limited number of Safecast Air Quality Monitoring Stations for participation in the Safeca
Quality (Particulate) Beta Testing Program. Similar

Help

Thank you!

… questions?
… suggestions?
… improvements?

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sebastian@nsrc.org