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Comparison of two IAM systems: a test case over Northern Italy

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Introduction

Assessing the reliability of future scenarios presents a methodological challenge because there are no measurements to compare with the results.
One approach to overcoming this problem is to compare different modeling systems.

Comparison of two IAM systems in the same domain (Northern Italy).
The models are:

MAQ (Multi-dimensional Air Quality) model, University of Brescia (IT).
MAQ is an integrated assessment model designed to support regional decision-makers in selecting efficient air pollution reduction policies. **Bottom-up**

SIMBAD (Simplified Air Quality Model based on DDM) model, RSE (IT).
SIMBAD is part of a harmonized model that evaluates national energy policies and has been designed to provide a rapid assessment of the air quality and health impacts of a wide range of energy scenarios.
Top-down

MAQ model

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Multi-objective approach:

$$\min_{x,z,s} J(x,z,s) = \min_{x,z,s} \left[AQI(x,z,s)\ ,C(x,z,s)\right]$$

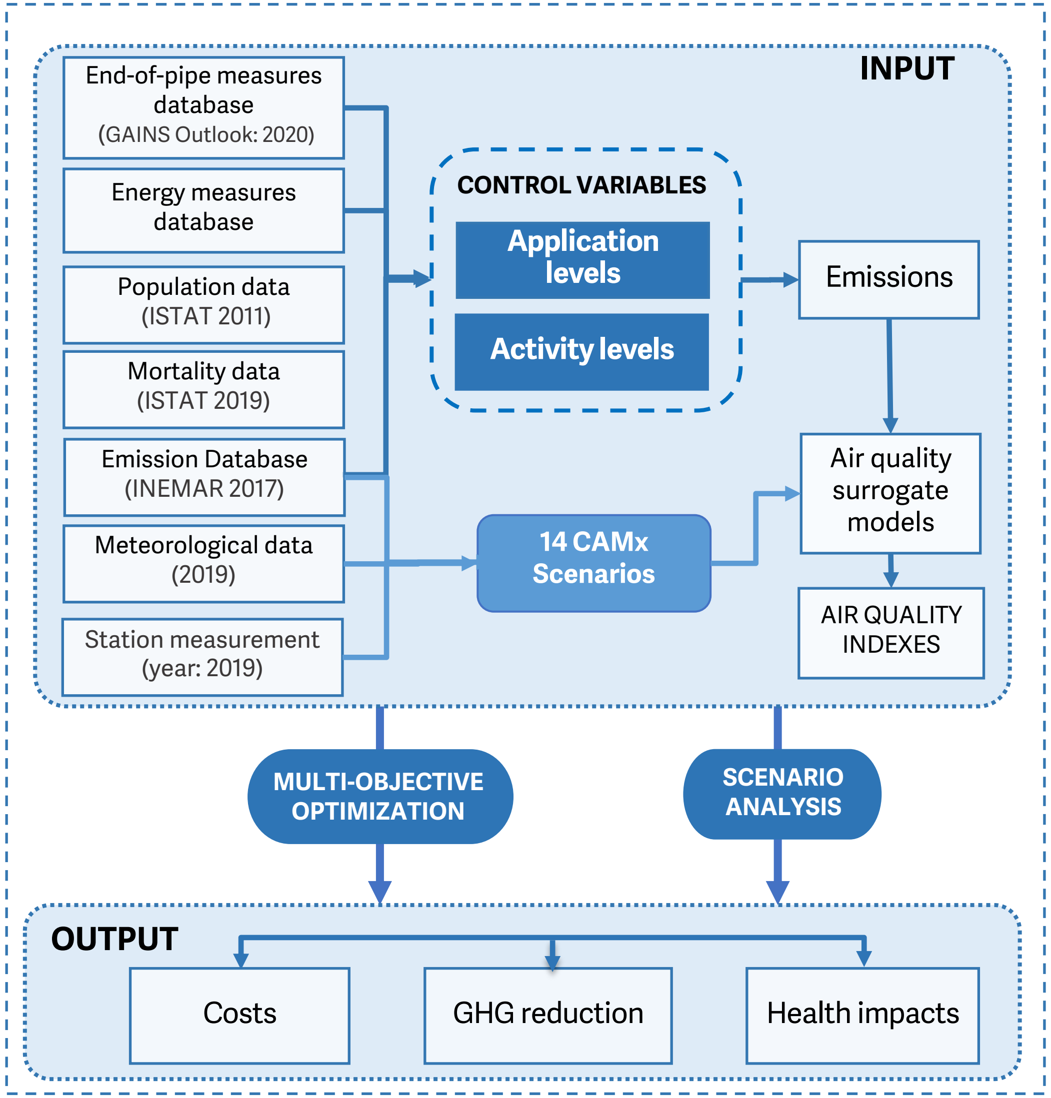
$$\frac{\partial AQI(x,z,s)}{\partial x \partial z \partial s} = \frac{\partial AQI(x,z,s)}{\partial E(x,z,s)} \cdot \frac{\partial E(x,z,s)}{\partial x \partial z \partial s}$$

AQ SURROGATE MODEL:
Artificial Neural Network

$$E^{d,p}(x,z,s) = \sum_{k \in K} \left\{ \left[A_k^d(1-(z_k+s_k))\right] \cdot ef_k^p \cdot \left(1 - \sum_{t \in T_k} eff_t^p \cdot x_k^t\right)\right\}$$

- k emission source
- A_k activity level
- ef unabated emission factor
- t end of pipe measure
- eff removal efficiency

E. Turrini, C. Carnevale, G. Finzi, M. Volta. A non-linear optimization programming model for air quality planning including co-benefits for GHG emissions, Sci. Total Environ., 621 (2018), pp. 980-989



INPUT

End-of-pipe measures database (GAINS Outlook: 2020)

Energy measures database

Population data (ISTAT 2011)

Mortality data (ISTAT 2019)

Emission Database (INEMAR 2017)

Meteorological data (2019)

Station measurement (year: 2019)

CONTROL VARIABLES

Application levels

Activity levels

Emissions

14 CAMx Scenarios

Air quality surrogate models

AIR QUALITY INDEXES

MULTI-OBJECTIVE OPTIMIZATION

SCENARIO ANALYSIS

OUTPUT

Costs

GHG reduction

Health impacts

SIMBAD model

Scenario Analysis:

$$c_{(scen)} = c_{(base)} + \sum_{i=1}^{Npre}\sum_{j=1}^{Nsec} \lambda_{i,j}\, S_{i,j}{}^{(g)}_{(base)}$$

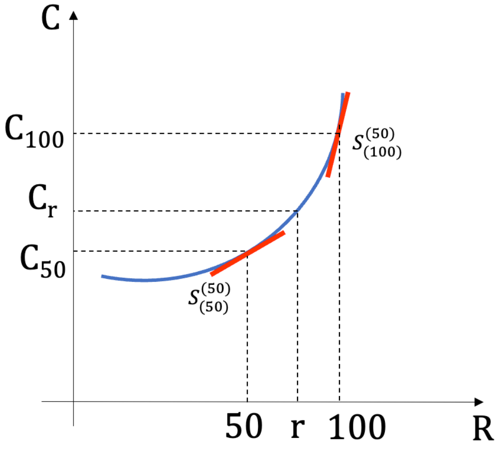
SENSITIVITY :
Decoupled Direct Method

g: maximum emissions perturbation

$\lambda_{i,j}$: emission variation of precursor i in sector j from base-case (fraction of g)

The concentration relative to variation coefficients $r_{i,j}$ is the weighted mean between two contributions, estimated starting from the base-case and from the configuration with emissions reduced to 50%.

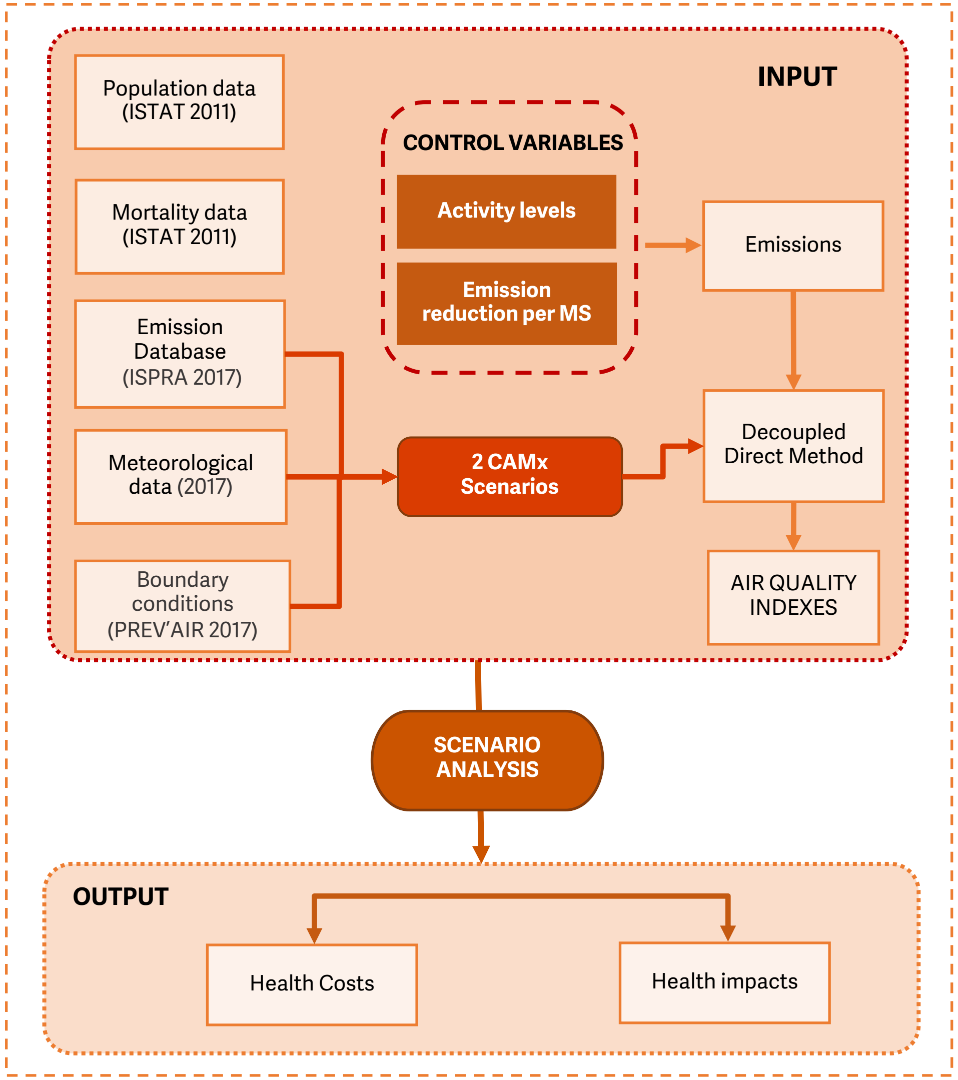
$$c_{(r)} = \overline{w_{(100)}}\left(c_{(100)} + \sum_{i=1}^{Nprec}\sum_{j=1}^{Nsec} \lambda_{i,j}\, S_{i,j}{}^{(50)}_{(100)}\right) + \overline{w_{(50)}}\left(c_{(50)} + \sum_{i=1}^{Npre}\sum_{j=1}^{Nsec} (1+\lambda_{i,j})\, S_{i,j}{}^{(50)}_{(50)}\right)$$



$$\lambda_{i,j} = \frac{r_{i,j} - 100}{50} \qquad r_{i,j} = \frac{Emix(scenario)}{Emix(base)}\,\%$$

Decision variables:
$r_{i,j}$: variation from the base-case of precursor i in sector j.

M. P. Costa, E. De Angelis, e G. Pirovano, «SIMBAD: a simplified emission-concentration model for a computationally efficient assessment of energy policies impact on air quality», *J. Phys.: Conf. Ser.*, vol. 2701, fasc. 1, p. 012074, feb. 2024, doi: 10.1088/1742-6596/2701/1/012074.



INPUT

Population data (ISTAT 2011)

Mortality data (ISTAT 2011)

Emission Database (ISPRA 2017)

Meteorological data (2017)

Boundary conditions (PREV'AIR 2017)

CONTROL VARIABLES

Activity levels

Emission reduction per MS

Emissions

2 CAMx Scenarios

Decoupled Direct Method

AIR QUALITY INDEXES

SCENARIO ANALYSIS

OUTPUT

Health Costs

Health impacts

MAQ vs SIMBAD

APPROACH

Scenario analysis $AQI(x,z,s) = f(E(x,z,s))$

Multi-objective optimization $\min_{x,z,s} J(x,z,s) = \min_{x,z,s}[AQI(x,z,s)\ , C(x,z,s)]$

CONTROL VARIABLES

Application rate of emission reduction measures (All macrosectors):
x: end of pipe measures
z: energy measures
s: switch measures

SOURCE-RECEPTOR MODEL

Artificial Neural network

HEALTH IMPACT

$$AD^{m}_{AQI} = \sum_{d\in m} AF^{d}_{AQI} \cdot D^{d}_{all}$$

$$AF^{d}_{AQI} = 1 - \frac{1}{\exp\left[\ln\left(RR_{AQI}\right) \cdot \left(AQI^{d} - AQI^{thr}\right)\right]}$$

AQI threshold (WHO):
$PM2.5^{tr} = 5\ \mu g/m^3$
$NO_2^{tr} = 10\ \mu g/m^3$

Relative risk (RR)*	RR PM2.5	RR NO2
Natural causes mortality	1.08 (1.06-1.09)	1.02 (1.011.04)

HEALTH COST

$$YLL^{d}_{AQI} = AF^{d}_{AQI} \cdot pop^{d} \cdot INC \cdot AYL$$

$$HC = \sum_{AQI} \sum_{d\epsilon D} VOLY \cdot YLL^{d}_{AQI}$$

APPROACH

Scenario analysis $AQI(\bar{r}) = f(\bar{r})$

CONTROL VARIABLES

Option 1: **emission reduction** per MS (01,02,07)

Option 2: **activity level** variation MS (01,02,07)

SOURCE-RECEPTOR MODEL

Decoupled Direct method

HEALTH IMPACT

$$M^{d}_{k} = \sum_{k=1}^{\max\_age} pop^{d} \cdot r^{k}_{d} \left(1 - \frac{1}{e^{\beta_k \Delta c_d}}\right)$$

$$\beta = \frac{\ln(RR)}{10}$$

AQI threshold (HRAPIE**):
$PM2.5^{tr} = 0\ \mu g/m^3$
$NO_2^{tr} = 20\ \mu g/m^3$

Relative risk (RR)**	RR PM2.5	RR NO2
Natural causes mortality	1.062 (1.040-1.083)	1.0076 (1.006-1.013)

HEALTH COST

$$YLL^{d}_{AQI} = \sum_{k=1}^{\max\_age} M^{d}_{k,AQI} \cdot LE_{k}$$

$$HC = \sum_{AQI} \sum_{d\epsilon D} VOLY \cdot YLL^{d}_{AQI}$$

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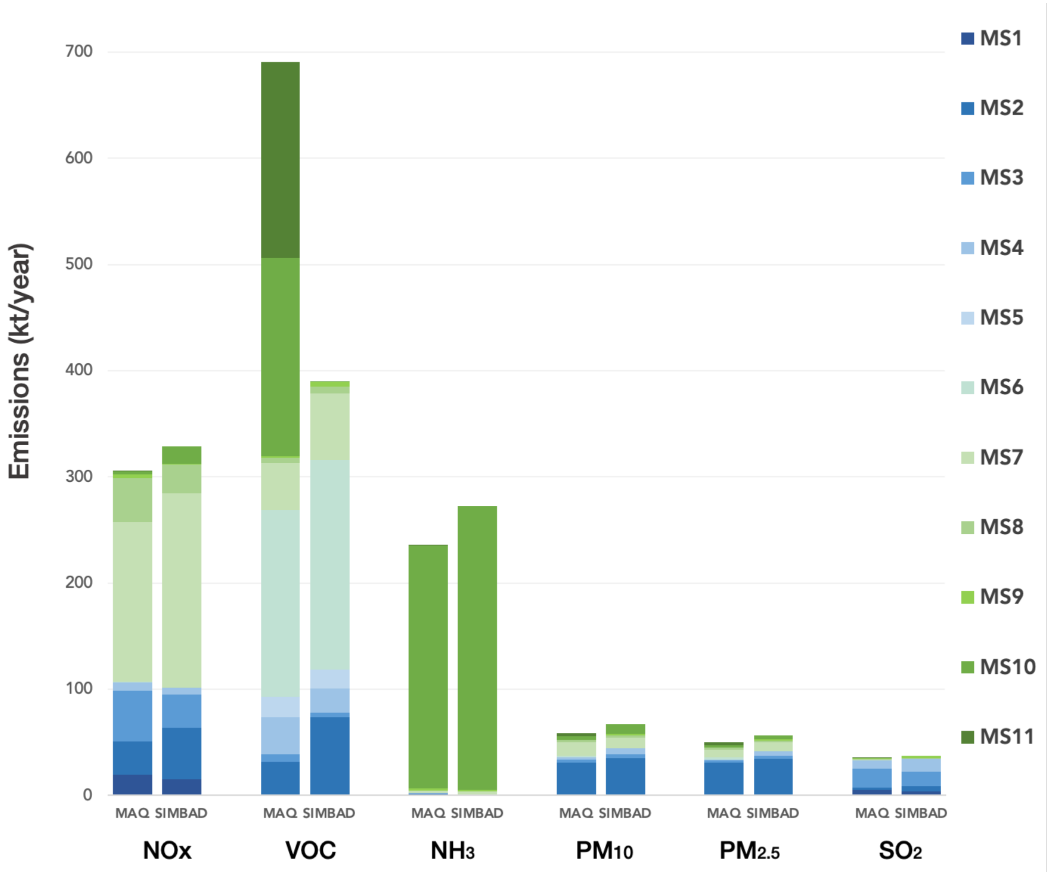
*J. Chen, G. Hoek, "Long-term exposure to PM and all-cause and cause-specific mortality: A systematic review and meta-analysis", Environ Int., vol. 143 . Huangfu, R. Atkinson, "Long-term exposure to NO2 and O3 and all-cause and respiratory mortality: A systematic review and meta-analysis," Environ Int., vol. 144.

**J. WHO Regional Office for Europe, «Health Risk of air pollution in Europe - HRAPIE project. Recommendations for concentration-response function for cost-benefit analysis of particulate matter, ozone and nitrogen dioxide,» 2013.,

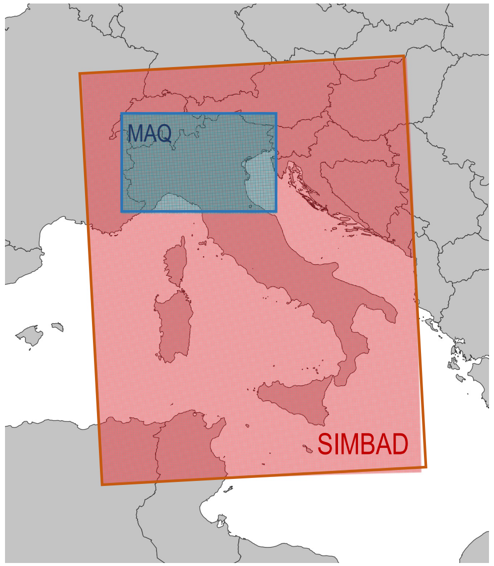
Input dataset

Input emissions inventory per macrosector



SIMBAD omitted emissions from macro-sector 11 (biogenic emissions), these are computed using the MEGAN model. **

Domain



	MAQ model (UNIBS)	SIMBAD model (RSE)
Domain	Po Valley	Italy
Grid	5890 cells: 6x6 km	179488 cells: 4x4 km
Emission database	INEMAR 2017 (municipality)*	ISPRA 2015 (NUTS3)
Meteorological data	year: 2019	year: 2017
Population data	ISTAT 2011	ISTAT 2011
Mortality data	ISTAT 2019	ISTAT 2011

*LIFE PREPAIR project (PREPAIR-LIFE15 IPE IT 013, https://www.lifeprepair.eu)

** B. Guenther *et al.*, «The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1): an extended and updated framework for modeling biogenic emissions», *Geosci. Model Dev.*, vol. 5, fasc. 6, pp. 1471–1492.

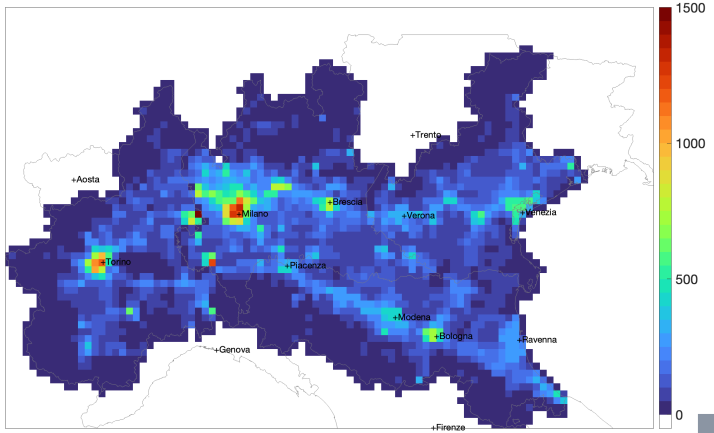
Base-case scenario

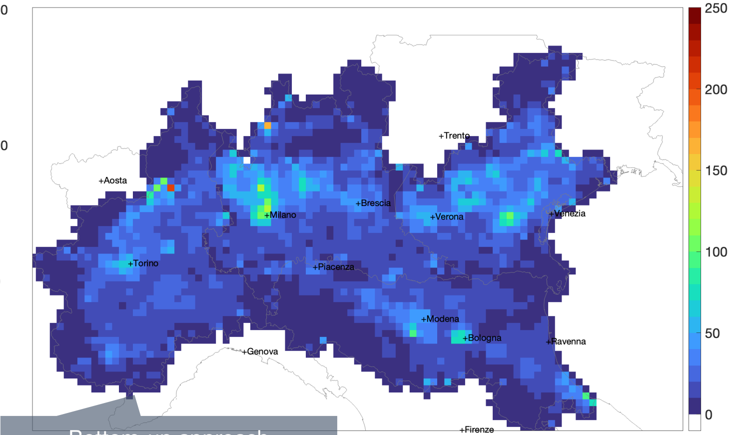
NO_x **emissions** per cell [t/year]

PM2.5 **emissions** per cell [t/year]

PM2.5 yearly average **concentration** [µg/m^3]

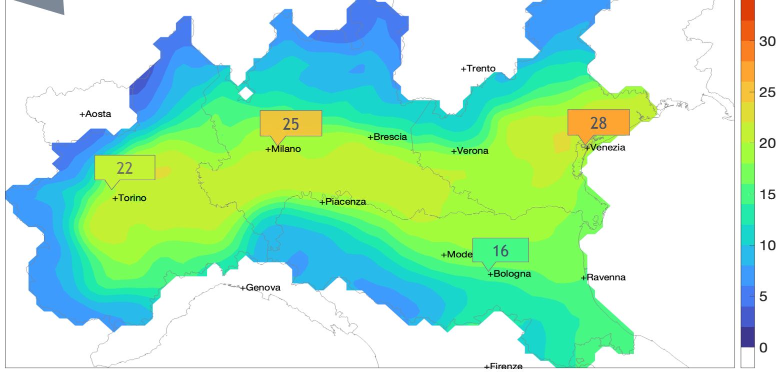
MAQ



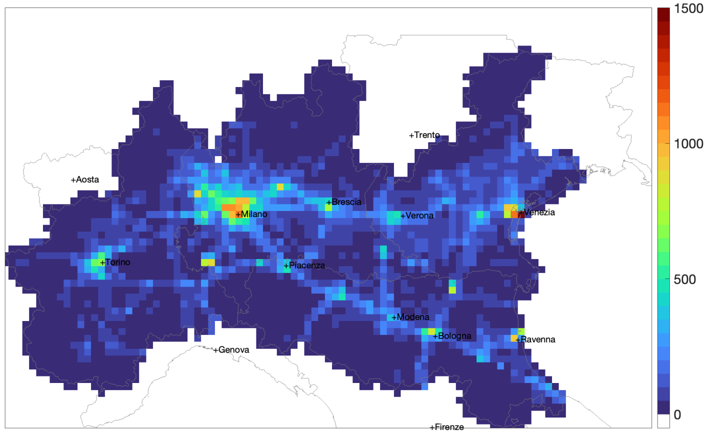


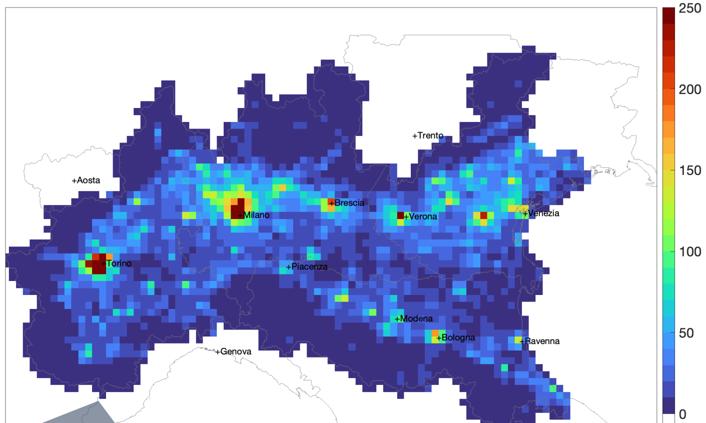
Bottom-up approach
Distributed per municipality

Concentration data:
2019



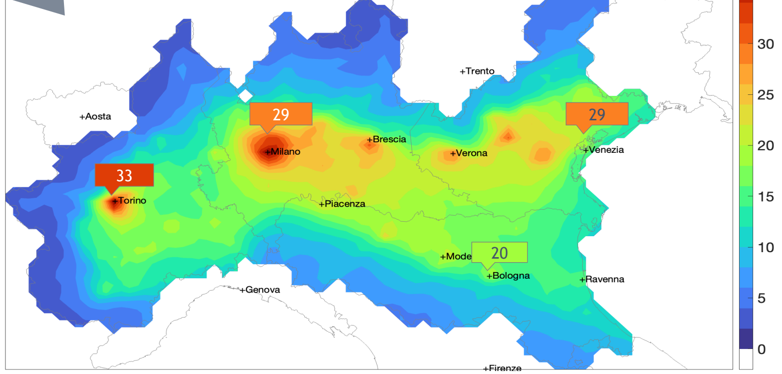
SIMBAD





Top-down approach
Using proxies on provinces

Concentration data:
2017



Measurements data:
https://www.istat.it/storage/rapporti-tematici/sdgs/2022/goal11.pdf

Energy scenarios

- **SCENARIO 1**: renewable energy communities and energy production reduction:
  - domestic energy consumption reduction of 24%
  - energy production reduction of 5% (MS01)

Emissions reduction per macrosector

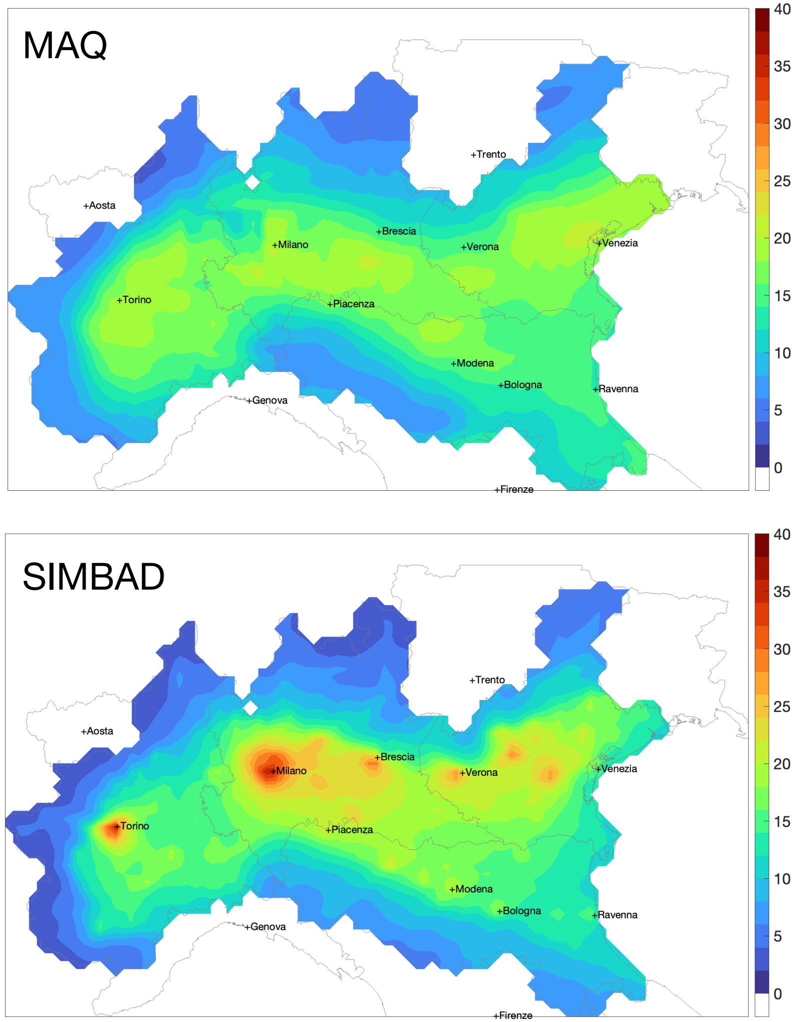
	NOx	VOC	NH3	PM10	PM25	SO2
MS01	5%	5%	5%	5%	5%	5%
MS02	24%	24%	24%	24%	24%	24%
TOTAL	3%	1%	0%	13%	15%	2%

- **SCENARIO 2**: renewable energy communities and vehicle fleet electrification:
  - domestic energy consumption reduction of 24%
  - road transport fuel consumption reduction of 10% (MS07)

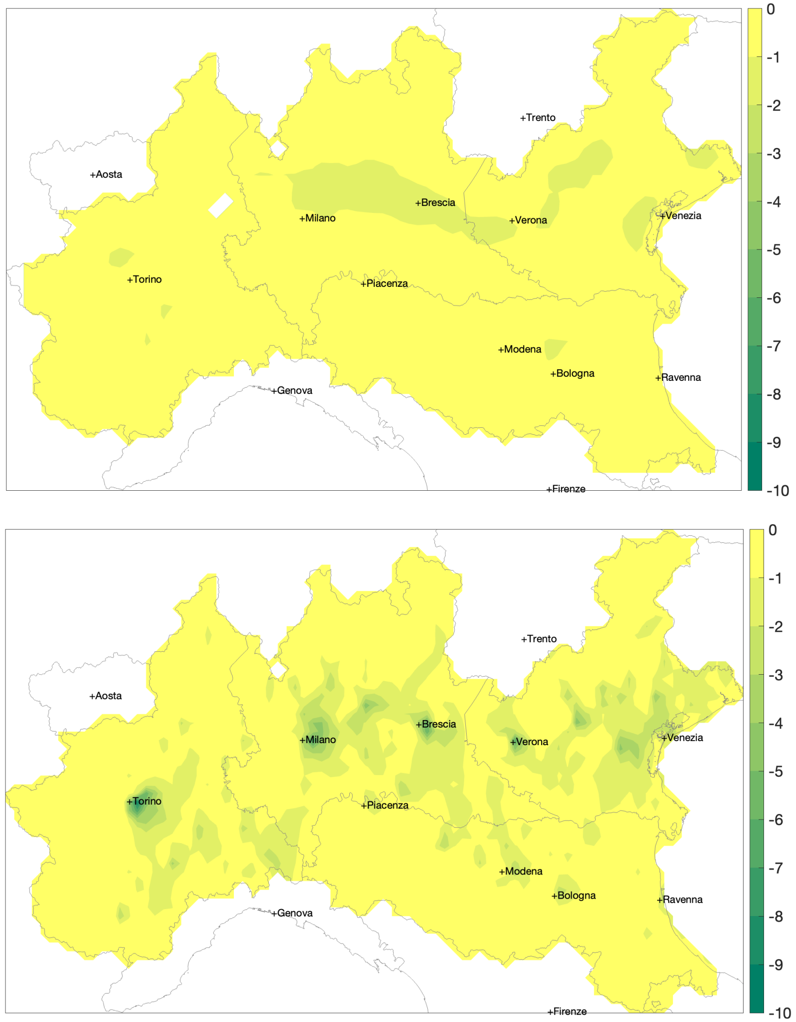
Emissions reduction per macrosector

	NOx	VOC	NH3	PM10	PM25	SO2
MS02	24%	24%	24%	24%	24%	24%
MS07	10%	10%	10%	10%	10%	10%
TOTAL	8%	30%	0%	20%	22%	2%

Results: Scenario 1



PM2.5 yearly mean concentration [µg/m³]



PM2.5 variation from the base-case [µg/m³]

Health Impact

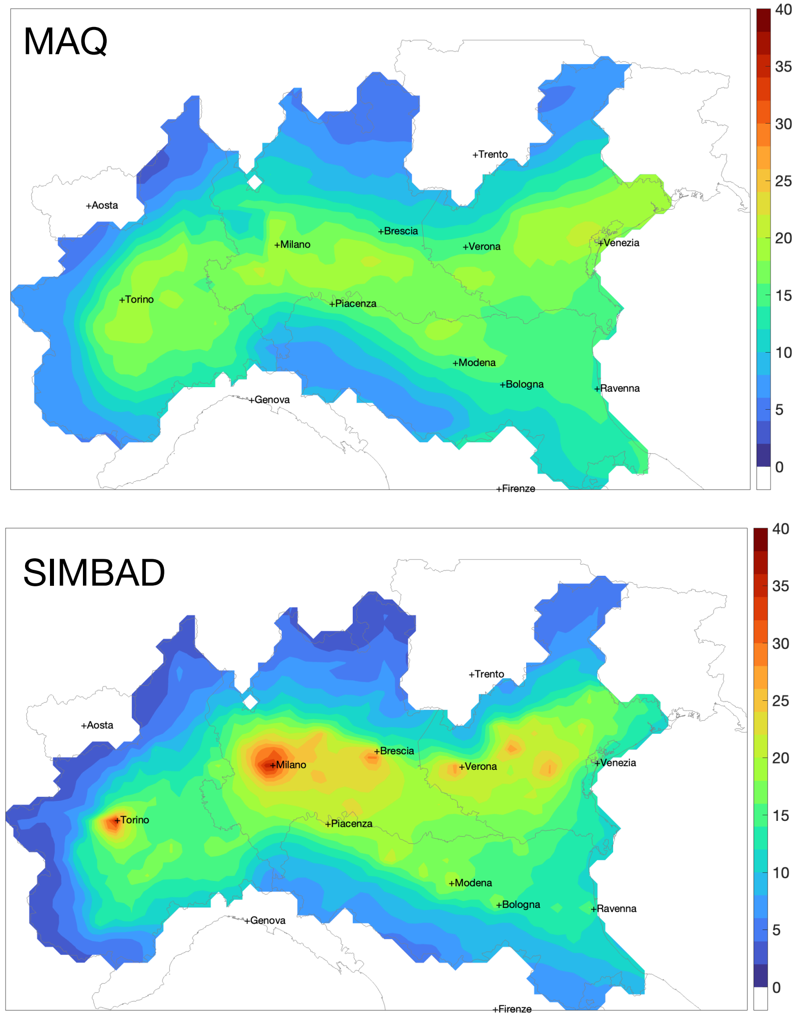
MAQ PM2.5 Attributable Deaths
[deaths/100000 inhabitants]

Regions	Base case	Scenario 1	Delta
Piedmont	102	96	-6%
Lombardy	95	88	-7%
Veneto	91	85	-6%
Emilia Romagna	79	75	-5%
Total	92	86	-6%

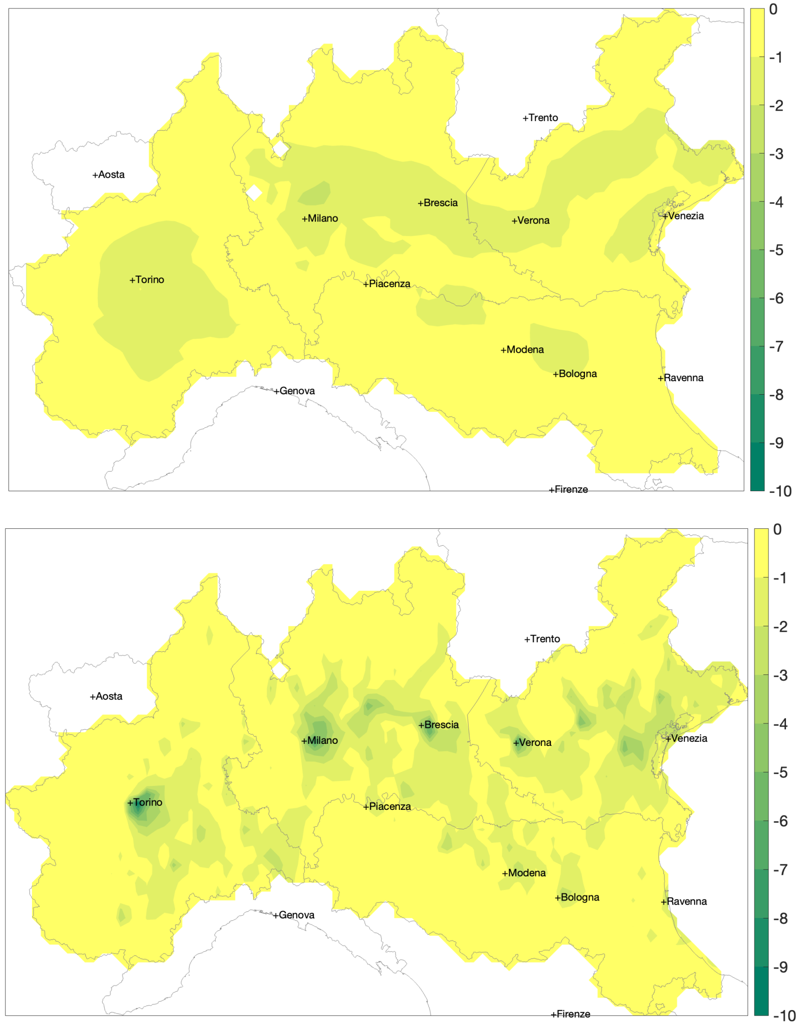
SIMBAD PM2.5 Attributable Deaths
[deaths/100000 inhabitants]

Regions	Base case	Scenario 1	Delta
Piedmont	135	122	-10%
Lombardy	139	129	-8%
Veneto	116	108	-6%
Emilia Romagna	102	99	-3%
Total	127	118	-7%

Results: Scenario 2



PM2.5 yearly mean concentration [$\mu g/m^3$]



PM2.5 variation from the base-case [$\mu g/m^3$]

Health Impact

MAQ PM2.5 Attributable Deaths [deaths/100000 inhabitants]

Regions	Base case	Scenario 1	Delta
Piedmont	102	93	-8%
Lombardy	95	85	-10%
Veneto	91	84	-7%
Emilia Romagna	79	73	-7%
Total	92	84	-9%

SIMBAD PM2.5 Attributable Deaths [deaths/100000 inhabitants]

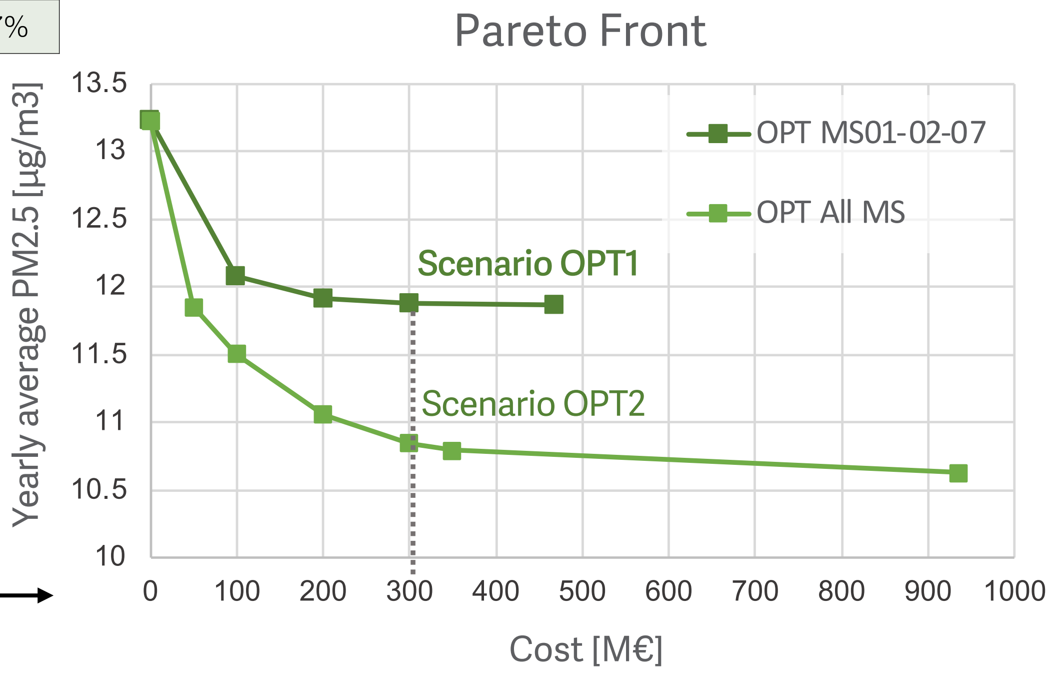
Regions	Base case	Scenario 1	Delta
Piedmont	135	120	-11%
Lombardy	139	125	-10%
Veneto	116	107	-8%
Emilia Romagna	102	97	-5%
Total	127	115	-9%

Efficient scenarios

OPT 1 (MAQ -> SIMBAD): Minimize PM2.5 and Cost.
Decision variables:
End of Pipe measures of **01, 02, 07 MS.**

Emissions reduction per macrosector

	NOx	VOC	NH3	PM10	PM2.5	SO2
MS 01	24%	21%	8%	53%	51%	42%
MS 02	26%	47%	0%	57%	57%	0%
MS 07	5%	5%	7%	0%	1%	0%
Total	7%	2%	0%	31%	37%	7%



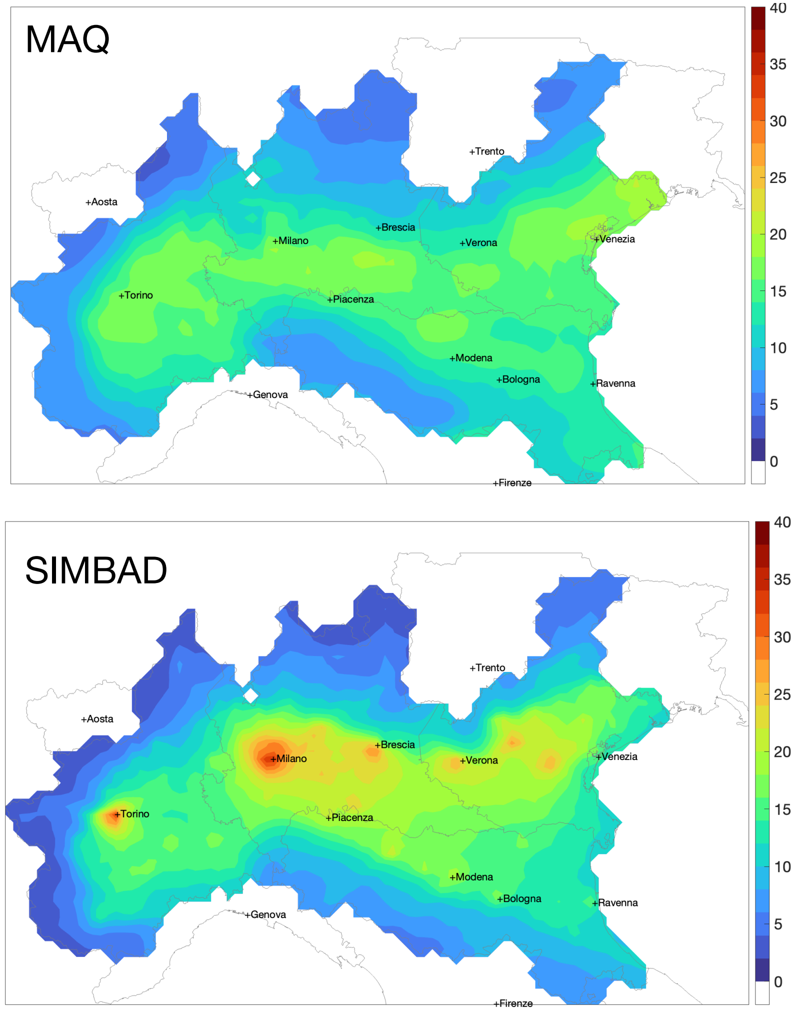
Results from the MAQ model →

OPT 2 (MAQ): Minimize PM2.5 and Costs.
Decision variables:
End of Pipe measures of **all MS.**

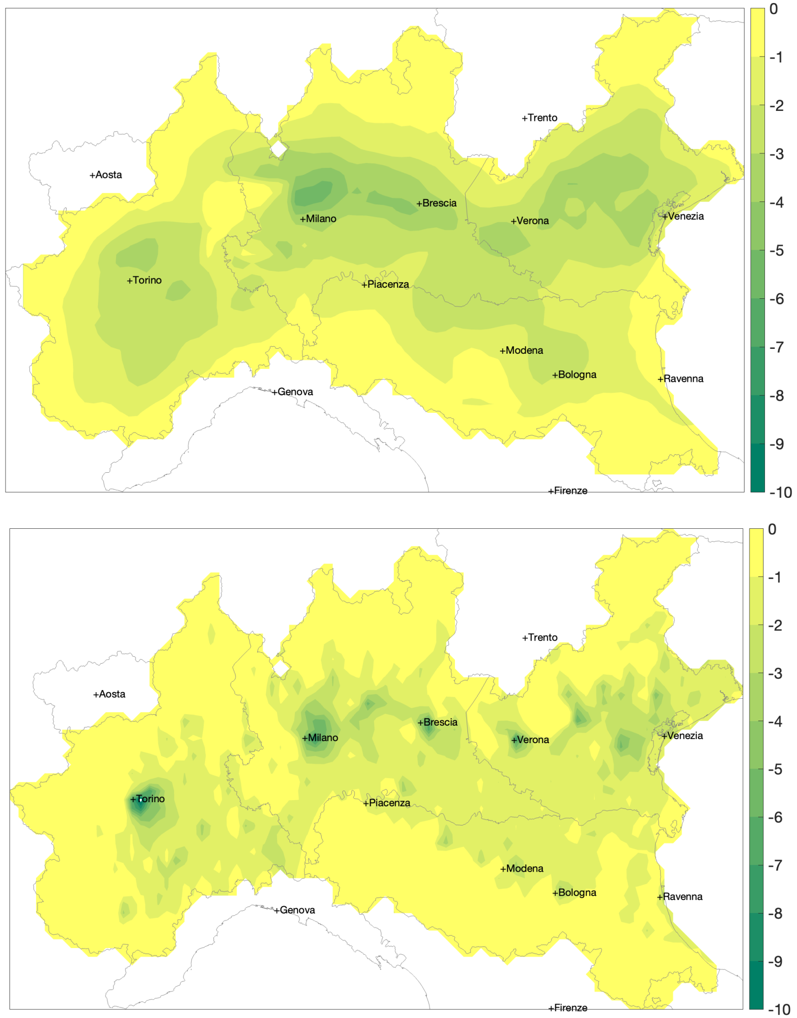
Emissions reduction per macrosector

	NOx	VOC	NH3	PM10	PM2.5	SO2
MS 01	10%	21%	2%	48%	46%	23%
MS 02	0%	37%	0%	57%	57%	0%
MS 03	10%	0%	5%	54%	47%	6%
MS 04	2%	1%	0%	21%	27%	4%
MS 07	4%	5%	6%	0%	1%	0%
MS 08	60%	38%	-24%	70%	70%	0%
MS 10	0%	0%	-35%	0%	0%	0%
Total	12%	2%	35%	36%	42%	8%

Results: Scenario OPT1



PM2.5 yearly mean concentration [μg/m³]



PM2.5 variation from the base-case [μg/m³]

Health Impact

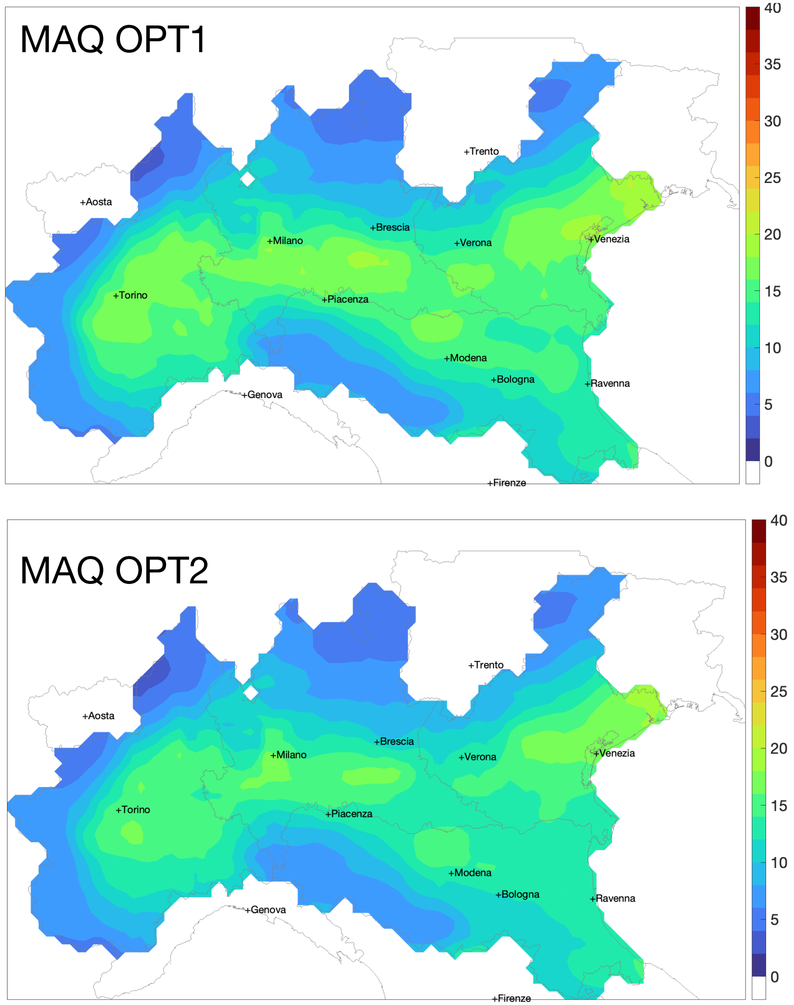
MAQ PM2.5 Attributable Deaths [deaths/100000 inhabitants]

Regions	Base case	Scenario OPT1	Delta
Piedmont	102	85	-16%
Lombardy	95	76	-20%
Veneto	91	74	-19%
Emilia Romagna	79	68	-13%
Total	92	76	-18%

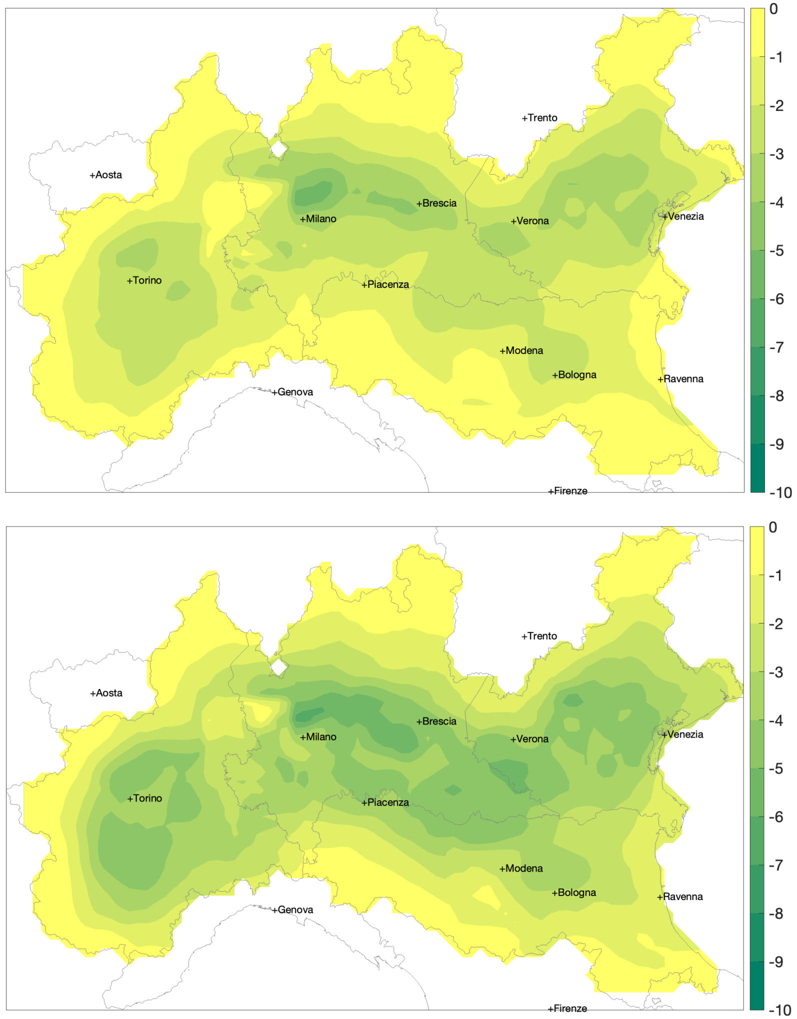
SIMBAD PM2.5 Attributable Deaths [deaths/100000 inhabitants]

Regions	Base case	Scenario OPT1	Delta
Piedmont	135	101	-25%
Lombardy	139	112	-19%
Veneto	116	96	-17%
Emilia Romagna	102	91	-11%
Total	127	103	-19%

Scenario OPT1 vs OPT2 (MAQ)



PM2.5 yearly mean concentration [µg/m³]



PM2.5 variation from the base-case [µg/m³]

Health Impact

MAQ PM2.5 Attributable Deaths [deaths/100000 inhabitants]

Regions	Base case	Scenario OPT1	Delta
Piedmont	102	85	-16%
Lombardy	95	76	-20%
Veneto	91	74	-19%
Emilia Romagna	79	68	-13%
Total	92	76	-18%

MAQ PM2.5 Attributable Deaths [deaths/100000 inhabitants]

Regions	Base case	Scenario OPT2	Delta
Piedmont	135	73	-28%
Lombardy	139	64	-32%
Veneto	116	66	-28%
Emilia Romagna	102	60	-24%
Total	127	65	-29%

Conclusions

- Comparing results obtained with different modeling systems can be an approach to assess the reliability of simulations of future scenarios.
- It is then required to identify indicators for comparing the results. In this case, the health impact index is selected, expressed as the reduction of attributable deaths,
- A comparison of the MAQ and SIMBAD model results reveals that **indicators are consistent between the two models**. The simulation of various scenarios showed that:
    - the reductions in attributable deaths are comparable in the scenarios close to the base case.
    - more significant emissions reductions from the base case scenario lead to more evident differences in results.
- Planning air quality policies with a multi-objective IAM approach provides **efficient strategies**

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Thank you!

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TFIAM 53, 15-17 April 2024, Paris