Italian National Agency for New Technologies,
Energy and Sustainable Economic Development

Developing Air Quality Sensors: Perspectives and Challenges for Real Applications

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US EPA AIR SENSORS 2018 WORKSHOP
EPA Campus, Research Triangle Park, Durham, NC, USA, 25-27 June 2018

EPA AIR SENSORS 2018 - Deliberating Performance Targets for Air Quality Sensors

OUTLINE

- ENEA profile
- Context of the air pollution control
- ENEA efforts in performance standards for AQ sensors
- Sensor performance: transducers, measurement parameters
- Rationale for the sensor performance:
  - ✓ *EU Directive 2008/50/EC, certification standards*
- Examples of certification standards in air quality:
  - ✓ WSN in Bari (Italy): PM_{10}, Saharan dust, AQI, mobile sensing (bus)
  - ✓ AQ sensors: biofuel-powered aircraft emissions
  - ✓ *EuNetAir* joint-exercise, Aveiro, Portugal (Oct. 2014)
- Sensor market and value chain
- Selected current European projects on AQ sensors
- Concluding remarks

ENEA

About ENEA

- **ENEA** - *Italian National Agency for New Technologies, Energy and Sustainable Economic Development*
- It is a public RTO (Research and Technology Organization) operating in the fields of energy, the environment and new technologies to support the Country's competitiveness and sustainable development
- ENEA's mission is to develop new technological solutions to meet the societal challenges, fostering transition to a low-carbon and circular economy
- The institutional mandate of the Agency is to disseminate and transfer knowledge, innovation and technology to industry, institutions and civil society at large

Activities ENEA

- ENEA's activities span many fronts ranging from basic to applied research and innovation
- Research: Basic, mission-oriented, applied and industrial research, also through the development of prototypes and product industrialization
- Technology Transfer: Dissemination and transfer of research results to industry and public administrations, and exploitation for production purposes
- Advanced services: Studies, measurements, tests and assessments tailored to both public and private bodies and enterprises
- Training and information: Activities aimed at broadening sector expertise and public knowledge and awareness

Research Facilities and Staff

Research facilities:

- **9** Research Centres
- **5** Research Laboratories
- **13** Territorial offices
- **Brussels** Liaison Office
- **Headquarters** in Rome

Human Resources:

About 2500 permanent staff:

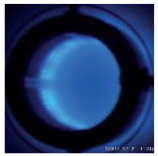
- **36%** women
- **59%** graduates







Research and Development



Fusion & Nuclear Safety

- Fusion
- Fission (new gen)
- Radiation protection
- Nuclear safety & security
- Ionizing/non ionizing radiation applications

Energy Technologies

- RES (PV, CSP)
- Energy efficiency technologies
- Bio-fuels
- Smart grids
- Storage
- Sustainable Mobility
- Advanced energy materials
- Sustainable use of fossil fuels

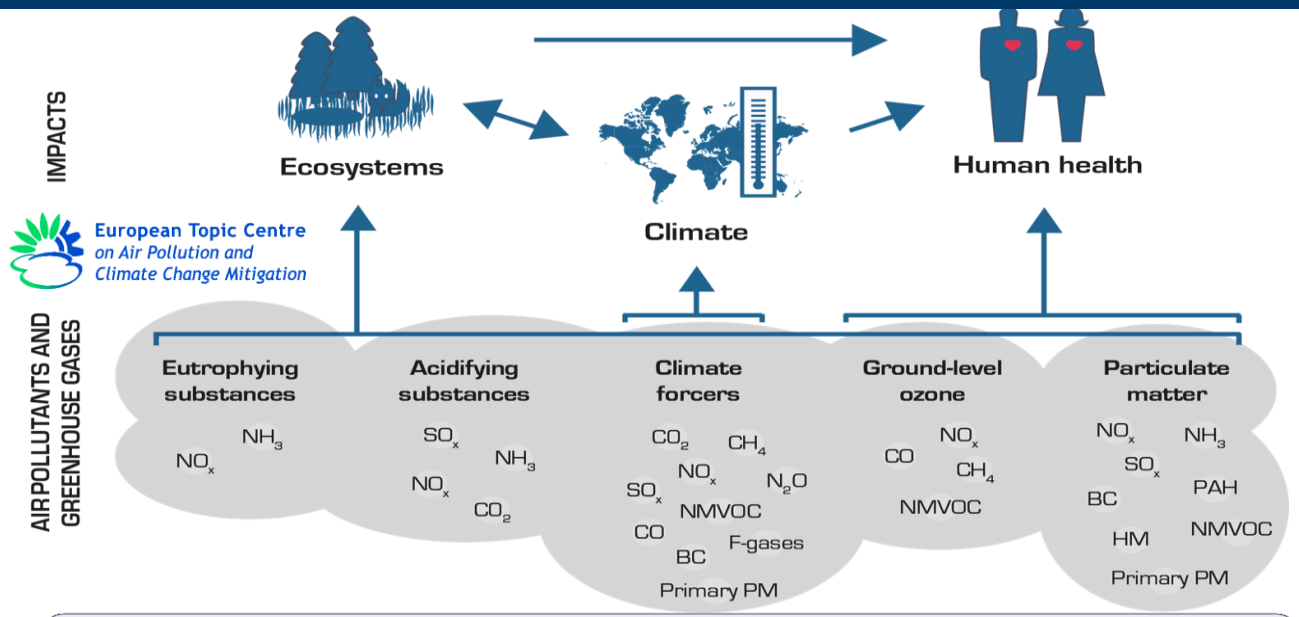
My Department

Sustainability

- Resource efficiency
- Climate change: modeling, adaptation and mitigation
- Environmental technologies
- Innovative materials
- Environmental characterization, prevention and recovery
- Seismic and natural hazards assessment and prevention
- Bio and nanotechnologies
- Agrifood
- Health
- Cultural heritage

Context of Air Pollution in Europe

Cristina Guerreiro



Almost one third of the Europe's citizens are exposed to excessive concentrations of airborne particulate matter.

Exposure to $PM_{2.5}$, NO_2 and O_3 lead to respectively 431 000, 75 000, and 17 000 premature deaths in Europe (2012 conc.).

Mitigation and Regulation: AMBIENT AIR QUALITY EU DIRECTIVE (2008/50/EC) and Daughters

Some Environmental Emergencies:

1930 - Meuse Valley (Belgium)
1952 - Great London Smog (UK)
1954 - Los Angeles (USA)
1984 - Bhopal (India)
2005 - Teheran (Iran)
2006 - Hong Kong
2008, 2015 - Shanghai, Peking (China)
2012 - Taranto (Italy)
……..

Regulated Limit of Detection	
Pollutant	**Limit Level**
NO_x	100, 200 ppb
CO	8 ppm
SO_2	130, 190 ppb
O_3	120 μg/m³
PM_{10}	50 μg/m³
BTEX	6 μg/m³
PAH (BaP)	1 ng/m³
$PM_{2.5}$	25 μg/m³

Severe very-low limits of detection to preserve human health, eco-systems and environment

ENEA efforts in performance standards for AQ sensors (1/2)

- **COST Action TD1105**: *European Network on New Sensing Technologies for Air Pollution Control and Environmental Sustainability - EuNetAir (2012-2016)*
  Chair: M. Penza - www.cost.eunetair.it
  International Networking *on sensor materials, gas sensors, sensor-systems, measurements, protocols, standards with more than 120 teams from 31 COST Countries and 7 International Partner Countries (including USA)*
- **ESSC**: *European Sensor Systems Cluster (2014-present)*
  Chairman: M. Penza - www.cluster-essc.eu
  Working Group *on sensor-systems to define a Roadmap Towards European Leadership in Sensor-Systems for H2020 Calls 2018-2020, as requested by EC*
- **Italian Project ABC**: *Aerocrafts powered by Biofuel (2017-2019)*
  Partnership: CNR, ENEA, Italian Air Force
  Working Group *to study the impact of the emissions from aircrafts powered by biofuel, as funded by Italian Ministry of Environment, Landscape and Sea*

ENEA efforts in performance standards for AQ & Climate (2/2)

- **MINNI**: *Italian National Atmospheric Modelling System (Italian Legislative Law 152/2010 (2010-present) by ENEA - www.minni.org*
  Air Quality Scenario Simulations at medium-long term to support the Italian Environment Ministry in negotiation to define European and International policies on air pollution, including *National Air Quality Forecasting System*
- **ENEA Station for Climate Observation "Roberto Sarao", Lampedusa (Sicilia)**: *ENEA - www.lampedusa.enea.it*
  A **Research Facility in the Mediterranean** to measure the climatic parameters. The atmospheric/oceanic observatory is composed by two sections:
  - **ground-based laboratory** (35.52°N, 12.63°E) since 1997
  - **oceanic buoy** (35.49°N,12.47°E) for air-sea and satellite observations since 2015
- **EIT CLIMATE-KIC**: *European Institute of Innovation and Technology (EIT) - Climate Knowledge and Innovation Community (KIC) - www.climate-kic.org*
  ENEA linked partner on *Innovation for Climate Action*

Transducers for air quality sensors

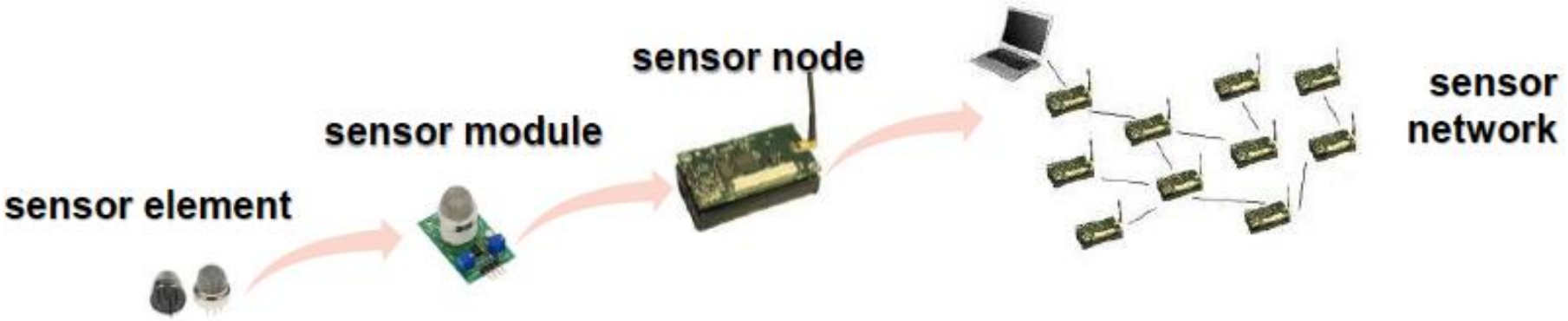
Type of Transducer	Air Pollutant	Prototype/Device
Electrochemical	NO_2, NO, O_3, CO, SO_2, H_2S	
Spectroscopic and NDIR	CO_2, CH_4, specific VOCs	
Photo-Ionisation Detector	total VOCs	
Optical Particulate Counter	PM_{10}, $PM_{2.5}$, $PM_{1.0}$, BC	
Metal Oxides	NO_2/NO, O_3, CO, SO_2, H_2S, VOCs	
Pellistors	CH_4, hydrocarbons	

Measurement parameters for air sensor performance

Transducer	Sensitivity	Selectivity	Stability	Limit of Detection	Open Questions
Electrochemical	*High*	*Variable*	*Improved*	*ppb*	*Interference, calibration, signal proc.*
Spectroscopic and NDIR	*High*	*Variable*	*Low*	*ppm*	*Interference, calibration, signal proc.*
Photo-Ionisation Detector	*High*	*Low*	*Improved*	*ppm*	*Interference, calibration, signal proc.*
Optical Particulate Counter	*High*	*Improved*	*Improved*	*$\mu g/m^3$*	*Interference , calibration, signal proc.*
Metal Oxides	*High*	*Variable*	*Low*	*sub-ppm*	*Interference, calibration, signal proc.*
Pellistors	*High*	*Low*	*Improved*	*ppm*	*Interference, calibration, signal proc.*

Good electronics (low noise), good mechanical design, software/firmware/cloud are needed

Sensor/Node/Network for air quality



- Study of sensor elements active control techniques on all levels:
  - **Sensor module ➔ enhanced electronics (i.e. for self-monitoring)**
  - **Sensor node ➔ improved selectivity and stability via information correlation**
  - **Sensor network ➔ enhanced reliability, auto-configuration/calibration**

Rationale for the choice of the sensor performance
EU Directive 2008/50/EC: *Sensors-versus-Analyzers* 1/2

EU Directive 2008/50/EC: *Ambient Air Quality and Cleaner Air for Europe*, art. 2

	Definition
Fixed Measurements	It means measurements taken at fixed sites to determine the levels in accordance with the relevant *Data Quality Objectives* (DQO). They are **mandatory** in zones and agglomerations where the upper assessment thresholds are exceeded.
Indicative Measurements	It means measurements which meet *Data Quality Objectives* (DQO) that are less strict than those required for "*Fixed Measurements*". The "Indicative Measurements" are considered as *Informative Measurements*.

EU Directive 2008/50/EC: *Sensors-versus-Analyzers* 2/2
Data Quality Objectives (DQO)

	Max UNCERTAINTY Requested by Directive				DEVICES FOR MEASURE
	$NO_2/NO/NO_x$, SO_2, CO	Benzene	O_3	$PM_{10}/PM_{2.5}$	
Fixed Measurements (High Accuracy)	**15%**	**25%**	**15%**	**30%**	**Analyzers:** Fluorescence, Chemilumin., GC, UV Photometry, Optical Absorption, Gravimetry
Indicative Measurements (Low Accuracy)	**25%**	**30%**	**30%**	**50%**	**Low Cost Sensors** (diffusive samplers)

Examples of certification standards for air quality

European Standard EN

➢ performance criteria and test procedures for certified *Automated Measuring Systems* (AMS) for ambient air quality for **gases and PM** are defined in:

- EN 14211:2012 for **NO_x**, and daughters
- EN 14212:2012 for **SO_2**, and daughters
- EN 14625:2012 for **O_3**, and daughters
- EN 14626:2012 for **CO**, and daughters
- EN 14662-3:2005 for **C_6H_6**, and daughters
- EN 12341:2014 for **PM_{10}**, and daughters
- EN 14907:2005 for **$PM_{2.5}$**, and daughters
- EN 16450: 2017 for **PM_{10} and $PM_{2.5}$**, and daughters
- Guide to the Demonstration of Equivalence of Ambient Air Monitoring - GDE

➢ **CEN/TS 16450** supposed to become an EN Standard in future after validation work

Air Quality Sensors Network operating in BARI (Italy)
Case-Study Italian Project RES-NOVAE: *Sensors-vs-Analyzers*

*11 Sensor Nodes (10 stationary + **1 mobile**) managed by ENEA and deployed in Bari*

Air Quality Monitoring Stations (10 units) managed by ARPA-Puglia in Bari

ENEA

ARPA PUGLIA

Air Quality Sensors Network operating in Bari (Italy)
Case-Study Italian Project RES-NOVAE: *Virtual Private Network*

CO-B4	Alphasense, UK
NO2-B4	Alphasense, UK
O3-B4	Alphasense, UK
SO2-B4	Alphasense, UK
CO2-IRC-A1	Alphasense, UK
VOCs-PID-A1	Alphasense, UK
PPD20V	Shinyei, JP
TC1047A	Microchip
HIH5031	Honeywell

Smart City Bari

AQ ENEA Sensors Fixed Nodes Network distributed in Bari (Italy)

ENEA Centro Ricerche Brindisi

ENEA Sensors Lab OpenVPN Status Monitor

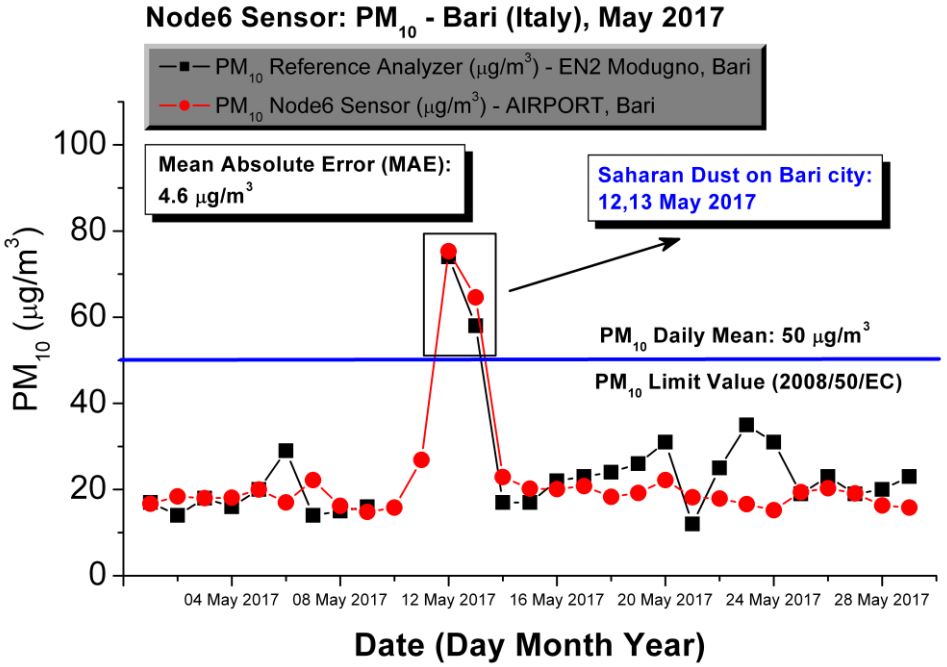
nea NasusPi - Connection up, pingable. 12 clients, 603847607 bytes in, 314525951 bytes out [172.17.0.1 tun]

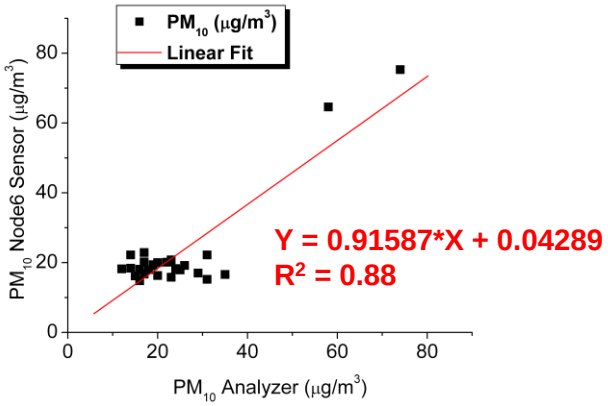
Username / Hostname	VPN IP Address	Remote IP Address	Port	Location	Recv	Sent	Connected Since	Last Ping	Time Online
nasuspi-5	172.17.0.6	37.19.108.20	52428		73065	73872	23/02/2016 15:28:09	23/02/2016 15:28:16	3:01:40
nasuspi-8	172.17.0.9	62.19.56.54	24059		16932314	8252487	14/02/2016 02:05:33	23/02/2016 18:26:23	9 days, 16:23:16
nasuspi-2	172.17.0.3	62.19.66.167	50059		61118723	29838611	19/01/2016 [illegible]31:29	23/02/2016 18:22:13	35 days, 2:58:20
nasuspi-12	172.17.0.1						[illegible]/2016 [illegible]1:11	23/02/2016 19:26:45	1 day, 5:58:38
nasuspi-3	172.17.0.						[illegible]/2016 59:28	23/02/2016 18:18:43	29 days, 3:30:21
nasuspi-13	172.17.0.1						[illegible]/2016 22:35	23/02/2016 18:19:49	4 days, 3:07:14
nasuspi-6	172.17.0						[illegible]/2016 35:05	23/02/2016 18:27:28	33 days, 8:54:44
airpoi-one	172.17.0.2						[illegible]/2016 20:28	18/02/2016 09:20:28	5 days, 9:09:21
nasuspi-1	172.17.0.						[illegible]/2016 05:49	23/02/2016 18:17:56	9 days, 16:24:00
nasuspi-9	172.17.0.1						[illegible]/2016 48:32	23/02/2016 18:26:32	4 days, 22:41:17
nasuspi-4	172.17.0.5	62.19.57.93	34803		25405886	12317796	09/02/2016 06:27:37	23/02/2016 18:25:51	14 days, 12:02:12
nasuspi-10	172.17.0.11	5.170.246.120	20180		17242918	8314106	14/02/2016 02:05:27	23/02/2016 18:18:10	9 days, 16:23:22

- 10 Stationary Nodes in City
- 1 Mobile Node on Public Bus
- Campaign Period: **30 Months**
  1 July 2015 - 31 Dec. 2017
- Big Data: 5Gb
- Sampling Rate: 10 sec

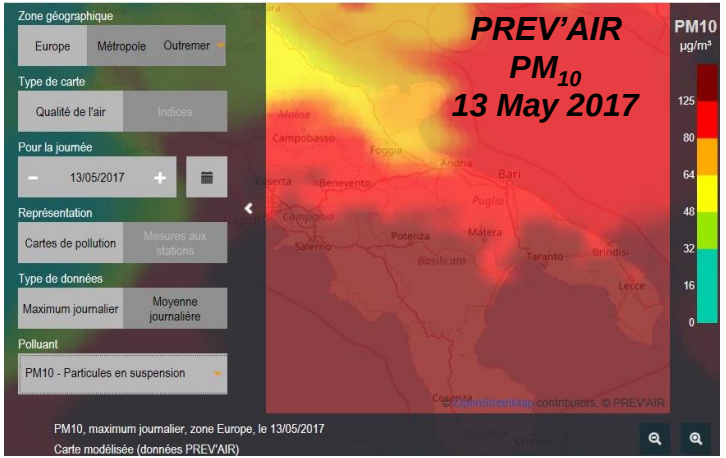
ENEA

PM_{10}: Sensors Network Data operating in Bari (Italy)
Node 6 Airport: May 2017, *Sensor vs Analyzer* - *Saharan Dust*





Node 6: *AIRPORT in Bari*
PM sensor (PPD20V, Shinyei)



Air Quality Sensors Network operating in Bari (Italy) Case-Study Italian Project RES-NOVAE

PM_{10} WSN Performance: Jan - Dec 2016

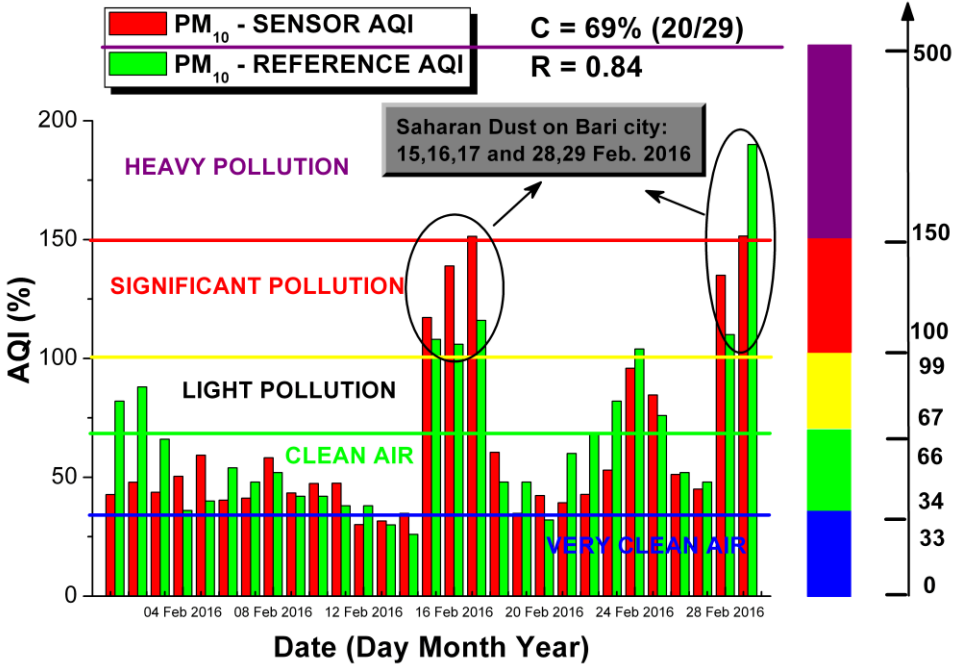
Node ID	Node Location	Sensor Node PM_{10} Yearly Mean ($\mu g/m^3$)	Closest AQMS PM_{10} Yearly Mean ($\mu g/m^3$)	Sensor Node PM_{10} Mean Absolute Error (*) ($\mu g/m^3$)	Sensor Node Accuracy (**) (%)
Node 1	ENEL	25.85	22.56	5.61	24.86
Node 2	ENEA	22.61	25.91	5.61	21.65
Node 3	PERONI	22.32	26.67	7.78	29.16
Node 4	AMTAB	21.40	26.67	8.16	30.60
Node 6	AIRPORT K. Wojtyla	22.37	27.31	5.61	20.54
Node 8	POLITECNICO	21.34	25.91	5.08	19.60
Node 9	COFELY	21.63	24.98	4.26	17.05
Node 10	UFFICI COMUNALI (°)	24.52	24.69	6.27	25.41

(*) MAE = Mean Absolute Error
(**) Accuracy is defined as sensor MAE divided by AQMS Yearly Mean
(°) Sensor performance considering Min value instead of Avg value for Node 10 only

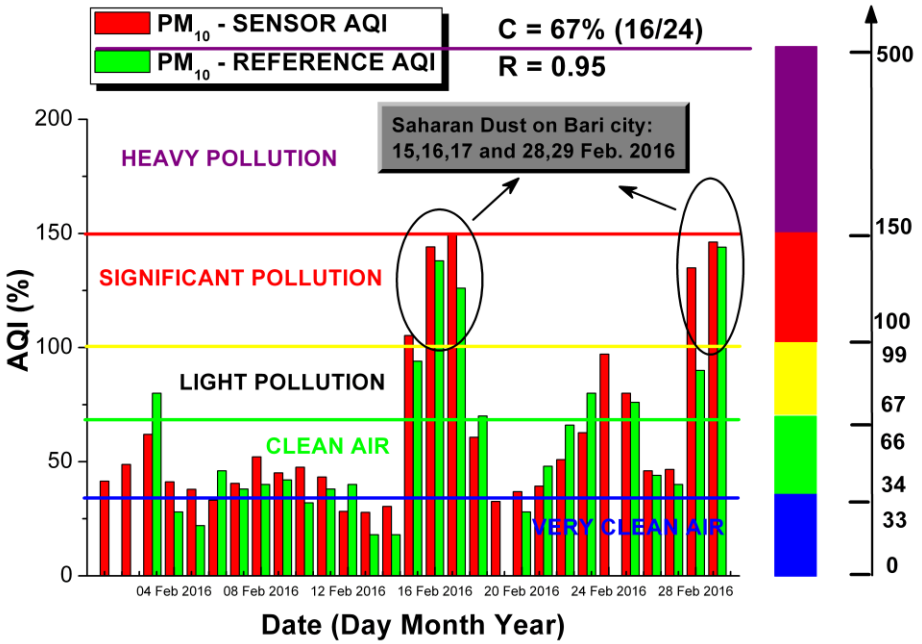
ENEA

PM_{10}: Sensors Network Data operating in Bari (Italy)
AQI - Node 2 and Node 6: Feb. 2016, *Sensor vs Analyzer*

Node 2 - Feb 2016



Node 6 - Feb. 2016



Air Quality Sensors Network operating in Bari (Italy)
Case-Study RES-NOVAE: *Mobile Sensing on Public Bus*

iAQI: CO — *9 November 2015* — **iAQI: NO_2**

Clean air: low CO AQI (blue) ***Clean air: low NO_2 AQI (blue - green)***

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Air Quality Sensors Network operating in Bari (Italy)
Case-Study RES-NOVAE: *Mobile Sensing on Public Bus*

iAQI: PM_{10} *9 November 2015* **iAQI: CO_2**

Polluted air: high PM_{10} AQI (yellow - red)

Polluted air: high CO_2 AQI (red - purple)

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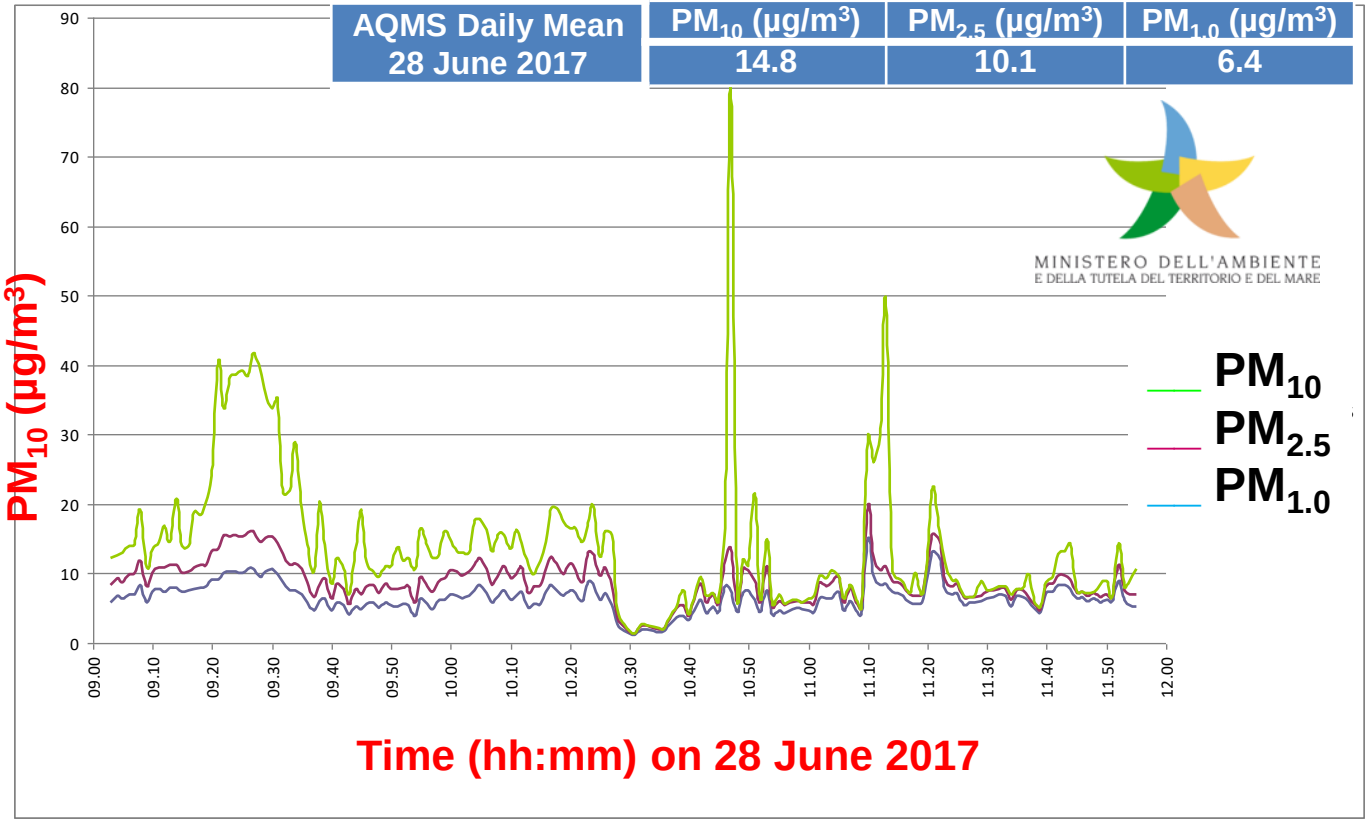
Air Quality Sensors: Biofuel-powered Aircraft Emissions

Airport *Pratica di Mare (Italy)*: PM_{10}/$PM_{2.5}$/$PM_{1.0}$ emissions monitored by OPC sensors



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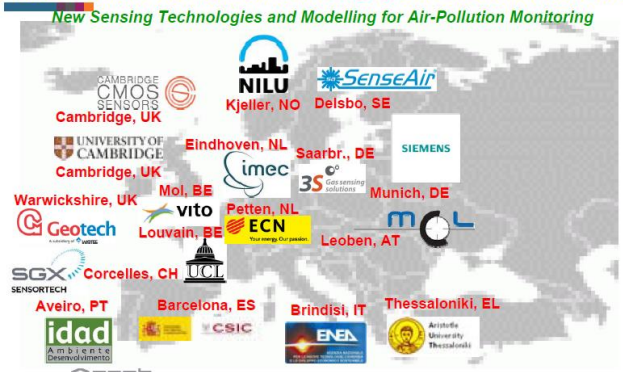
Joint-Exercise *EuNetAir*: *Sensors-versus-Analyzers* 1/2

COST Action TD1105 *EuNetAir*: Aveiro INTERCOMPARISON

New Sensing Technologies and Modelling for Air-Pollution Monitoring



cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

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Aveiro Joint-Exercise Intercomparison & WG Meeting

13 - 27 October 2014: Starting Joint-Exercise (2 weeks duration)

14 - 15 October 2014: EuNetAir WG1-WG4 Meeting

EuNetAir Air Quality Joint-Exercise Intercomparison 2014

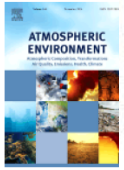
Local Organizers: Prof. Carlos Borrego and Dr. Ana Margarida Costa (IDAD)

Air Quality Monitoring campaign at Aveiro (Portugal) city centre 2014

Continuous measurements: CO, benzene, NOx, SO_2, PM_{10}, VOC

Temperature, humidity, wind velocity, wind direction, solar radiation, precipitation

COST partners (15 teams joined from 12 COST Countries) installed their microsensors side-by-side to compare performance with referenced equipment in the Air-Quality Mobile Laboratory



Assessment of air quality microsensors versus reference methods: The EuNetAir joint exercise

Original Research Article

In Press, Accepted Manuscript, Available online 22 Sept. 2016

C. Borrego[a,b], A. M. Costa[a], J. Ginja[a], M. Amorim[a], M. Coutinho[a], K. Karatzas[c], Th. Sioumis[c], N. Katsifarakis[c], K. Konstantinidis[c], S. De Vito[d], E. Esposito[d], P. Smith[e] , N. André[f] , P. Gérard[f], L. A. Francis[f], N. Castell[g], P. Schneider[g], M. Viana[h], M.C Minguillón[h], W. Reimringer[i], R.P. Otjes[j], O. v.Sicard[k], R. Pohle[k], B. Elen[l], D. Suriano[m], V. Pfister[m], M. Prato[m], S. Dipinto[m], M. Penza[m]

Highlights

- Several air quality microsensors were tested against reference methods.
- Significant differences in the results depending on the platform and on the sensors.
- Promising results were observed for O_3, CO and NO_2 sensors.
- The sensors can improve spatiotemporal resolution of data to complement existing air quality monitoring networks.

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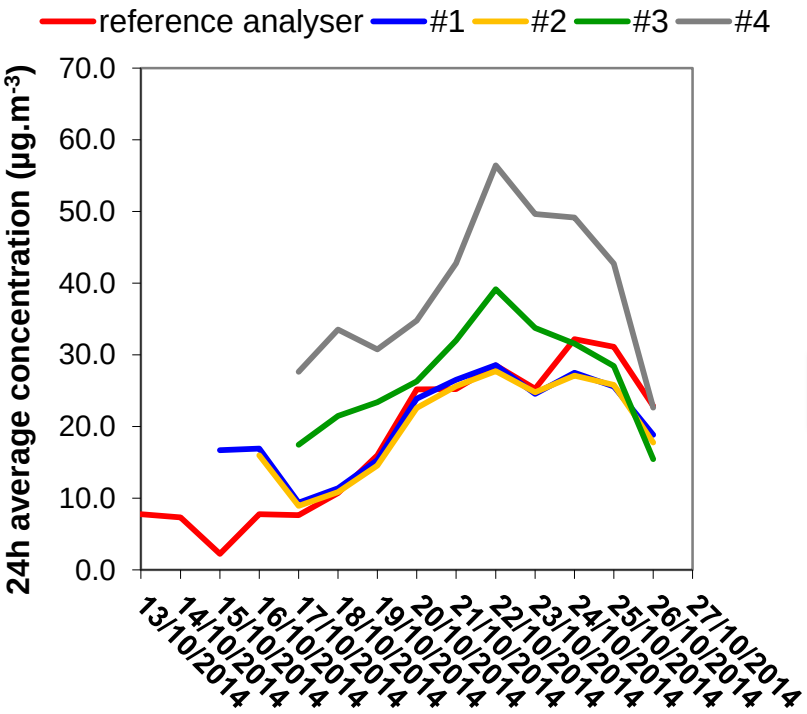
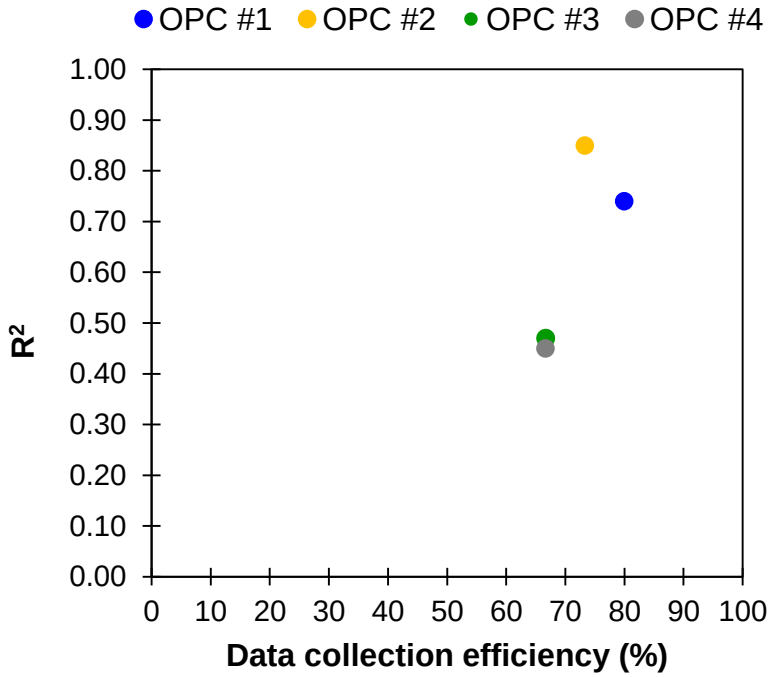
Joint-Exercise *EuNetAir*: *Sensors-versus-Analyzers* 2/2



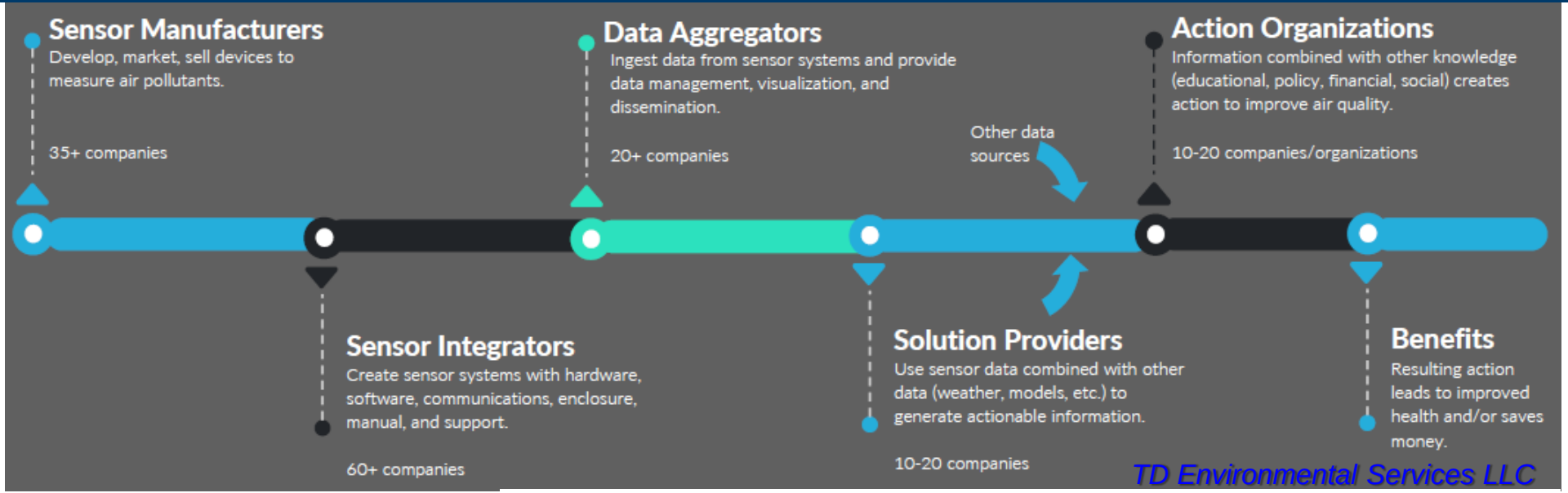
$PM_{2.5}$



The optical particle counters (OPC) for $PM_{2.5}$ presented correlations varying between 0.45-0.85 and data collection efficiencies in the range of 67-80%.

C. Borrego et al., Atmospheric Environment 147 (2016) 246-263

Value Chain for Air Quality Sensors



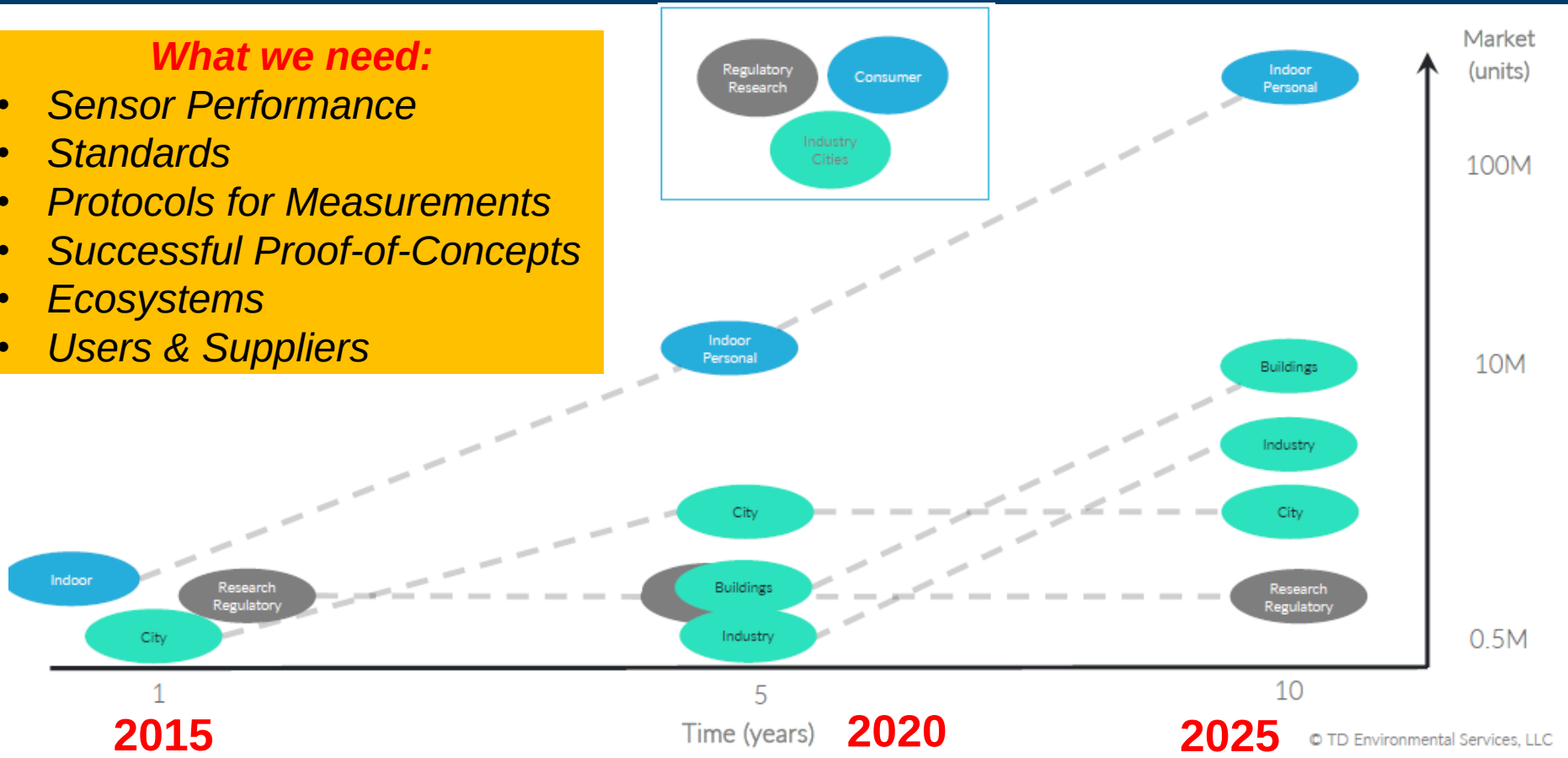
State of the Market:

- Dominated by startups and small hardware/software companies
- Large unknowns about sensor performance
- Few standards exist, no regulations accepting of sensors
- Lots of interest in monitoring local air quality
- Funding for demonstration and proof-of-concept projects
- Some early results are promising

Sensors Market Evolution

What we need:

- *Sensor Performance*
- *Standards*
- *Protocols for Measurements*
- *Successful Proof-of-Concepts*
- *Ecosystems*
- *Users & Suppliers*



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Selected EU projects on air quality sensors (1/2)

Project Acronym	Title of Project / Coordinator / Website
iSCAPE H2020-SC5-04-2015	***Improving the Smart Control of Air Pollution in Europe*** **Coordinator**: *Dr. Francesco Pilla, University College Dublin, Ireland* - **Website**: *www.iscapeproject.eu*
ClairCity H2020-SC5-04-2015	***Citizen-led Scenarios to Improve Air Quality in EU Cities*** **Coordinator**: *Prof. Enda Hayes, University of the West of England, Bristol, UK* - **Website**: *www.claircity.eu*
ICARUS H2020-SC5-04-2015	***Integrated Climate forcing and Air pollution Reduction in Urban Systems*** **Coordinator**: *Prof. Dimosthenis Sarigiannis, Aristotle University of Thessaloniki, Greece* - **Website**: *www.icarus2020.eu*
ENoLL	***European Network of Living Labs*** **-** *www.openlivinglabs.eu*

Selected EU projects on air quality sensors (2/2)

Project Acronym	Title of Project / Coordinator / Website
CAPTOR H2020 GA: 688110	***Collective Awareness Platform for Tropospheric Ozone Pollution*** **Coordinator***: Prof. Jorge Garcia Vidal, Universitat Politecnica de Catalunya, Barcelona, Spain* - **Website***: www.captor-project.eu*
PREPAIR LIFE15 IPE IT013	***Po Regions Engaged to Policies of Air*** **Coordinator***: Regione Emilia-Romagna, Bologna, Italy* - **Website***: www.lifeprepair.eu*
PhotoCityTex LIFE13 ENV/ES/000603	***Air Pollution Treatment in European Urban Environments by means of Photocatalytic Textiles*** **Coordinator***: Dr. Amalia Muñoz Cintas, CEAM, Valencia, Spain* - **Website***: www.ceam.es/PHOTOCITYTEX/home.htm*

Air Quality Sensors Network: Lessons Learned (1/2)

Open Questions of the Air Quality Sensors

- Lower Accuracy compared to Reference Methods
- Cross-sensitivity and low Selectivity
- Low Stability and Drift to be corrected periodically
- Calibration needs periodically (e.g., at least 1 calibration/month ??)
- Regular Maintenance of the in-field AQ sensor nodes
- Data Quality Objective (European Directive 2008/50/EC) to be addressed for *Indicative Measurements* by demonstration of the equivalence to use microsensors for AQ monitoring

Air Quality Sensors Network: Lessons Learned (2/2)

Advantages and Benefits of the Air Quality Sensors

- Low-cost for deployment in Cities at high spatial-temporal resolution
- Suitability for personal exposure studies
- Suitability for emission source information
- Outdoor monitoring of gases (NO_2/NO, O_3, CO, SO_2, H_2S, tVOCs, CO_2, NH_3, etc.)
- Outdoor monitoring of particulate matter (PM_{10}, $PM_{2.5}$, $PM_{1.0}$, UFP)
- Indoor monitoring of gases (CO, VOCs, benzene, formaldehyde, naphthalene, toluene, etc.) and PM (PM_{10}, $PM_{2.5}$, $PM_{1.0}$)
- Combination of sensors with modelling for micro-scale analysis (1-2 mt resolution)

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CONCLUSIONS

- Micro-Sensors should not substitute but supplement routine environmental monitoring equipments/devices
- Future Routine Environmental Networks may look very different from today and include low-cost and accurate Sensors ?
- *Green Routes* through the city or access to information about air-pollution load at specific local address might be future goals
- Pervasive low-cost Micro-Sensors for Indoor Energy Efficiency should be a must for future *Green-Buildings*
- What do we want to provide (e.g. AQI) on the long-term in relation to Routine Monitoring and Public Information to enhance Environmental Awareness ?

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C. Borrego et al., Atmospheric Environment 147 (2016) 246-263

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