



Integrated assessment of impacts on NO₂ and PM_{2.5} concentrations, population exposure, and CO₂ emissions of biomethane deployment scenarios

Michele Francesco Arrighini , Claudio Marchesi ^{*} , Laura Zecchi , Marialuisa Volta

Department of Mechanical and Industrial Engineering, University of Brescia, Brescia, Italy

ARTICLE INFO

Keywords:

Biomethane
Air pollution
Exposure assessment
NO₂
PM_{2.5}
GHGs emissions
Integrated assessment modeling

ABSTRACT

Climate mitigation strategies increasingly prioritize interventions that deliver simultaneous benefits for greenhouse-gas reduction, air quality and public health. This study quantifies the co-benefits of scaling biomethane deployment in the Po Valley (Northern Italy), a European air pollution hotspot, comparing two policy-relevant supply levels (2.3 and 6 bcm). An integrated pathway is assessed where biomethane is used for electricity generation to support partial electrification of the vehicle fleet, while digestate, the solid and liquid residue of the anaerobic digestion process, is utilized in agriculture with improved manure management protocols. A bottom-up integrated assessment framework links energy, traffic and agricultural measures to emission changes, ambient concentrations of NO₂ and PM_{2.5}, population exposure, and attributable mortality, and provides the analysis of uncertainty propagated across the modelling chain. Both deployment levels reduce CO₂ emissions and lower population exposure to NO₂ and PM_{2.5}, yielding measurable public health benefits. Direct comparison of 2.3 and 6 bcm scenarios estimates the marginal co-benefits of scaling biomethane deployment and highlights how coordinated actions across the energy, transport, and agricultural sectors can enhance health-relevant decarbonization in highly polluted regions. Scalability indicators, namely ΔCO_2 , ΔNO_2 , and $\Delta\text{PM}_{2.5}$ per bcm of biomethane, and the incremental benefits of scaling from 2.3 to 6 bcm are estimated, providing a basis for comparing alternative decarbonization pathways in other settings.

1. Introduction

Climate-change mitigation increasingly targets interventions that also reduce exposure to air pollution and the associated health burden [1]. In Europe, population exposure to nitrogen dioxide (NO₂) and fine particulate matter (PM_{2.5}) remains a leading environmental risk factor for premature mortality, and strategies that jointly address greenhouse gases and air quality precursor emissions are therefore of growing interest. Achieving such co-benefits requires approaches that connect energy-system changes to emission patterns, ambient concentrations, population exposure, and health outcomes.

Among renewable options, biomethane has emerged as a key option to reduce greenhouse gas (GHG) emissions [2]. With appropriate regulatory frameworks and sustainable feedstocks, the biogas and biomethane sector could contribute to 10–13% of the global GHG reduction potential [3]. Moreover, the use of biomethane may also reduce emissions of short-lived climate pollutants and air quality precursors, such as

black carbon and nitrogen oxides, thereby contributing to both climate mitigation and health protection. [4]. Owing to these advantages, biomethane has attracted increasing international attention as a renewable energy carrier for power generation and transport [5–9]. While the carbon neutrality of biomethane ensures equivalent CO₂ balances across applications, its air quality implications depend on how both it is used and managed. In the pathway assessed here, biomethane is utilized to increase electricity generation, providing additional power to meet the demand from an electrified vehicle fleet. In parallel, digestate is applied in agriculture as a substitute for fertilizers, using incorporation/injection practices to limit ammonia (NH₃) volatilization. NH₃ emissions are further reduced through improved animal-manure management aimed at preserving the biomethane potential of the feedstock, thereby limiting losses during storage and handling. This configuration requires an integrated assessment framework that links energy conversion, transport electrification, and agricultural emission controls to changes in NO₂ and PM_{2.5} exposure and related health outcomes.

^{*} Corresponding author. Department of Mechanical and Industrial Engineering, University of Brescia, Via Branze 38, Brescia, Italy.

E-mail address: claudio.marchesi@unibs.it (C. Marchesi).

<https://doi.org/10.1016/j.bmf.2026.100062>

Received 27 April 2026; Received in revised form 15 July 2026; Accepted 16 July 2026

Available online 16 July 2026

3051-4444/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Such interactions are particularly relevant in the Po Valley (Northern Italy), one of the most polluted regions in Europe. Intensive agriculture and livestock production, high population density, and concentrated industrial and transport activities occur within a topographically basin that frequently inhibits atmospheric dispersion [10]. Under these conditions, PM_{2.5} concentrations are driven by both primary emissions (e. g., biomass combustion and road transport) and secondary formation from precursors (NO_x, VOCs, NH₃, and SO_x) emitted by combustion sources, agriculture, and industry [11–13].

In parallel, the region generates substantial quantities of biomass and organic residues suitable for biogas and biomethane production [14], thereby creating a direct linkage between renewable-gas deployment and local air pollution dynamics.

This work assesses the impact on air quality and CO₂ emissions in the Po Valley when biomethane is used to generate additional energy for vehicle fleet electrification, considering two scenarios across three key macrosectors (MS) responsible for CO₂ and PM precursor emissions: energy production, road transport, and agriculture. In the first scenario, a production of 2.3 bcm of biomethane is considered, aligning with the objectives outlined in the Italian Recovery and Resilience Plan (RRP) [15].

The second scenario involves 6 bcm, representing the maximum potential biomethane production in Italy according to the National Plan for Energy and Climate (PNIEC) [16] and REPowerEU 2030 [17]. The impact of these scenarios on air quality in terms of NO₂ and PM_{2.5} mean concentrations, health impacts, and CO₂ emission reduction is performed. By comparing 2.3 and 6 bcm scenarios, the marginal, health-relevant benefits of biomethane scale-up are quantified and reported through scalability indicators (e.g., changes in CO₂, NO₂, and PM_{2.5} per bcm of biomethane), enabling comparison across decarbonization pathways and supporting transferability to other highly polluted regions.

2. Materials and methods

2.1. Study area

The study domain covers the four main regions of the Po Valley (Piedmont, Lombardy, Veneto, and Emilia-Romagna; Fig. 1), a densely populated (more than 23 million people) and economically relevant area in Northern Italy with more than 50 percent of the national GDP. The Po

Valley is characterized by frequent atmospheric stagnation due to its orography, which limits dispersion and favors the accumulation of primary pollutants and secondary PM_{2.5} and NO₂.

2.2. Scenario design

The two biomethane deployment levels are evaluated via a scenario analysis approach, which can be formalized as Equation (1).

$$AQI_{PM2.5,NO_2}^c = f(E_p^c(\theta)) \quad \theta \in \Theta \quad (1)$$

where AQI_n^c is the annual mean concentration of PM_{2.5} and NO₂ in the domain cell (c), which depends on the emission (E_p^c), of a set of precursors p determined by the application rate of the set of measures θ . Therefore, the scenario design requires three steps. First, the set of measures and their application rate is identified. Second, the emission variation is computed accordingly. Third, concentrations are estimated according to Equation (1).

In this study, biomethane production and utilization is assumed to affect the energy, transport, and agricultural MS. Biomethane is allocated to combined-cycle gas turbine (CCGT) plants to increase electricity generation. The additional electricity is used to supply part of the demand associated with partial electrification of the road vehicle fleet (section 2.2.1). Digestate is used in agriculture as a substitute for mineral nitrogen fertilizers, adopting low-ammonia application practices (e. g., injection, rapid incorporation, band spreading, trailing hose/shoe, strip-till). Additional NH₃ reductions are achieved through improved livestock-manure management practices implemented along the collection, storage, and handling chain, with the dual objective of reducing volatilization losses and preserving the biomethane potential of the feedstock (section 2.2.2). The adoption level of agricultural measures is scaled proportionally with biomethane deployment. A feedstock mix of 80% vegetal and 20% animal residues is assumed for anaerobic digestion [18] to ensure net zero CO₂ emission when biomethane is burned.

2.2.1. Energy production and electrification of vehicle fleet

Annual electricity ($A_{b,CCGT}$) generated from biomethane in CCGT plants is computed as the product of biomethane volume available under the scenario V_{bm} , biomethane lower heating value LHC_{bm} , and an overall

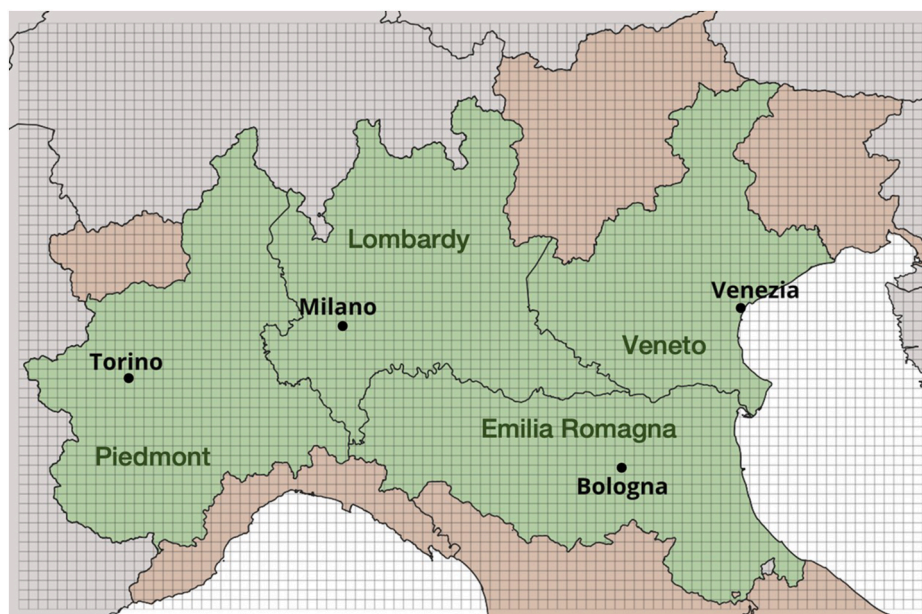


Fig. 1. Domain of the study (green area).

conversion-and-delivery efficiency η_{pd} that accounts for turbine efficiency and distribution losses [19], as follows:

$$A_{b,CCGT} = V_{bm} * LHC_{bm} * \eta_{pd} \quad (2)$$

The share of the vehicle fleet that can be electrified (S) is derived by comparing the additional electricity produced from biomethane (A_{ene}) with the electricity demand required to electrify the full road fleet (W_{tot}):

$$S = \frac{A_{b,CCGT}}{W_{tot}} \% \quad (3)$$

Where road-transport energy demand W_{tot} is derived from fuel consumption by vehicle class and fuel type of the present vehicle fleet. Internal combustion energy demand is converted to an equivalent electricity demand using the relative efficiencies of conventional and electric powertrains:

$$W_{tot} = \sum_{f \in F} \frac{\eta_{IC_f} * W_f}{\eta_{EV}} \quad (4)$$

where.

- F is the set of fuels that power the fleet: diesel, gasoline, natural gas, and LPG.
- W_f is the total energy consumed by the vehicles of fuel f . It is approximated as the fuel sold, derived from the Italian oil bulletin [20].
- η_{IC_f} is the efficiency of Internal Combustion Engines (ICE) powered by fuel f .
- η_{EV} is the efficiency of electric vehicles.

The electrification share is applied to reduce the baseline internal-combustion activity of each vehicle class and fuel ($A_{f,tra}$), resulting in an emission decrease in the road-transport macrosector:

$$A_{f,tra} = (A_f)_{BC2020} * \left(1 - \frac{S}{100}\right) \quad (5)$$

The energy parameters of equations (1)–(3) are reported in the supplementary information.

2.2.2. Agricultural measures: digestate substitution and manure management

Digestate substitution is represented by replacing part of mineral nitrogen fertilization and assuming the adoption of low-ammonia application techniques. Because digestate contains a substantial

ammoniacal nitrogen fraction [21], incorporation or injection is assumed to substantially reduce NH_3 volatilization compared with surface spreading.

In parallel, manure-management improvements are introduced to reflect the additional collection and handling required by increased biomethane production. Measures include actions that limit volatilization during storage and handling (e.g., covered storage) and practices that reduce nitrogen losses upstream. Measure definitions and efficiencies follow the GAINS Outlook2017 database [22] and are implemented within the agricultural macrosector.

This set of measures, hereafter denoted as “Manure management,” is summarized in the supplementary information.

2.3. AQ and health impact assessment modeling

The impact on emissions and air quality is estimated using a bottom-up integrated assessment model, [23,24]. The IAM developed in this work is modular, enabling the implementation of specific air quality and low carbon policies through scenario analysis. Fig. 2 illustrates the overall workflow of the IAM.

Biomethane is used in MS1 to generate extra electricity from combined-cycle gas turbine, thus increasing CCGT activity level ($A_{b,CCGT}$). This extra energy can then fuel a share of electric vehicles (S) that substitute internal combustion engines, reducing their activity level ($A_{f,tra}$). At the same time, digestate is used as fertilizer, while the implementation of improved manure management practices increases with biomethane production, increasing their application rate (AR_{agr}). These changes are then fed into the input module of the IAM, along with baseline emission database and other inputs. Emissions are then estimated under the selected scenario and then converted into annual mean NO_2 and $PM_{2.5}$ concentrations using a Source-Receptor Model. Finally, the output module performs the health impact assessment, estimating health indicators, NO_2 and $PM_{2.5}$ exposure maps, GHG emissions, and scenario costs.

2.3.1. IAM input module and emission database

The IAM input module provides the spatially resolved emission baseline, the database of anthropogenic activities, and abatement measures used throughout the analysis. Emissions of NO_x , SO_x , VOC, PPM10, $PM_{2.5}$ and NH_3 are estimated over the study domain by merging.

- A 2020 projection of the GAINS (Greenhouse Gas-Air Pollution Interactions and Synergies) “EUoutlook2017” [22] database, which

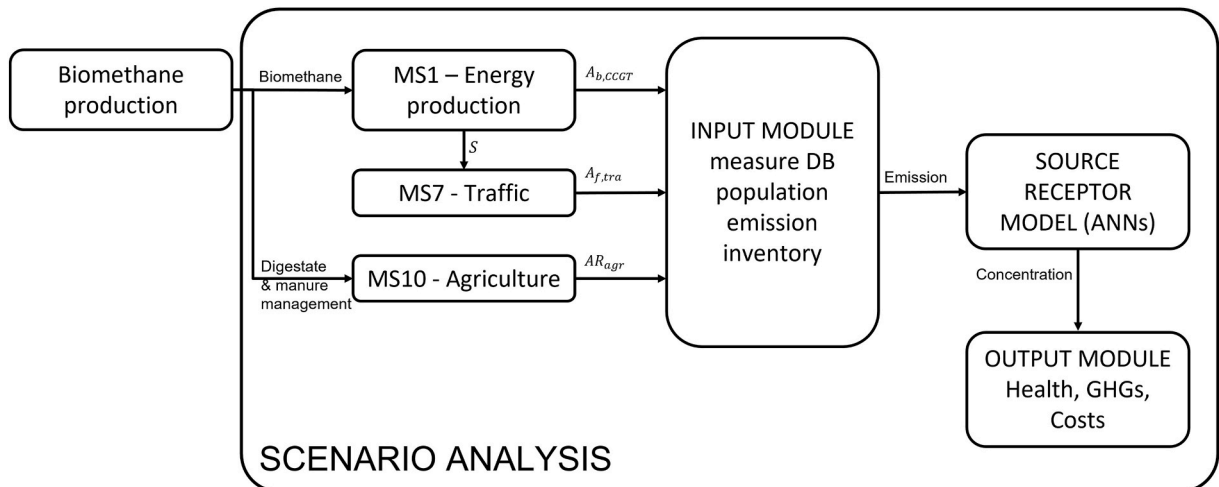


Fig. 2. IAM modules.

provides emission factors and a comprehensive list of potential reduction methods for each activity [25].

- The INEMAR inventory for the year 2017, developed by the ARPA agencies of the Po Valley region as part of the LIFE PREPAIR project (PREPAIR-LIFE15 IPE IT 013, accessible at <https://www.lifeprepare.eu>).

Fig. 3 illustrates the structure of the IAM input module and the pre-processing steps used to generate gridded emissions.

2.3.2. Emission model

Each domain cell's precursor p emission (E_p^c) is calculated as a function of the predetermined, selected set of emission reduction measures (θ) using Equation (6):

$$E_p^c(\theta) = \sum_f \left[A_{f,a}^c * ef_{f,a}^p * \left(1 - \sum_{m \in M_{f,a}} r_m^p * \theta_m \right) \right] \quad \theta \in \Theta \quad (6)$$

where.

- f, a is the anthropogenic fuel-activity.
- $A_{f,a}^c$ is the activity level of the activity-fuel f in the cell c . In particular, for the energy MS, it corresponds to the energy produced by bio-methane in CCGT plants ($A_{b,CCGT}$), and for the transport MS, to the energy required for the non-electrified share of the vehicle fleet ($A_{f,tra}$).
- ef_f^p is the emission factor of the precursor p for the activity-fuel f .
- $M_{f,a}$ is the set of all end-of-pipe measures m available for the activity-fuel f .
- r_m^p is the removal efficiency of the measure m for the precursor p .

- θ_m is the application level of the measure m , defined as a variation with respect with a base-case scenario CLE (Current LEgislation), which represents the level of application for each measure as specified by European legislation for the year under consideration.

In Equation (6), the first term ($A_{f,a}^c * ef_{f,a}^p$) represents the unabated emissions, while the second term within the parentheses corresponds to the fraction of emissions removed, which depends on the removal efficiency of each measure m and its application rate θ_m .

This work adopts the CORINAIR SNAP 97 classification, as reported in the Supplementary Information, for emissive sector categorization.

2.3.3. Source-receptor model

The AQI value for each cell is estimated by artificial neural networks (ANNs) as a function of precursor emissions in the receptor cell and surrounding area [26]. Four ANNs are developed, one for each region of the modelling domain: Emilia-Romagna, Lombardy, Piedmont, and Veneto. The ANNs are trained using emission-concentration scenarios generated with the CAMx Chemical Transport Model (<https://www.camx.com/>). The training dataset includes 14 emission scenarios over 5890 grid cells; 90% of the dataset is used for training and 10% for validation. Each ANN includes 20 input nodes, accounting for precursor emissions over the neighboring cells and for the spatial coordinates of the receptor cell.

The ANN source-receptor models are evaluated against CAMx simulations and European Environment Agency (EEA) gridded observations. The comparison with CAMx simulations is performed for each regional network. For PM_{2.5}, R^2 is equal 0.99 in all four regions, with RMSE values of 0.40 $\mu\text{g}/\text{m}^3$ in Emilia-Romagna, 0.50 $\mu\text{g}/\text{m}^3$ in Lombardy, 0.46 $\mu\text{g}/\text{m}^3$ in Piedmont, and 0.46 $\mu\text{g}/\text{m}^3$ in Veneto. For NO₂, R^2 is equal to 0.99 in all four regions, with RMSE values of 0.74, 0.67, 0.74, and 0.65 $\mu\text{g}/\text{m}^3$ for Emilia-Romagna, Lombardy, Piedmont, and Veneto, respectively. The comparison with EEA gridded observations for the

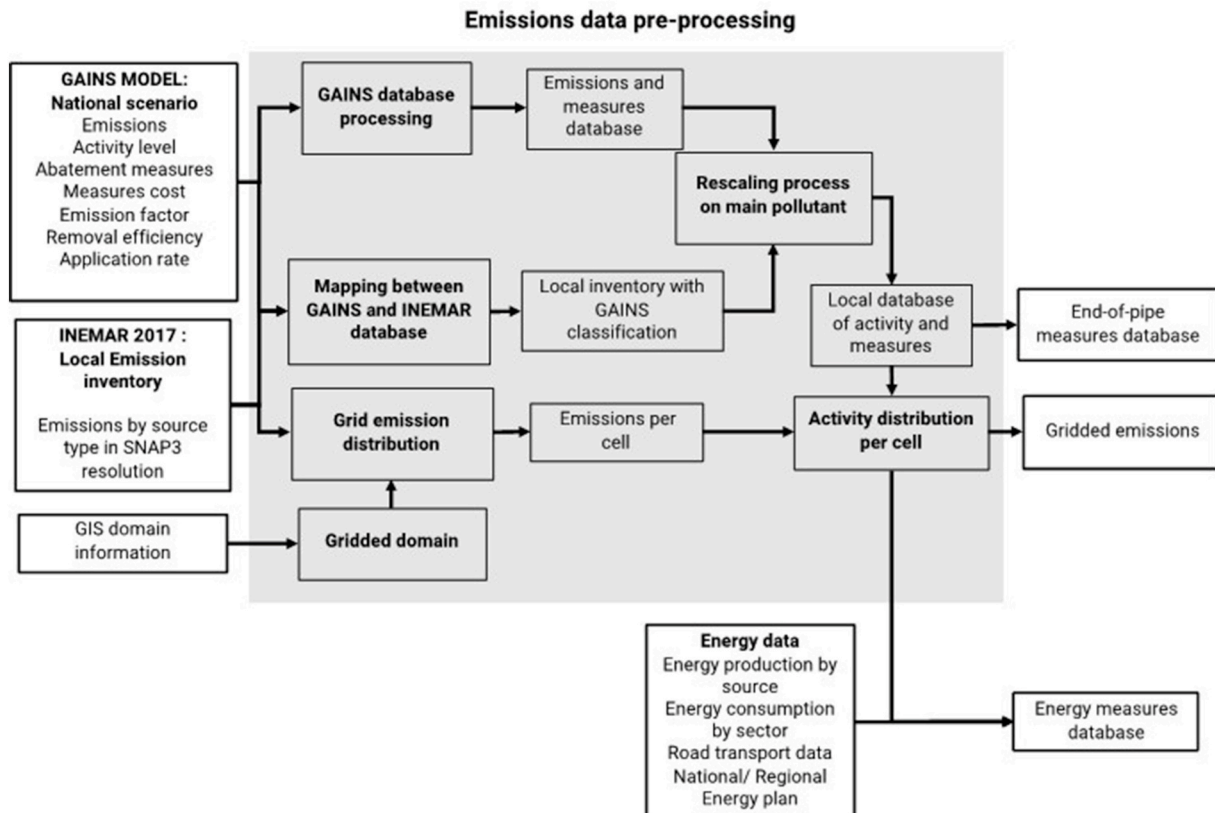


Fig. 3. Input module scheme.

baseline scenario for 2019 gives R^2 values of 0.87 for PM_{2.5} and 0.74 for NO₂, with RMSE values of 2.91 and 5.16 $\mu\text{g}/\text{m}^3$. Details on ANN architecture, training procedure, additional validation metrics, are provided in the Supplementary Information.

2.3.4. Health impact model

The reduction of emission results in lower concentration levels, population exposure and health impact. The health impact assessment is carried out to estimate the effect of PM_{2.5} and NO₂ exposure for each scenario. The AQI exposure-attributable deaths (AD_{AQI}) are estimated using an Exposure Response Function (ERF), from the latest European Topic Centre Human health and the environment report that quantifies the association between air pollution and mortality [27]

$$AD_{AQI} = af_{AQI} * MR \quad (7)$$

where.

- MR is the mortality rate and it represents the all-cause mortality rate of the population aged 30 years and over in each municipality
- af_{AQI} is the attributable fraction (8), which depends on the relative risk RR_{AQI} that correlates AQI and mortality. Each pollutant has a *threshold*, the minimum AQI value under which no harmful effects are estimated to human health, set to 5 $\mu\text{g}/\text{m}^3$ for PM_{2.5} and 10 $\mu\text{g}/\text{m}^3$ for NO₂ by WHO [28]. The af_{AQI} is estimated as follows:

$$af_{AQI} = \frac{e^{\ln(RR_{AQI}) * \left(\frac{AQI - \text{threshold}}{10}\right)} - 1}{e^{\ln(RR_{AQI}) * \left(\frac{AQI - \text{threshold}}{10}\right)}} \quad (8)$$

The values of Relative Risks can be found in Table 1.

A Monte Carlo approach is adopted to propagate the uncertainties, obtaining point estimates and confidence intervals (CIs) for attributable deaths [26]. Uncertainty in premature mortality is quantified through a two-step Monte Carlo procedure. First, 1000 simulations are performed for each municipality using the mean and standard deviation of the Source-Receptor Models (SRM), with σ derived from the validation phase (see Supplementary Information). The 2.5th–97.5th percentiles of the resulting distribution are taken as the confidence interval for air quality indicators. For each simulated value, a second Monte Carlo is applied to propagate the uncertainty of the relative risk (RR), with its standard deviation defined as

$$\sigma_{\ln RR} = \frac{\ln(RR_{sup}) - \ln(RR_{inf})}{3.82} \quad (9)$$

where RR_{inf} and RR_{sup} denote the lower and upper bounds of the 95% confidence interval (Table 1). The final distribution of attributable deaths, obtained by combining both steps, provides the 2.5th and 97.5th percentiles as uncertainty bounds.

3. Results

In this section energy assumptions, emissions, concentrations, and health impacts on the Po Valley domain for a base case and two scenarios of biomethane production and use are presented. The results are divided as follows: the first section discusses the main features of two scenarios: biomethane extra-energy production, fleet electrification, digestate ratio used in agriculture. In the second section the emissions of

the two scenarios are estimated, while the third section analyses the scenario concentrations. In the last section the scenarios are compared with respect to health impact.

3.1. Emission scenario setup

In the first scenario (hereafter referred to as S2.3), the total biomethane production equals 2.3 bcm. This amount of biomethane produces 44.26 PJ of electrical energy, increasing energy production of the power sector (MS1) by 10.47% starting from BC2020's production of 423 PJ [29]. This extra-energy allows to electrify 20% of the total vehicles fleet ($S = 20\%$, $W_{tot} = 216$ PJ) based on (2) and (3). To produce 2.3 bcm of biomethane, it is necessary to allocate 5% of the total livestock waste produced in the area to the digester. This fraction is treated by the application of the livestock management measures described in Section 2.2.

In the second scenario (hereafter referred to as S6), the total biomethane production equals 6 bcm. This quantity of biomethane can provide 115.45 PJ of electric energy surplus (27.32% production increase to BC2020). This energy can power 53% of the total vehicles for the road transport sector (MS7) ($S = 53\%$). In this case, the application of manure management techniques is increased by 16% to account for the extra animal waste required for the biomethane production. A summary of the results is provided in Table 2.

3.2. Basecase2020 and scenario emissions

Table 3 shows the emissions for the BC2020 scenario, for each Macrosector (MS). Only anthropogenic emissions are reported.

The total emission variations estimated for S2.3 scenario with respect to BC2020 for all MS are summarized in Table 4. The increased emissions in MS1 come from the use of biomethane to generate extra energy. For MS7, a 20% reduction in emissions is expected for all pollutants, with the exception of PPM, as brake and tire wear persist in EVs. Additionally, for agriculture (MS10), an emission reduction by 3% can be estimated for ammonia due to manure management techniques.

Table 5 displays the emissions variation for S6 scenario compared with BC2020. In MS10, ammonia is reduced by 8% thanks to the increase in manure management and the overall reduction in NO_x emissions is 26. Therefore, by converting half of the vehicle fleet to EVs, about a quarter of NO_x emissions can be avoided.

It is worth noting that since the implemented measures affect the energy, road transport, and agriculture macro sectors, the resulting emission changes are spatially heterogeneous and occur in areas where these source activities are located.

Biomethane deployment also contributes to greenhouse gas mitigation through the combined effect of fuel substitution and transport electrification. Total CO₂ emissions decrease from 165 Mt/y under the baseline scenario to 156 Mt/y in S2.3 and 142 Mt/y in S6, corresponding to reductions of approximately 5% and 14%, respectively.

These reductions are primarily driven by the electrification of the vehicle fleet, which lowers emissions from internal combustion engines, while biomethane is treated as carbon-neutral in the energy sector. The marginal CO₂ reduction associated with scaling biomethane availability is estimated at 3.82 MtCO₂ per bcm, providing a normalized measure of the climate benefit of additional deployment. A spatial overview of emission changes is provided through maps of precursor emissions reported in the supplementary material.

Table 1

Relative Risks value used in the study and their 95% confidence interval in square brackets.

Parameter	Meaning	Value
RR_{NO_2}	nitrogen dioxide relative risk	1.02 [1.01-1.04]
$RR_{PM2.5}$	fine particulate matter relative risk	1.08 [1.06-1.09]

Table 2

Generated electrical energy, share of electrified vehicles, and required livestock manure management percentage for the two biomethane deployment scenarios.

	$A_{b,CCGT}$	S	% Manure management
S2.3	44.26 PJ	20%	5%
S6	115.45 PJ	53%	16%

Table 3BC2020 emissions of precursors (kton/yr) and CO₂ (Mton/yr).

MS	NO _x	VOC	NH ₃	PPM10	PPM25	SO ₂	CO ₂
1-Energy	20.47	1.98	0.11	0.27	0.24	5.10	28.78
2-Domestic	29.03	29.88	1.15	30.63	28.75	1.75	35.30
3-Industry	36.07	7.99	0.39	2.78	2.02	13.37	26.34
4-Production processes	7.18	35.28	0.18	1.52	0.84	8.07	4.34
5-Distribution	0.00	17.49	0.00	0.00	0.00	0.00	2.87
6-Solvent use	0.39	165.41	0.04	1.83	1.60	0.02	1.1×10^{-5}
7-Transportation	142.24	35.89	2.28	12.12	5.98	0.24	42.82
8-Other transportation	37.59	4.64	0.01	1.96	1.85	0.58	3.91
9-Waste	0.89	0.63	1.53	0.83	0.73	0.18	2.70
10-Agriculture	1.67	173.18	215.05	2.28	0.50	0.12	17.93
TOTAL	275.53	472.36	220.74	54.20	42.51	29.44	165.00

Table 4

S2.3 scenario emission variation relative to BC2020 scenario.

MS	NO _x	VOC	NH ₃	PPM10	PPM25	SO ₂	CO ₂
1-Energy	7.97%	6.75%	1.47%	6.15%	6.57%	0.61%	-
7-Transportation	-20.00%	-20.00%	-20.00%	-7.63%	-14.04%	-20.00%	-20.00%
10-Agriculture	-	-	-2.72%	-	-	-	-
TOTAL	-9.73%	-1.49%	-2.85%	-1.67%	-1.94%	-0.06%	-5.19%

Table 5

S6 scenario emission variation relative to BC2020 scenario.

MS	NO _x	VOC	NH ₃	PPM10	PPM25	SO ₂	CO ₂
1-Energy	20.78%	17.61%	3.84%	16.05%	17.13%	1.59%	-
7-Transportation	-53.00%	-53.00%	-53.00%	-20.21%	-37.22%	-53.00%	-53.00%
10-Agriculture	-	-	-8.19%	-	-	-	-
TOTAL	-25.82%	-3.95%	-8.52%	-4.44%	-5.14%	-0.16%	-13.76%

To improve comparability across contexts and to assess how co-benefits vary with deployment scale, normalized scalability metrics are calculated as average impacts per bcm for each scenario and as the marginal impact associated with scaling biomethane availability from 2.3 to 6 bcm. The results are reported in Table 6. Across emission indicators, the responses are approximately linear within the evaluated range. For CO₂, the average reduction increases from 3.72 to 3.78 MtCO₂/bcm between S2.3 and S6, while the marginal reduction (3.82 MtCO₂/bcm) is slightly higher than both averages. NO_x shows a similar pattern, with marginal reductions exceeding the scenario averages. NH₃ presents a more pronounced increase in per-bcm reductions with scale, indicating a deviation from proportional scaling. In contrast, primary PM2.5 reductions remain nearly constant across scenarios, with marginal values close to the corresponding averages, suggesting limited scale dependence.

3.3. Air quality scenarios

Once emission changes are estimated, ambient concentrations are computed for each scenario using the source receptor models identified

Table 6

Normalized emission reductions per bcm of biomethane for S2.3 and S6 scenarios and marginal effects of scaling from 2.3 to 6 bcm.

Emission	Unit per bcm	S2.3 (average per bcm)	S6 (average per bcm)	Scale-up 2.3 → 6 (marginal per bcm)
CO ₂ reduction	MtCO ₂ /bcm	3.72	3.78	3.82
NO _x reduction	kt/bcm	11.66	11.86	11.98
NH ₃ reduction	kt/bcm	2.74	3.13	3.21
PPM2.5 reduction	kt/bcm	0.36	0.36	0.37

on the Po Valley (see supplementary information). The annual-average NO₂ and PM2.5 concentrations estimated for the two emission scenarios are reported in Table 7 as domain-wide means.

Domain-wide mean concentrations decrease in both deployment levels relative to BC2020. In S2.3, the reductions are modest (-4% for NO₂ and -2% for PM2.5), reflecting the limited scale of the intervention. In S6, larger changes are observed (-16% for NO₂ and -6% for PM2.5), consistent with a stronger reduction of NO_x and primary PM emissions associated with the higher biomethane availability and the linked electrification pathway.

To assess the statistical significance of the air quality improvements induced by biomethane deployment, two-sample t-tests are conducted comparing the baseline scenario with the S2.3 and S6 cases for both PM2.5 and NO₂ concentrations over the domain cells. Results indicate that all differences are highly significant ($p < 0.001$). For PM2.5, the mean reduction between the baseline and S2.3 scenario is estimated between 0.366 and 0.387 µg/m³ (95% CI), while the reduction between the baseline and S6 scenario ranged between 0.929 and 0.966 µg/m³ (95% CI). For NO₂, the mean reductions are 0.723-0.763 µg/m³ for S2.3 and 2.51-2.62 µg/m³ for S6, again with $p < 0.001$ in both cases. Because exposure is spatially heterogeneous and highest in urban areas, we also report city-level mean concentrations of NO₂ and PM2.5, together with ANN-derived uncertainty bounds, in the Supplementary Materials. The main spatial patterns are discussed below.

Normalized metrics are calculated as average concentration

Table 7NO₂ and PM2.5 mean concentrations over the domain for the scenarios.

Scenario	NO ₂ [µg/m ³]	PM2.5 [µg/m ³]
BC2020	15.89	13.66
S2.3	15.16	13.38
S6	13.34	12.81

reductions per bcm for each scenario and as the marginal reduction associated with scaling biomethane availability from 2.3 to 6 bcm. The results are displayed in Table 8. For NO₂, the average reduction increases from 0.32 $\mu\text{g m}^{-3}/\text{bcm}$ in S2.3 to 0.43 $\mu\text{g m}^{-3}/\text{bcm}$ in S6, while the marginal reduction reaches 0.49 $\mu\text{g m}^{-3}/\text{bcm}$. The marginal value exceeds the scenario averages, indicating increasing per-bcm effectiveness within the evaluated range.

For PM_{2.5}, the average reduction increases from 0.12 to 0.14 $\mu\text{g m}^{-3}/\text{bcm}$, and the marginal value is 0.15 $\mu\text{g m}^{-3}/\text{bcm}$. The marginal effect is only slightly higher than the corresponding averages, indicating an approximately proportional response over the evaluated range. This behavior is consistent with the contribution of multiple precursors and regional transport processes to PM_{2.5} formation, which moderate the sensitivity of concentrations to sector-specific emission changes.

The spatial pattern of NO₂ is displayed in Fig. 4 and shows the expected concentration peaks in major cities under BC2020, primarily driven by road-traffic emissions. The same hotspot structure persists in S2.3 and S6, but with systematic reductions, indicating that the scenarios lower urban NO₂ levels without changing the underlying geographical distribution of sources.

PM_{2.5} concentration along the domain is presented in Fig. 5. The particulate is more diffuse across the Po Valley, reflecting the contribution of multiple source categories and the role of secondary aerosol formation. Nonetheless, a consistent reduction trend is visible from BC2020 to S2.3 and further to S6. In our attribution, PM_{2.5} reductions are mainly linked to decreases in primary PM_{2.5} and to precursor reductions, particularly NO_x for MS7 and NH₃ for MS10. At the city level, however, the response is not uniform. As reported in the Supplementary Information, PM_{2.5} concentrations increase in few cities (Como, Lecco, Milan, Monza, and Novara) under S2.3. These increases are associated with higher NO_x and primary PM emissions from the energy sector (MS1) in cells surrounding the receptor cells. Since the source-receptor models account for emissions within a 36 km radius, these local emission increases offset part of the reductions achieved in road transport and agriculture, leading to higher simulated PM_{2.5} concentrations in the corresponding urban areas. Under S6, the larger emission reductions in MS7 and MS10 compensate for the increase in MS1 emissions, resulting in a more uniform reduction of PM_{2.5} concentration.

3.4. Health impact assessment

Table 9 and Table 10 report AD related to long-term exposure to NO₂ and PM_{2.5} in the main cities of the Po Valley under the BC2020 and the two biomethane deployment scenarios (S2.3 and S6). The comparison allows assessment of how changes in concentrations translate into health outcomes and how these effects evolve as biomethane availability increases. Reductions in attributable deaths are observed in almost all cities and for both pollutants.

City-level results indicate that the magnitude of the benefits varies across them. Differences arise from variation in baseline exposure levels, population size, and local emission structures. Cities with higher

baseline concentrations and larger populations generally show larger absolute reductions in attributable deaths for a given concentration decrease. In contrast, cities with lower baseline exposure show smaller absolute changes even when relative reductions are similar.

Examples illustrate this variability. In Milan, NO₂ attributable deaths decrease from 527 [141-915] under BC2020 to 468 [118-800] under S6. In Bergamo, they decrease from 45 [9-78] to 31 [8-53], while in Brescia they decrease from 72 [13-126] to 49 [12-87]. These changes are consistent with the reduction in traffic-related emissions associated with vehicle fleet electrification.

PM_{2.5}-related mortality presents a more heterogeneous city-level response than NO₂. As reported before an increase of concentration can be observed at the city level for S2.3. As a result, PM_{2.5}-attributable deaths increase from 45 [30-62] to 53 [37-70] in Como, from 21 [12-30] to 24 [15-33] in Lecco, from 1338 [1049-1638] to 1346 [1053-1646] in Milan, from 106 [82-132] to 113 [86-140] in Monza, and from 101 [80-125] to 104 [82-127] in Novara. Under the S6 scenario, larger reductions in NO_x and primary particulate matter emissions from road transport together with larger NH₃ reductions from agriculture offset the increase in MS1 emissions. Consequently, the central estimates decrease below the BC2020 values in all cities, except Como that remains close to the baseline value.

In other urban areas, PM_{2.5}-attributable deaths decrease across both scenarios. For example, in Turin they decrease from 1060 [847-1288] under BC2020 to 1025 [817-1250] under S2.3 and 956 [756-1168] under S6, while in Bologna they decrease from 339 [242-448] to 327 [231-432] and 297 [204-399].

The relative (percentage) average reductions over the entire domain in attributable deaths exhibit non-linear scaling across deployment levels. Relative to BC2020 scenario, PM_{2.5} attributable deaths decrease from -2% (S2.3) to -9% (S6), while NO₂ attributable deaths decrease from -7% to -26%, indicating a large increase in health benefits under the higher deployment scenario.

For policy interpretation, health outcomes can also be expressed as avoided attributable deaths per bcm of biomethane. The results are reported in Table 11.

All over the domain, the avoided mortality per bcm, calculated relative to the BC2020 baseline, increases from 164 to 251 deaths/bcm for NO₂ and from 211 to 310 deaths/bcm for PM_{2.5} when moving from S2.3 to S6. The marginal values associated with scaling biomethane availability from 2.3 to 6 bcm reach 305 deaths/bcm for NO₂ and 372 deaths/bcm for PM_{2.5}.

4. Discussion

The results show that the effects of biomethane deployment arise from the interaction among energy production, transport electrification, and agricultural emission controls. In the assessed pathway, biomethane combustion in CCGT plants increases emissions from the energy sector, while vehicle fleet electrification reduces emissions from road transport and manure management decreases NH₃ emissions from agriculture. The net reductions in air pollutant emissions, NO₂ and PM_{2.5} concentrations, CO₂ emissions, and attributable mortality result from the balance among these sectoral changes. Since the affected activities are not uniformly distributed over the domain, the resulting emission changes are spatially heterogeneous and produce local, non-linear responses in air quality. These concentration responses differ between NO₂ and PM_{2.5} because the two pollutants are controlled by different emission sources and atmospheric processes. NO₂ is mainly influenced by road-transport NO_x emissions and therefore responds directly to vehicle fleet electrification. In contrast, PM_{2.5} depends on primary particulate matter together with several precursor emissions, including NO_x and NH₃. Consequently, PM_{2.5} reductions show a weaker response to changes in individual sectors than those observed for NO₂.

The concentration patterns are reflected in the health-impact results. The lower NO₂ levels observed in urban areas with high traffic emissions

Table 8

Normalized scalability metrics for concentration responses: average reductions per bcm and marginal reductions associated with scaling biomethane availability from 2.3 to 6 bcm.

Outcome	Unit per bcm	S2.3 (average per bcm)	S6 (average per bcm)	Scale-up 2.3 → 6 (marginal per bcm)
NO ₂ concentration reduction	$\mu\text{g m}^{-3}/\text{bcm}$	0.32	0.43	0.49
PM _{2.5} concentration reduction	$\mu\text{g m}^{-3}/\text{bcm}$	0.12	0.14	0.15

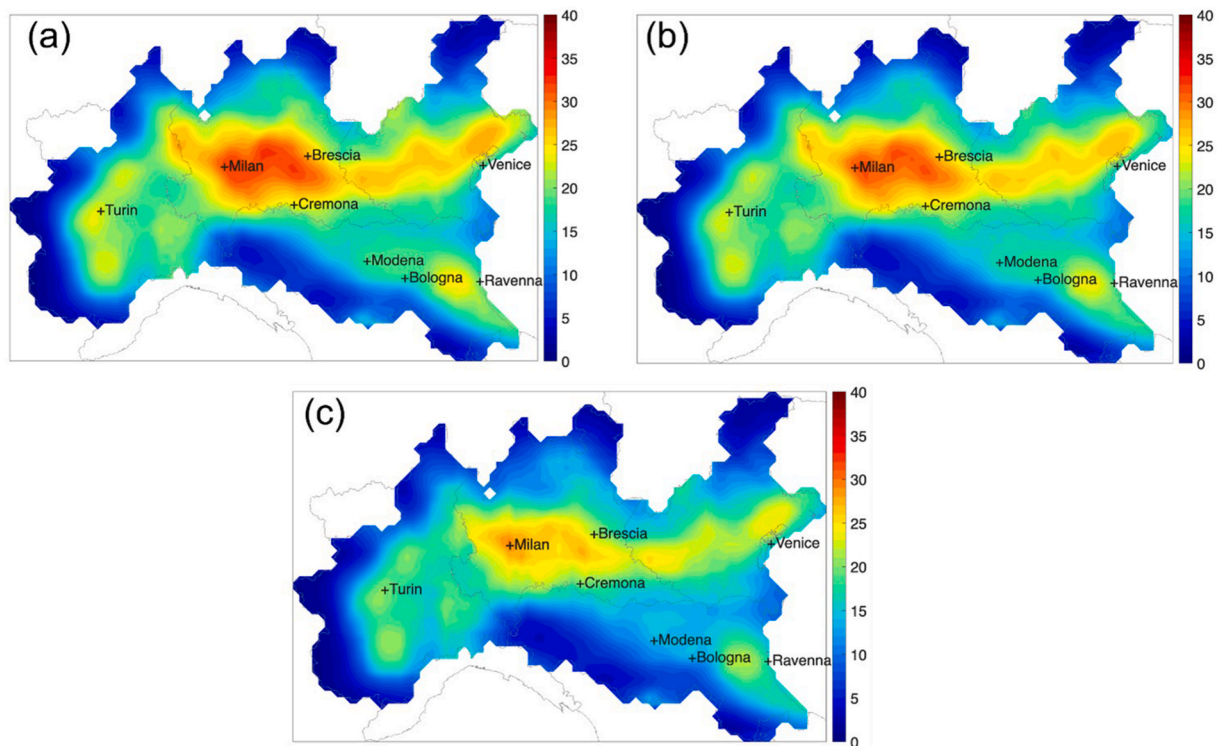


Fig. 4. Yearly average concentration of NO_2 ($\mu\text{g}/\text{m}^3$) for BC2020 (a), S2.3 (b), and S6 (c) scenarios, over the domain.

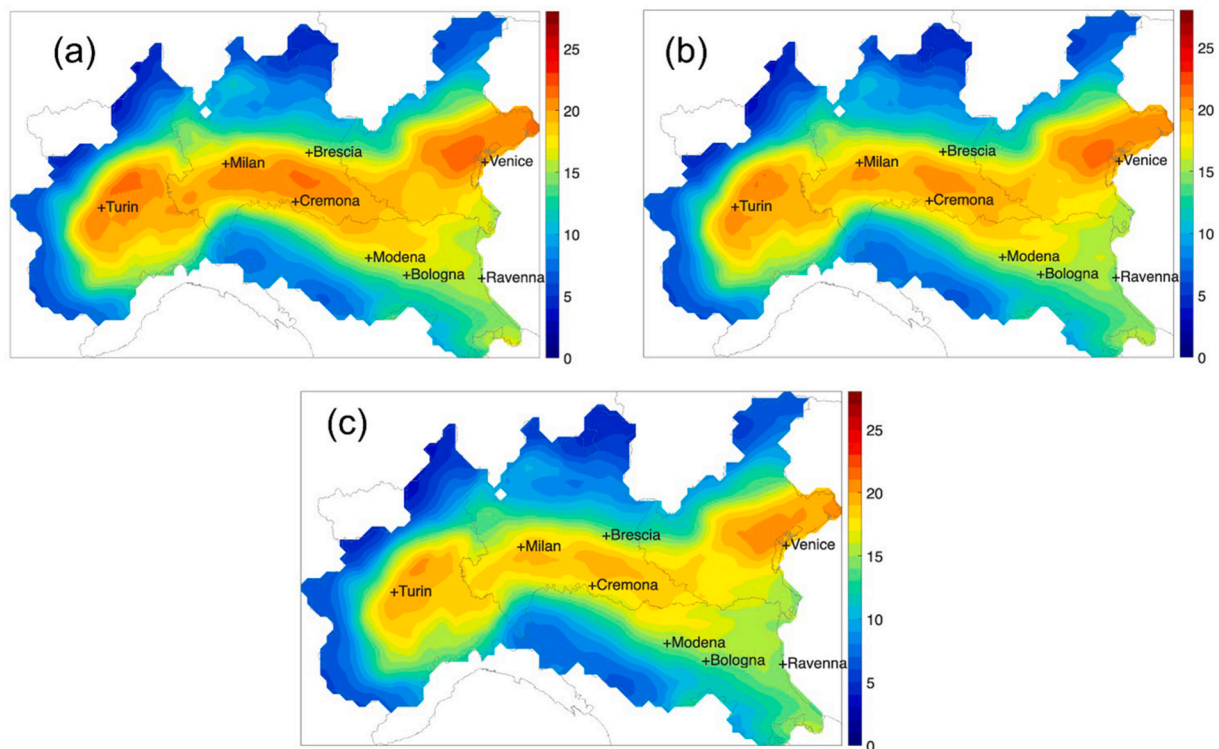


Fig. 5. Yearly average concentration of $\text{PM}_{2.5}$ ($\mu\text{g}/\text{m}^3$) for BC2020 (a), S2.3 (b), and S6 (c) scenarios, over the domain.

and population density translate into corresponding reductions in attributable mortality. $\text{PM}_{2.5}$ shows a more heterogeneous response. Under S2.3, $\text{PM}_{2.5}$ -attributable mortality is higher in Como, Lecco, Milan, Monza, and Novara despite the overall improvement observed at the domain scale. This behavior is associated with local NO_x emission

increases from the energy sector in cells surrounding the affected cities, which offset part of the benefits achieved through road-transport electrification and agricultural measures. Under S6, the larger reductions in NO_x and primary particulate matter emissions from road transport, together with the larger NH_3 mitigation in agriculture, compensate for

Table 9

Premature mortality (number of attributable deaths) for the main cities of the domain associated to NO₂ exposure across BC2020, S2.3, and S6 scenarios. Values in square brackets indicate the 95% confidence interval.

Cities	BC2020	S2.3	S6
Alessandria	24 [6-41]	23 [6-41]	19 [5-33]
Asti	16 [4-28]	15 [4-26]	12 [3-21]
Bergamo	45 [9-78]	43 [11-73]	31 [8-53]
Bologna	64 [13-113]	56 [14-98]	26 [6-48]
Brescia	72 [13-126]	67 [16-116]	49 [12-87]
Como	23 [5-40]	21 [7-37]	13 [3-22]
Cremona	22 [5-38]	21 [5-37]	16 [4-27]
Ferrara	21 [6-37]	19 [5-35]	13 [3-22]
Lecco	12 [3-21]	11 [2-19]	5 [1-8]
Milan	527 [141-915]	508 [115-870]	468 [118-800]
Modena	28 [7-49]	24 [5-42]	12 [3-22]
Monza	47 [13-86]	45 [11-80]	39 [9-67]
Novara	25 [7-44]	23 [7-41]	19 [4-35]
Padua	77 [17-132]	75 [23-129]	57 [12-99]
Parma	19 [4-35]	17 [4-29]	7 [2-13]
Pavia	26 [8-44]	24 [6-42]	22 [6-39]
Piacenza	25 [5-42]	24 [5-41]	18 [4-33]
Ravenna	39 [10-67]	36 [10-64]	29 [6-52]
Reggio Emilia	17 [4-31]	14 [3-26]	6 [1-11]
Rimini	29 [5-50]	26 [6-45]	21 [5-38]
Turin	241 [55-425]	222 [45-395]	183 [45-336]
Treviso	30 [6-50]	28 [7-48]	22 [5-38]
Varese	23 [6-41]	20 [5-36]	11 [3-19]
Venice	78 [19-139]	75 [15-134]	63 [14-107]
Verona	73 [14-130]	70 [16-121]	55 [14-96]
Vicenza	34 [7-61]	33 [8-57]	25 [6-44]

Table 10

Premature mortality (number of attributable deaths) for the main cities of the domain associated to PM2.5 exposure across BC2020, S2.3, and S6 scenarios. Values in square brackets indicate the 95% confidence interval.

Cities	BC2020	S2.3	S6
Alessandria	121 [97-147]	117 [92-142]	111 [87-135]
Asti	100 [79-121]	96 [76-117]	91 [72-111]
Bergamo	90 [66-116]	88 [65-115]	80 [57-105]
Bologna	339 [242-448]	327 [231-432]	297 [204-399]
Brescia	176 [136-220]	168 [130-210]	153 [118-194]
Como	45 [30-62]	53 [37-70]	46 [30-63]
Cremona	88 [70-108]	83 [66-102]	76 [60-95]
Ferrara	158 [120-202]	151 [112-193]	142 [103-183]
Lecco	21 [12-30]	24 [15-33]	20 [11-29]
Milan	1338 [1049-1638]	1346 [1053-1646]	1258 [974-1551]
Modena	161 [118-209]	155 [112-203]	140 [99-185]
Monza	106 [82-132]	113 [86-140]	105 [81-132]
Novara	101 [80-125]	104 [82-127]	95 [75-119]
Padua	282 [225-343]	278 [222-338]	263 [206-320]
Parma	140 [97-186]	131 [90-176]	117 [77-158]
Pavia	96 [76-117]	90 [71-111]	82 [63-101]
Piacenza	101 [75-130]	95 [69-124]	86 [60-113]
Ravenna	144 [101-189]	140 [98-184]	136 [94-177]
Reggio Emilia	126 [91-164]	120 [86-158]	109 [76-145]
Rimini	131 [92-173]	126 [88-168]	122 [86-164]
Turin	1060 [847-1288]	1025 [817-1250]	956 [756-1168]
Treviso	113 [90-137]	111 [88-135]	108 [85-131]
Varese	56 [41-73]	54 [39-70]	48 [33-65]
Venice	360 [286-436]	356 [284-433]	340 [268-416]
Verona	219 [167-274]	213 [161-269]	203 [152-257]
Vicenza	112 [87-137]	110 [86-135]	105 [82-129]

the additional MS1 emissions, leading to lower PM2.5-attributable mortality across almost all cities.

The normalized indicators provide information on the scalability of the assessed pathway. Expressing emission reductions, concentration changes, and avoided attributable deaths per bcm of biomethane allows comparison between deployment levels and with alternative mitigation strategies. The marginal benefits associated with scaling biomethane availability from 2.3 to 6 bcm exceed the average benefits estimated for

Table 11

Normalized avoided attributable deaths per bcm of biomethane for S2.3 and S6 scenarios and marginal effects of scaling from 2.3 to 6 bcm.

Outcome	Unit per bcm	S2.3 (average per bcm)	S6 (average per bcm)	Scale-up 2.3 → 6 (marginal per bcm)
NO ₂ -attributable deaths avoided	deaths/bcm	164	251	305
PM2.5-attributable deaths avoided	deaths/bcm	211	310	372

the lower deployment scenario. This result reflects the larger share of vehicle electrification achieved under S6 and the distribution of emission reductions in densely populated areas. The increase in marginal benefits is more pronounced for NO₂ than for PM2.5 because the response of PM2.5 is controlled by multiple precursor emissions.

This study has several methodological strengths and policy-relevant implications. It applies an integrated assessment framework that links biomethane deployment to emissions, concentrations, exposure, health impacts, and CO₂ mitigation within the same modelling chain. This structure allows the analysis of interactions among energy production, transport electrification, and agricultural emission controls. Moreover, the analysis considers two deployment levels that are relevant for Italian and European biomethane policies. Furthermore, the spatial framework allows benefits to be evaluated where emissions occur and where people are exposed, which is relevant in a region with heterogeneous emissions and population density. ANN-based source receptor models allow several scenarios to be assessed with reduced computational cost while retaining non-linear emission-concentration relationships derived from chemical transport model simulations. The health-impact assessment also includes uncertainty propagation, which supports the interpretation of the mortality estimates. Despite these strengths, the study has several limitations. Only one biomethane allocation pathway is assessed. Biomethane is used for electricity generation to support vehicle electrification, while other uses, such as direct use in heavy-duty transport, industrial processes, heating, or grid injection, are not evaluated. The results should therefore be interpreted as pathway-specific. Implementation constraints are not modelled. These include permitting, infrastructure development, grid integration, feedstock logistics, land availability, and adoption of agricultural measures. Moreover, biomethane combustion is assumed to be carbon-neutral under the selected feedstock mix. Potential upstream methane leakage and methane reductions associated with improved manure management are not quantified in the greenhouse-gas balance. The health-impact assessment focuses on long-term exposure to NO₂ and PM2.5 and on attributable mortality. Other endpoints, including morbidity outcomes and distributional effects across population groups, are outside the scope of this work.

The transferability of the results depends on regional conditions. The Po Valley has high baseline pollution levels, high population density, large agricultural NH₃ emissions, and meteorological conditions that favor pollutant accumulation. These characteristics influence the magnitude of the estimated benefits. In other regions, the effects of biomethane deployment may differ according to the energy mix, vehicle fleet, agricultural structure, population distribution, and chemical regimes. The normalized indicators can support comparisons with other mitigation pathways and provide a basis for applications in other polluted regions. Likewise, the integrated assessment framework provides a flexible basis for evaluating alternative biomethane allocation pathways and additional mitigation strategies. Future applications may include economic and infrastructure constraints, additional health endpoints, and assessments in other regions.

5. Conclusions

This study evaluates the effects of biomethane deployment on air quality, public health, and greenhouse gas emissions in the Po Valley (Northern Italy). The analysis considers an integrated pathway in which biomethane is used for electricity generation to support partial electrification of the vehicle fleet, while agricultural practices associated with anaerobic digestion contribute to emission reductions. Biomethane deployment leads to reductions in both NO₂ and PM_{2.5} concentrations across all the domain. NO₂ concentrations decrease by 4% under S2.3 and 16% under S6, while PM_{2.5} decreases by about 2% and 6%, respectively. The difference reflects the role of road-transport emissions in shaping NO₂ concentrations, compared with the contribution of multiple sources and precursors to PM_{2.5} formation.

Normalized indicators show that concentration reductions per unit of biomethane increase with deployment. Average reductions range from 0.32 to 0.43 µg m⁻³/bcm for NO₂ and from 0.12 to 0.14 µg m⁻³/bcm for PM_{2.5} between S2.3 and S6, with marginal values exceeding the corresponding averages. This indicates that the effect per bcm increases within the evaluated range.

Reductions in concentrations are associated with decreases in attributable mortality. At the domain level, mortality decreases by 7% for NO₂ and 2% for PM_{2.5} under S2.3, and by 26% and 9% under S6. When expressed per unit of biomethane, avoided mortality increases from 164 to 251 deaths/bcm for NO₂ and from 211 to 310 deaths/bcm for PM_{2.5}, with marginal values of 305 and 372 deaths/bcm, respectively. In both cases, marginal values exceed scenario averages, indicating that avoided mortality per unit of biomethane increases with deployment.

Spatial variability influences the distribution of health benefits. Reductions occurring in densely populated areas contribute more to avoided mortality, particularly for NO₂, which is linked to transport emissions. PM_{2.5} responses are influenced by regional transport and secondary formation processes, which reduce the sensitivity of concentrations to sector-specific emission changes.

Biomethane deployment also contributes to greenhouse gas mitigation. Total CO₂ emissions decrease from 165 Mt/y under BC2020 to 156 Mt/y in S2.3 and 142 Mt/y in S6. The marginal reduction associated with scaling biomethane availability is 3.82 MtCO₂ per bcm.

The proposed integrated assessment framework provides a flexible methodology for evaluating the combined effects of energy and agricultural measures on emissions, air quality, health, and greenhouse-gas mitigation. The use of normalized scalability indicators supports the comparison of alternative mitigation pathways and deployment scenarios.

Funding sources

This research was funded by Fondazione Cariplo under the grant “AgriAir: Data science to reduce agri-food impact on air quality in the Po Valley”. Call 2021 “Data Science for science and society”, Grant Number 2020-4295.

CRediT authorship contribution statement

Michele Francesco Arrighini: Data curation, Formal analysis, Investigation, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Claudio Marchesi:** Writing – review & editing. **Laura Zecchi:** Data curation, Formal analysis, Investigation, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Marialuisa Volta:** Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful to A. Tonola, K. Kumari, C. Carnevale, A. Basak (University of Brescia), G. Guariso and L. Ferrari (Politecnico di Milano), for their contribution in the research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.bmf.2026.100062>.

Data availability

Data will be made available on request.

References

- [1] World Health Organization (WHO), Health and air quality co-benefits of climate change mitigation: technical brief, health and Air pollution Co-Benefits of climate change mitigation. <https://doi.org/10.2471/B09460>, 2025.
- [2] S. Bakaloglu, A. Hawkes, A comparative study of biogas and biomethane with natural gas and hydrogen alternatives, *Energy Environ. Sci.* 17 (2024) 1482–1496, <https://doi.org/10.1039/D3EE02516K>.
- [3] M. Farghali, A.I. Osman, K. Umetsu, D.W. Rooney, Integration of biogas systems into a carbon zero and hydrogen economy: a review, *Environ. Chem. Lett.* 20 (5 2022) 2853–2927, <https://doi.org/10.1007/S10311-022-01468-Z>, 2022.
- [4] S. Ramachandran, M. Rupakheti, R. Cherian, M.G. Lawrence, Climate benefits of cleaner energy transitions in east and south Asia through Black carbon reduction, *Front. Environ. Sci.* 10 (2022) 842319, <https://doi.org/10.3389/FENVS.2022.842319/BIBTEX>.
- [5] D.M. Wall, S. McDonagh, J.D. Murphy, Cascading biomethane energy systems for sustainable green gas production in a circular economy, *Bioresour. Technol.* 243 (2017) 1207–1215, <https://doi.org/10.1016/J.BIORTECH.2017.07.115>.
- [6] K. Kawamura, S. Taniguchi, T. Nomura, T. Oshima, T. Kawabata, K. Sasaki, Results of continuous 200kW SOFC power generation using biomethane gas from a brewery's wastewater treatment process, *ECS Trans.* 111 (2023) 111, <https://doi.org/10.1149/11106.0111ECST>.
- [7] M. Noussan, V. Negro, M. Prussi, D. Chiaramonti, The potential role of biomethane for the decarbonization of transport: an analysis of 2030 scenarios in Italy, *Appl. Energy* 355 (2024) 122322, <https://doi.org/10.1016/J.APENERGY.2023.122322>.
- [8] H. Lin, M.J. Black, O. Lin, T. Minter, A. Borrión, Biogas utilisation – life cycle assessment of enabling technology for transport biomethane – UK case study, *Bore Hill farm Biodigester, Biomass Bioenergy* 190 (2024) 107402, <https://doi.org/10.1016/J.BIOMBIOE.2024.107402>.
- [9] N.M. Power, J.D. Murphy, Which is the preferable transport fuel on a greenhouse gas basis: biomethane or ethanol? *Biomass Bioenergy* 33 (2009) 1403–1412, <https://doi.org/10.1016/J.BIOMBIOE.2009.06.004>.
- [10] L. Zecchi, M.F. Arrighini, G. Guariso, M. Volta, The role of energy policies for air pollution control in the Po Valley, *IFAC-PapersOnLine* 58 (2024) 174–179, <https://doi.org/10.1016/J.IFACOL.2024.07.110>.
- [11] D. Pala, V. Casella, C. Larizza, A. Malovini, R. Bellazzi, Impact of COVID-19 lockdown on PM concentrations in an Italian Northern City: a year-by-year assessment, *PLoS One* 17 (2022) e0263265, <https://doi.org/10.1371/JOURNAL.PONE.0263265>.
- [12] K. Raffaelli, M. Deserti, M. Stortini, R. Amorati, M. Vasconi, G. Giovannini, Improving air quality in the Po Valley, Italy: some results by the LIFE-IP-PREPAIR Project, *Atmosphere* 2020 11 (2020) 429, <https://doi.org/10.3390/ATMOS11040429>. Page 429 11.
- [13] A. Robotto, S. Barbero, R. Cremonini, E. Brizio, Improving air quality and health in Northern Italy: limits and perspectives, *medRxiv* (2022) 2021.12.31.21268581, <https://doi.org/10.1101/2021.12.31.21268581>.
- [14] M. Negri, J. Bacenetti, M. Brambilla, A. Manfredini, A. Cantore, S. Bocchi, Biomethane production from different crop systems of cereals in Northern Italy, *Biomass Bioenergy* 63 (2014) 321–329, <https://doi.org/10.1016/J.BIOMBIOE.2014.01.041>.
- [15] Italian Government, Piano Nazionale Di Ripresa E Resilienza (PNRR), 2021. Rome, <https://www.governo.it/sites/governo.it/files/PNRR.pdf>. (Accessed 15 April 2024).
- [16] Italian Ministry of the Environment and Energy Security, Piano Nazionale Integrato per L'Energia E Il Clima, Rome, 2023.
- [17] European Commission, Repowereu Plan, Brussels, 2022.
- [18] T. Amon, B. Amon, V. Kryvoruchko, A. Machmüller, K. Hopfer-Sixt, V. Bodiroza, R. Hrbek, J. Friedel, E. Pötsch, H. Wagentristl, M. Schreiner, W. Zollitsch, Methane

- production through anaerobic digestion of various energy crops grown in sustainable crop rotations, *Bioresour. Technol.* 98 (2007) 3204–3212, <https://doi.org/10.1016/j.biortech.2006.07.007>.
- [19] V. Konstantinos, A. David, C. Johan, P. Ioulia, Z. Ghassan, *Study on the State of Play of Energy Efficiency of Heat and Electricity Production Technologies*, Westerduinweg, 2012.
- [20] Bollettino petrolifero - Statistiche energetiche e minerarie - ministero dell'ambiente e della sicurezza energetica, (n.d.). <https://sisen.mase.gov.it/dgsaie/bollettino-petrolifero?anno=2024> (accessed March 5, 2026).
- [21] F.A. Nicholson, A. Bhogal, A. Rollett, M. Taylor, J.R. Williams, Precision application techniques reduce ammonia emissions following food-based digestate applications to grassland, *Nutrient Cycl. Agroecosyst.* 110 (2018) 151–159, <https://doi.org/10.1007/S10705-017-9884-4/FIGURES/1>.
- [22] P. Rafaj, G. Kiesewetter, T. Gül, W. Schöpp, J. Cofala, Z. Klimont, P. Purohit, C. Heyes, M. Amann, J. Borken-Kleefeld, L. Cozzi, Outlook for clean air in the context of sustainable development goals, *Glob. Environ. Change* 53 (2018) 1–11, <https://doi.org/10.1016/j.gloenvcha.2018.08.008>.
- [23] 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) 980–989, <https://doi.org/10.1016/J.SCITOTENV.2017.10.129>.
- [24] L. Zecchi, M.F. Arrighini, G. Guariso, M. Volta, Efficiently supporting decision-making in a multi-pollutant environment, *J. Environ. Manag.* 396 (2025) 128056, <https://doi.org/10.1016/J.JENVMAN.2025.128056>.
- [25] M. Amann, I. Bertok, J. Borken-Kleefeld, J. Cofala, C. Heyes, L. Höglund-Isaksson, Z. Klimont, B. Nguyen, M. Posch, P. Rafaj, R. Sandler, W. Schöpp, F. Wagner, W. Winiwarter, Cost-effective control of air quality and greenhouse gases in Europe: modeling and policy applications, *Environ. Model. Software* 26 (2011) 1489–1501, <https://doi.org/10.1016/J.ENVSOFT.2011.07.012>.
- [26] L. Zecchi, M.F. Arrighini, C. Marchesi, F. Donato, M. Volta, Progress and policies to achieve the zero pollution action plan and EU 2024/2881 PM2.5 targets in Northern Italy, *Sci. Rep.* 15 (1 15) (2025) 31439, <https://doi.org/10.1038/s41598-025-17176-x>, 2025.
- [27] S. de Bruyn, Health costs of air pollution in European cities and the linkage with transport. www.cedelft.eu, 2020. (Accessed 2 May 2024).
- [28] World Health Organization (WHO), WHO global air quality guidelines. Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide, Geneva, <https://iris.who.int/bitstream/handle/10665/345329/9789240034228-eng.pdf?sequence=1&isAllowed=y>, 2021. (Accessed 2 May 2024).
- [29] Pubblicazioni Statistiche - Terna Spa, (n.d.). <https://www.terna.it/it/sistema-elettico/statistiche/pubblicazioni-statistiche> (accessed June 6, 2024).