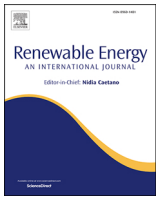
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Biomethane-driven SOFC vehicles: Dual role in emission reduction and renewable energy production

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ABSTRACT

Fossil fuel combustion in road transport significantly contributes to greenhouse gas emissions and air pollution, necessitating sustainable alternatives. Solid Oxide Fuel Cells (SOFCs) fueled by biomethane offer a viable decarbonization pathway, leveraging existing biofuel infrastructure and enabling internal fuel reforming. This study employs an Integrated Assessment Model to assess the environmental benefits of introducing a biomethane-powered SOFC fleet. Additionally, this study explores the potential of SOFC vehicles to operate as prosumers, generating surplus energy to the grid during idle periods, thereby enhancing renewable energy integration. The impact assessment is analyzed in terms of $CO_{2\text{-eq}}$ emission reduction and air quality benefits. The scenario focuses on the emissions variation affected by the substitution of traditional light-duty vehicles with SOFC vehicles, the replacement of energy produced by non-renewable sources with the energy produced by the fleet, and the influence of the biomethane production process (including biomethane production sites and feedstock waste management). The case study is the Lombardy region in Northern Italy, characterized by elevated pollution levels. Results indicate that replacing conventional vehicles with SOFCs can reduce GHG, NOx, and NH_3 emissions substantially, leading to measurable air quality improvements and decreased fossil fuel dependence in transport and energy sectors.

1. Introduction

Nowadays, fossil fuels are the main energy source, significantly contributing to greenhouse gases and air pollution emissions [1], with severe environmental consequences and dramatic effects on human health and quality of life [2]. To face this problem, a higher use of renewable energy carriers is required. Among these, biomethane has gained significant attention at the European level due to its carbon-neutral characteristics and potential to decarbonize multiple sectors [3].

Biomethane is produced by the anaerobic digestion of organic materials, including agricultural waste, food waste, sewage sludge, and organic residues [4]. It serves as a sustainable alternative to conventional natural gas, as both fuels are chemically equivalent; however, the biogenic component of biomethane has already sequestered CO_2, rendering it carbon neutral [5].

At the European level, the REPowerEU [6] aims to enhance biomethane production through targeted investments. At the National level, different member states establish a country-specific production target. In Italy, a biomethane target is introduced by the National Recovery and Resilience Plan (PNRR) [7] and distributed in regional plans [8] based on the availability of matrices.

In the transport sector, biomethane offers a promising solution for reducing emissions, as recent studies demonstrate the significant potential of biomethane to decarbonize this sector at both national [9] and regional levels [10]. However, when biomethane is used in a conventional Internal Combustion Engine (ICE), the benefits are mainly limited to climate change mitigation, while local air pollutant emissions remain unchanged. In fact, ICE vehicles contribute 23% of total CO_2 emissions at the European level (https://www.iea.org/regions/europe/emissions) and are a major source of nitrogen oxides (NOx), which are precursors to local air pollutants such as nitrogen dioxide (NO_2) and particulate matter (PM2.5) [11]. As a result, there is a growing interest in exploring alternative technologies that can provide sustainable solutions for both GHG emissions and air quality [12].

One promising technology under investigation is Solid Oxide Fuel

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Cells (SOFC) [13]. These fuel cells have solid oxide electrolytes that allow them to operate at high temperatures and perform internal fuel reforming. This, in turn, gives SOFCs the flexibility to operate with conventional fuels such as bioethanol, biogas [14], or biomethane [15] instead of relying solely on hydrogen as is required with different types of fuel cells, such as PEMFC (Proton Exchange Membrane Fuel Cells) [16].

The use of traditional biofuels presents several advantages: (i) lower costs, (ii) compatibility with existing refueling infrastructure, and (iii) storage in conventional tanks without the need for high-pressure containment required for hydrogen. Moreover, SOFCs generate electricity, heat, and water as primary outputs, making them environmentally sustainable [17].

However, it also poses challenges, such as extended startup times and material durability issues [13]. This technology nowadays is commonly integrated into stationary applications in different sectors, such as energy and heat production [18] and off-grid infrastructure [19]; however, recent studies have demonstrated its viability for vehicle powertrains in hybrid configurations [20], including trucks [21], passenger vehicles [22], and maritime applications [23].

Previous studies on biomethane-powered SOFC vehicles focus primarily on energy optimization [24] and life-cycle emission estimation [25]. While these studies demonstrate the technical feasibility and environmental advantages of SOFC technology, they generally evaluate the system at the vehicle scale. The regional implications of deploying an SOFC fleet remain largely unexplored.

The present work addresses this gap by integrating vehicle-level performance into a regional Integrated Assessment Model (IAM) to evaluate the regional environmental implication of introducing a fleet of biomethane-powered SOFC hybrid light-duty vehicles. The analysis includes a preliminary estimation of regional biomethane production capacity and then determines the corresponding potential penetration level of SOFC vehicle that is assumed to replace conventional ICE vehicles. Additionally, the study explores the innovative use of SOFCs as prosumers, whereby the SOFC not only powers the vehicle during operation but also supplies renewable energy to the grid while the vehicle is parked.

To quantify these aspects, an Integrated Assessment Model (MAQ, Multi-scale Air Quality model) is implemented [26]. This model allows linking variation in transport, energy, and agriculture activities with GHG and pollutant precursor emissions, and their regional environmental impacts.

The proposed framework combines vehicle-level simulation results derived from the literature [27] with regional energy and emission data, allowing the evaluation of the large-scale environmental and energy impacts of fleet deployment. The impacts are assessed through a scenario analysis, commonly used to future perspective analysis [28], involving two assumptions regarding biomethane production capacity. The selected case study is the Lombardy region in Northern Italy, characterized by elevated pollution levels [29] that affect the population's health [30]. The region is characterized by high population density, resulting in significant traffic, and a robust agricultural sector, which makes it suitable for biomethane production [31].

This systems-level perspective provides a comprehensive assessment of the environmental benefits associated with regional-scale deployment of biomethane-powered SOFC vehicles.

The paper is structured as follows: Section 2 describes the proposed methodology, including the vehicle-level performance data, the estimation of regional biomethane production potential, the scenario definition and the description of IAM model used. Section 3 introduces the Lombardy case study and the input datasets. Section 4 presents the scenario results in terms of energy production, emissions and air quality impacts, while Section 5 discusses the main findings, limitations and future research directions.

2. Materials and method

The proposed methodology consists of the flowchart represented in Fig. 1 and consists of three main steps: (i) the definition of the scenario hypothesis, (ii) the evaluation of emissions variation, and (iii) the impact assessment.

First, the vehicle operational data and regional biomethane availability are defined. These data are combined through a mass balance to estimate the number of SOFC vehicles that can be powered. The resulting fleet size is then used to compute the electricity generated by the vehicles during the parking. This energy is associated with the auxiliary energy required for biomethane production in the regional energy balance. Finally, the corresponding changes in transport, energy, and agricultural activities are introduced into the MAQ model to quantify variations in emissions and air quality.

The next three sections describe the main steps required for the analysis, and the final section 2.4 introduces the case study and the inputs required.

2.1. Scenario assumptions

The first part of the study consists of defining the assumptions that are used to develop the scenarios. The first data is the operational performance of SOFC-vehicle, necessary to estimate the yearly average biomethane consumption and energy generation of a single vehicle. The second input required is the regional quantity of biomethane production capacity, used to estimate the number of vehicles that can be supplied.

2.1.1. SOFC vehicles

The vehicle architecture and operational data used in this study are derived from the previously published vehicle-level simulation by Sandrini et al. [27]. In that work, a biomethane-powered SOFC/battery light-duty vehicle was modelled using a known mission profile and a 3 kW SOFC, which works as an auxiliary power unit (APU) coupled with a battery pack of 30 Ah. In this configuration, the SOFC is powered by biomethane and generates energy to power a battery pack. The hybrid powertrain system comprises: (i) a tank for biomethane; (ii) a battery pack to store the electrical energy produced by the SOFC stack and direct it to the electric motor; (iii) an energy management system to control the power flux and maintain the SOFC at its optimal working condition [15].

An innovative aspect analyzed in the study was to consider these vehicles as a prosumer, assuming that they can feed the electricity produced by the fuel cells into the grid while they are parked during the night, when the production of renewable energy sources is lower.

The work [27] analyzes the energy consumption of a single light-duty vehicle in a simulation that covers two weeks of operation, using real data obtained on different driving cycles.

The study returns as output: the total time of traction (t_{trac}, where the SOFC produces energy used by the electric motor), time of stationary mode (t_{grid}, where the energy is supplied to the electric grid), and the corresponding energy produced by the SOFC (a_{trac}, a_{grid}), and the biomethane consumption (γ_{CH4}).

These data are processed to compute the yearly average values required as input data for the scenario definition.

The average quantity of methane consumed by the vehicles is estimated to be equal to 0.23 m^3/kWh (γ_{CH4})[27]. Therefore, the average consumption of methane required by a single vehicle in a year is computed as in equation (1).

$$v_{CH4}\ (year) = \gamma_{CH4} * \left(a_{trac} + a_{grid}\right) * 26 \quad (1)$$

Where 26 is the number of intervals (2 weeks) present in a year. Table 1 summarizes the data obtained from the vehicle simulation and the corresponding value referred to a year. The resulting volume required for a year of operation per SOFC-vehicle is equal to 6044 m^3.

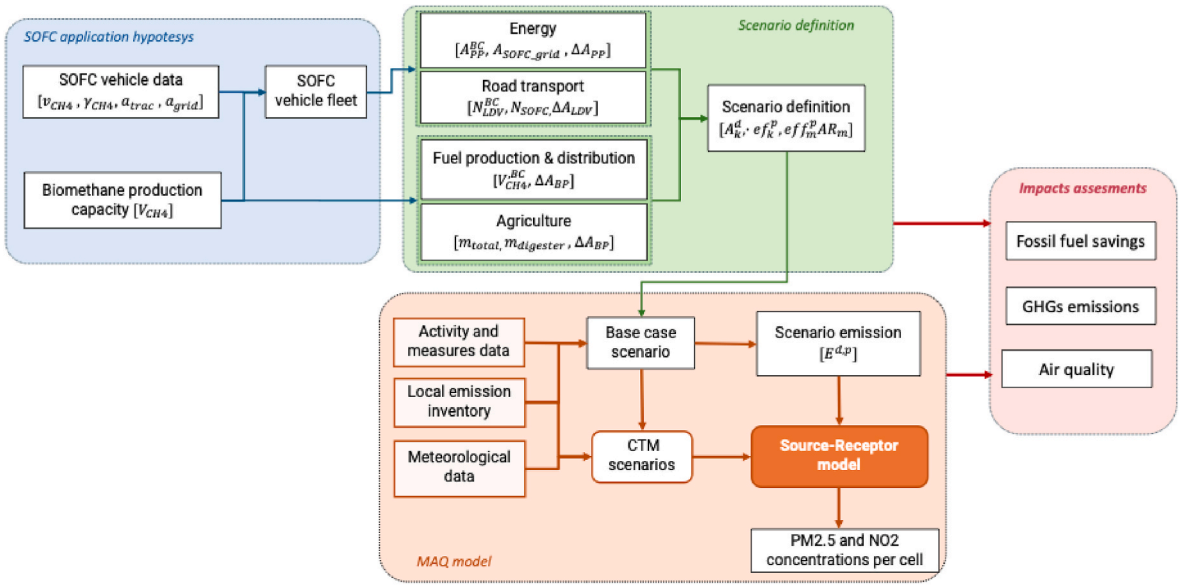


Fig. 1. Flowchart of the scenario definition and implementation.

Table 1
Data for two weeks of operation for a single vehicle was obtained in Ref. [27], and computed for an entire year, subdivided between the traction and energy supply phases.

Value	2 Weeks			Year		
	Traction	Energy supply	Total	Traction	Energy supply	Total
Time (days)	3.5	10.5	14	91	274	365
Energy (GJ)	0.9	2.7	3.6	23.4	70.9	94.3
Biomethane used (m^3)	57.5	174.3	231.8	1493.0	4533.1	6044.1

2.1.2. Biomethane production capacity

Currently, not all organic waste from plants and animals is used for biogas generation; therefore, the production capacity could increase. The calculation of maximal output is based on the knowledge of the whole available substrate. The first step involves the computation of the maximum biomass potential suitable for biogas production.

The biomasses of interest are predominantly waste biomasses originating from three sectors:

- Livestock (solid and liquid manure from livestock farms)
- Agro-industrial (waste from the processing and transformation of food products)
- Agricultural production (crop residues from the fruit and vegetable and arable crops sectors).

The data on the amounts of available matrices are first collected. Determining the biomethane production capacity of biomass requires knowing certain chemical parameters: total solids content, volatile solids content, biogas potential, and average methane concentration. In the present project, to determine the methanogenic potential of the biomasses available, bibliographic values were used [32]: analyze the biogas production from crops (e.g., cereals, maize, sunflower, and grass) [33]; from food production (e.g., from rice, grape, tomato, barley, potato, and olive) [34], from manure waste and [35] from sewage sludge. The data collected correspond to a total of 34.5 Mt/year of animal waste and 19.3 Mt/year of vegetal waste. Input data and elaboration are reported in Table S1 and Table S2 in the supplementary material.

Carbon-neutral combustion of biomethane generation via digesters is frequently achieved by using a substrate of 80% vegetative matter and 20% animal products. Therefore, the maximum amount of biomethane is computed by limiting the use of one of these two sources to maintain this ratio and not by considering all the biomass available.

2.2. Scenario design

The scenarios examine the introduction of a light-duty vehicle fleet equipped with SOFC technology, replacing conventional vehicles powered by internal combustion engines. This sector is suitable for the use of this technology as it consists of a large part of the vehicle fleet with a fixed, or at least predictable, mission.

The proposed scenarios are developed through three sequential balances that ensure consistency between biomethane production, energy generation and environmental impacts. First, a mass balance is performed to estimate the amount of biomethane effectively available after accounting for methane losses occurring along the production and distribution chain. Second, an energy balance determines the electricity generated by the SOFC fleet and the auxiliary energy required for biomethane production. Finally, the resulting variations in transport, energy and agricultural activities are introduced into the Integrated Assessment Model to quantify the corresponding emission changes.

2.2.1. Mass

The mass balance estimates the amount of biomethane effectively available for road transport. Starting from the annual gross biomethane production (V_{CH4_gross}), methane losses occurring during upgrading, compression, and gas distribution are considered through a global methane leakage factor (λ), derived from recent European assessments of biomethane supply chains [36]. The delivered biomethane is therefore computed as:

$$V_{CH4_net} = V_{CH4_{gross}}(1-\lambda) \quad (2)$$

where V_{CH4_net} is the quantity of biomethane effectively delivered to the final users.

The delivered biomethane is then divided by the annual biomethane demand of one SOFC vehicle (v_{CH4}), taken from the vehicle simulations presented in Section 2.1.1, to estimate the number of vehicles that can be supplied:

$$N_{SOFC} = \frac{V_{CH4_net}}{v_{CH4}} \quad (3)$$

this quantity defines the penetration level of SOFC vehicles within the regional light-duty fleet.

2.2.2. Energy

The energy balance quantifies both the renewable electricity generated by the SOFC fleet and the auxiliary energy required to produce the corresponding biomethane. The resulting net energy determines the reduction in electricity demand from conventional power plants.

The gross annual electricity generated by the fleet is computed (A_{SOFC_grid}) by multiplying the total number of SOFC vehicles by the energy produced by a single vehicle in a year (a_{SOFC_grid}) as shown in Table 1.

$$A_{SOFC_grid} = N_{SOFC} \cdot a_{SOFC_grid} \tag{4}$$

This energy production is assumed to promote energy savings in the electricity production system (*PP*). The total energy balance also considers the additional energy consumption from biomethane plants (A_{bCH4}). The total auxiliary energy demand is evaluated as the sum of the electricity consumed during anaerobic digestion (A_{AD}) and biomethane upgrading (A_{UP}), following equation (5), where each contribution is derived from literature values representative of biomethane production studies as reported in Table 2.

$$A_{bCH4} = A_{AD} + A_{UP} \tag{5}$$

The percentage reduction in energy generation is equal to the ratio between the energy generated by the SOFC fleet less the auxiliary energy required by the biomethane production chain and the total energy generated by electric power plants (A_{PP}^{BC}) in the reference base-case scenario (Table S6 of Supplementary Material).

$$\Delta A_{PP} = \frac{A_{SOFC_{grid}} - A_{bCH4}}{A_{PP}^{BC}} \tag{6}$$

On the site of the road transport sector, the shift from traditional ICE to SOFC vehicles causes a reduction of fuel consumption from the light-duty vehicles activity (ΔA_{LDV}). The total number of shifted vehicles is computed as the number of vehicles powered by SOFC over the total number of light-duty vehicles circulating in the region (N_{LDV}^{BC}).

$$\Delta A_{LDV} = \frac{N_{SOFC}}{N_{LDV}^{BC}} \tag{7}$$

2.2.3. Emission

The quantities derived from the mass and energy balances are translated into activity variations within the Integrated Assessment Model. The scenario definition starts with an assessment of how the introduction of SOFC impacts human activities. The reduction of fuel use or the introduction of an efficient measure has an impact on the total emissions. As detailed before, the definition of an emissions scenario is the starting point to compute the environmental and health impact. The emission evaluation is implemented with an IAM model [26], where the emission ($E^{d,p}$) is computed for each activity (k) and precursor (p) in each portion of the domain (d) as in the equation in (2).

$$E^{d,p} = \sum_k \left[A_k^d \cdot ef_k^p \cdot \left(1 - \sum_{m \in M_k} eff_m^p \cdot AR_m \right) \right] \tag{8}$$

Where A_k^d is the energy consumption of the activity k, ef_k^p is the emission factor of the precursor p per a single unit of activity k. The right side of the equation represents the application of end-of-pipe measures, which could reduce the final emission. Where $m \in M_k$ is the set of measures that could be applied to the activity k, AR_m is the degree of application of the single measure m in the domain, and eff_m^p is the removal efficiency of the measures.

Emissions can be reduced by the decrease of energy use (ΔA_k) with the application of an energy measure. In this case, not only are the emissions released reduced, but also the fuel consumption, resulting in lower $CO_{2\text{-eq}}$ emissions. Also, the application of end-of-pipe measures could change from the base-case, by changing the application rate relative to the base case, with a variation equal to ΔAR_m.

$$E^{d,p} = \sum_k \left[A_k^d \cdot ef_k^p \cdot (1 - \Delta A_k) \cdot \left(1 - \sum_{m \in M_k} eff_m^p \cdot (AR_m^{BC} + \Delta AR_m) \right) \right] \tag{9}$$

In scenario analysis, the degree of adoption of each measure (ΔA_k, ΔAR_m), is modified according to the policy selected.

The first phase of scenario definition is to estimate the number of vehicles that the available biomethane could power.

The total amount of biomethane useable from the vehicle fleet is computed by considering the methane leakage in the production and distribution phase. The delivered biomethane (V_{CH4_net}) is divided by the annual biomethane required for a single vehicle (v_{CH4}), computed in equation (1), to obtain the number of light-duty vehicles powered (N_{SOFC}):

The last point concerns the production of biomethane, which involves two aspects: the treatment of the manure that enters the digester and the emissions produced by the biomethane production plants themselves.

The direct application of manure as fertilizer generates high ammonia and methane emissions. The proportion of the total manure that is directed to the digester instead must be subject to controlled management that reduces the amount of emissions released into the atmosphere.

This reduction, on the scenario application, consists of an end-of-pipe measure because the quantity of product remains the same, but the management is improved. The chosen measure consists of the combined application of "*Covered outdoor storage of manure*" and "*Low ammonia application*" (defined as ΔAR_{CS_LNA} and described in Table S5 in supplementary materials). The species considered are cattle, pigs, and poultry.

$$\Delta AR_{CS_LNA} = \frac{m_{digester}}{m_{total}} \tag{10}$$

The second aspect regards the emission from biomethane production plants. In this case, it is expected a rise in emissions due to the increasing production. This increase (ΔA_{BP}) is computed as the ratio between the new volume of biomethane produced and the base case scenario production (in this case, the quantity produced in 2019, which is assumed as base-case). This ratio corresponds to an increase in this activity; therefore, it required a minus, following equation (2).

$$\Delta A_{BP} = -\frac{V_{CH4}}{V_{CH4}^{BC}} \tag{11}$$

The increase in production is assumed to be guaranteed through an increase in the demand for existing plants. The activity of individual plants is estimated as a percentage share of the total biogas produced in 2019.

Table 2
Input parameter description and literature reference data.

Parameter	Unit	Literature range	Value adopted in this study	Reference
Methane leakage during biomethane production and distribution (λ)	% leakage	1.6%	1.6%	[36]
Energy consumption for anaerobic digestion	kWh/ton	18.3-33.3	25.8	[37]
Energy consumption for biomethane upgrading	kWh/m^3 of biogas	0.14-0.34	0.2	[38]
Emission from biomethane production process	kg $CO_{2\text{-eq}}$/MJ	0.027-0.029	0.028	[5]

To evaluate the influence of the selected literature parameters on the environmental assessment, a sensitivity analysis was performed. Two additional scenarios were defined by simultaneously assigning the most favorable (best-case) and least favorable (worst-case) values reported in the literature to all the parameters listed in Table 2. The corresponding assumptions are reported in Section S10 of the Supplementary Materials.

2.3. Impact assessment

The environmental impact assessed is referred to as a reduction in air pollution concentration and $CO_{2\text{-eq}}$ emissions in the studied domain. The air pollution is evaluated with Air Quality Indexes (AQIs) that refer to the yearly average concentration of NO_2 and PM2.5. The two pollutants are selected because they have the worst impact on human health [39] and their concentration values are controlled by EU directives [40].

The scenario analysis is performed starting from the complete regional emission inventory, which includes emissions from all anthropogenic sectors. The proposed scenarios do not redefine the emission inventory but modify only the activities directly affected by the introduction of biomethane-powered SOFC vehicles (see Fig. 1). All remaining emission sources retain their base-case values. Consequently, the impact assessment is always performed on the complete regional emission inventory, with the scenario represented as a perturbation of the selected activities.

The environmental assessment is performed using the MAQ model [26], an air quality IAM developed by the University of Brescia for evaluating alternative environmental and energy policy scenarios. The framework integrates sectoral activity data, emission inventories, energy balances, and the source-receptor model to quantify changes in air quality and greenhouse gas emissions. Owing to its modular structure, the same modelling framework can be applied to different research questions by modifying the scenario definition, input datasets, and sector-specific assumptions [41].

In this study, the AQIs are estimated with a source-receptor model that reproduces the relations between precursor emissions and pollutant concentration. The IAM model integrates artificial neural networks (ANNs). ANN structure is defined to reproduce non-linear relationships involved in the formation of secondary air pollutants. The ANNs are identified in a training phase on a series of data computed around a base case scenario with chemical and transport model simulations. These scenarios cover the space of the possible emission variation for the domain under study, and they must also be able to represent the possible cause-and-effect relationships between emissions and AQIs.

Because the concentration of a pollutant in a cell does not only depend on the emissions of the cell itself but also upon the emissions from surrounding cells, the ANNs' input corresponds to a quadrant shape configuration, represented in Fig. 2. The emissions summed according to these four quadrants are used to compute the AQI value in the central cell. The ANNs performances are reported in Section S4 of Supplementary material and used and described in Ref. [42].

3. Case study

The case-study area is the Lombardy region, located in Northern Italy. The region covers an area of 23863 km^2 and hosts more than 10 million inhabitants. It is noteworthy that this area is among the most urbanized and polluted regions in Europe [29]. This can be attributed to its distinctive orographic profile, which restricts the dispersion of pollutants.

The simulated domain considers a rectangle divided into 95x62 cells of 6×6 km^2, as shown in Fig. 3, covering all Northern Italy. The area in which the policies are applied is the Lombardy Region alone (red area in Fig. 3), which has 688 cells, while emissions outside the policy domain are constant.

In each cell of the domain, the source type and its precursor emissions are specified. To obtain an emissions dataset with this level of detail, two data inputs are used:

- The regional emission inventory (the reference year is 2017) specifies the emissions by source in each municipality. The inventory is compiled by the ARPA agencies in the scope of the LIFE PREPAIR project (PREPAIR – LIFE15 IPE IT 013, https://www.lifeprepair.eu).
- The GAINS (Greenhouse Gas – Air Pollution Interactions and Synergies, https://gains.iiasa.ac.at/models/gains_models4.html) database, from IIASA, defines for each activity the emission factors and all the applicable reduction technologies [43]. The GAINS scenario gives information about the activity levels, the unabated emission factor, emission reduction measures, and costs. The GAINS scenario used is Outlook 2017 for the year 2020 (data are available every 5 years from 2005 to 2030). The inventory provides emissions data on a national scale, so the activity levels are rescaled from a national to a regional level.

The projection is obtained from total precursor emissions by sources, available at the national level, via GAINS, and at the regional level via INEMAR regional emission inventory. This process defines the regional activity levels for each emissions source in each cell of the domain.

The scenario definition phase required the use of data on the total number of light-duty vehicles (https://www.anfia.it), energy production by source [44], available biomass for biomethane production, and the location of biogas production plants surveyed as of 2019 by the Lombardy Region [45] (see Supplementary Material Section S2-S3).

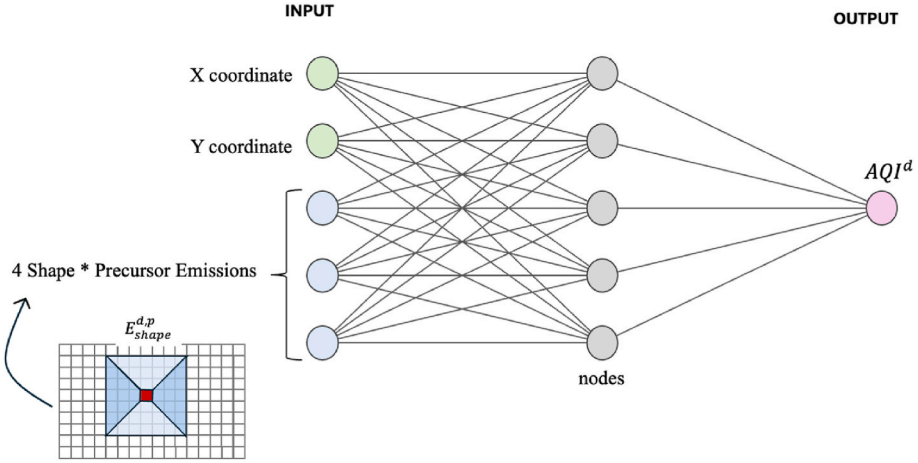


Fig. 2. Artificial Neural Network architecture.

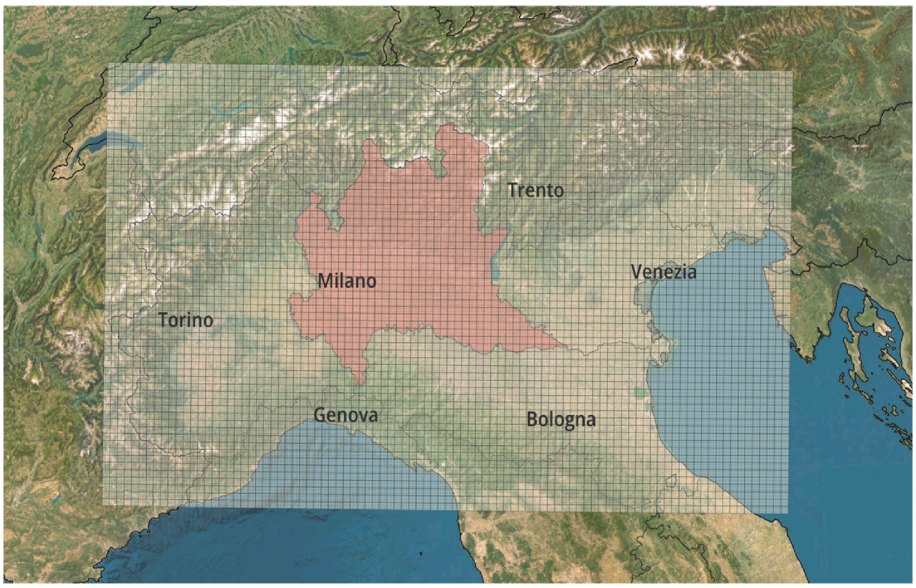


Fig. 3. Gridded domain: Lombardy region (red) and boundary domain. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Another input is the population per cell, used to estimate the population exposure. The population data is the total number of inhabitants per municipality in 2023, according to the National Institute of Statistics database (http://dati.istat.it).

4. Results

This section presents the results of the base case and SOFC scenarios. The SOFC scenarios' results are presented for the three main steps, with their variation from the base-case scenario. First, the variations in energy demand and production across the two scenarios are analyzed, emphasizing how different sectors and activities are affected. Second, the impact on pollutant emissions is evaluated to quantify the potential environmental benefits. Finally, it is assessed how these emission reductions translate into changes in air quality, providing an integrated view of the overall effects.

4.1. Base case scenario

The first scenario is intended to represent the current situation in terms of emissions, air quality, and GHG emissions, and it is referred to as the base-case scenario (BC2019). It is defined using the data presented in Section 3. Table 3 presents pollutant precursors and $CO_{2\text{-eq}}$ emissions in BC2019, categorized by the Corinair SNAP97 macro sector classification. The yearly average concentration in the base-case scenario is represented in Fig. 5a for PM2.5 and Fig. 5b for NO_2.

4.2. SOFC scenarios

The maximum biomethane production capacity in the region is estimated to be nearly 2 billion cubic meters per year (Table S3 in supplementary materials).

The production projection of the regional energy plan (PREAC) expects a lower biomethane production capacity, equal to 783 million cubic meters in 2030 [8]; therefore, a second, more conservative scenario is assessed.

The two scenarios are referred to as SOFC-PREAC, the one with the biomethane projected by the regional plan, and SOFC-MAX, the second with the maximum biomethane production capacity.

In the case of maximum production, the total amount of vegetal biomass available is 14 266 919 tons/year and 22 480 197 tons/year of animal biomass. Assuming the complete use of the vegetal part, it is possible to use only 3 566 729 tons/year of animal biomass in the digesters, corresponding to 15% of the total amount. Therefore, for this ratio, the manure management process involves the adoption of the CS_LNA techniques. This quantity is reduced in the SOFC-PREAC scenario, where only 6% of the animal matrix is used.

This increase in biomethane production leads to a direct increase in the emissions released by biomethane production plants and a reduction of ammonia emissions due to the application of CS_LNA techniques.

It is supposed to use all the biomethane to power the SOFC fleet, with except of a fraction that is lost during the production and distribution. From equations (4) and (7), the estimated biomethane availability

Table 3
Emissions per macro sectorsector at BC2019 scenario.

Macrosector	NO_x [kt/year]	VOC [kt/year]	NH_3 [kt/year]	PPM10 [kt/year]	PPM2.5 [kt/year]	SO_2 [kt/year]	$CO_{2\text{-eq}}$ [Mt/year]
Combustion in energy	7.9	0.8	0.1	0.2	0.2	3.3	14 0.1
Non-industrial combustion plants	9.2	6.9	0.7	6.6	6.4	0.5	15.6
Combustion in manufacturing industry	18.6	3.5	0.4	1.5	1.1	4.1	12.1
Production processes	2.3	11.3	0.1	0.7	0.4	2.2	2.9
Extraction and distribution of fossil fuels	-	6.2	-	-	-	-	1.1
Solvent and other product use	0.1	73.4	0.1	0.7	0.7	-	-
Road transport	62.2	16.5	1.2	4.1	2.4	0.2	17.8
Other mobile sources and machinery	9.4	1.0	-	0.4	0.3	0.2	1.4
Waste treatment and disposal	0.2	0.2	0.1	0.3	0.2	0.1	2.4
Agriculture	0.6	79.0	93.7	0.8	0.2	-	8.6
Biogenic	0.5	55.2	0.2	1.6	1.3	0.1	-
Total	111.0	254.0	96.4	16.8	13.1	10.5	75.9

corresponds to the quantity of ICE vehicles that are converted to SOFC vehicles. In the PREAC scenario, 127 533 vehicles are converted, and in MAX, 325 608 vehicles. In 2019, the number of light-duty vehicles in the region was equal to 640 569, resulting in the SOFC conversion of 20% in the SOFC-PREAC scenario and of 51% in the SOFC-MAX scenario. Finally, from this data, the energy produced by the fleet in a year is computed, which substitutes part of the energy produced by power plants. The energy savings correspond to 7% of the total annual energy production from power plants in the SOFC-PREAC and 17% in the SOFC-MAX scenario. Table 4 summarizes the main actions applied to define the two scenarios.

4.3. Emissions

The two SOFC scenarios result in the emissions variation represented in Tables 5 and 6. As described in the previous section, energy output from power plants with natural gas decreases, while emissions from biomethane-producing plants increase. Road transport emissions decline due to the phase-out of some internal combustion engine vehicles, while the agricultural sector experiences a drop in emissions within the manure management field. The overall fluctuation in emissions leads to an overall decrease in all precursors and $CO_{2\text{-eq}}$, as seen in the last line of the tables.

The maximum reduction is experienced in NH_3 (−3.1% in the SOFC-PREAC scenario and −7.8% in the SOFC-MAX scenario) and NOx (−1.8% and −4.6% respectively). The other precursors have a reduction lower than 1%. The $CO_{2\text{-eq}}$ reduction is equal to −1.4% in SOFC-PREAC and −2.9% in SOFC-MAX. Spatially, the NO_x and NH_3 variation from the base-case scenario is depicted in Fig. 4.

NO_x variation has been marked by reductions attributed mainly to the road transport sector and a lower punctual reduction linked to the energy generation sector. Punctual increments are explained by the rise in biomethane production plants (the yellow square in Fig. 4). There is a general reduction in NH_3 emissions, which is more pronounced in the lower part of the region, where most crops and livestock farms are located.

4.4. Air quality

The emission scenarios are simulated to derive the yearly average concentrations of PM2.5 and NO_2 per cell, as depicted in Fig. 5, for the three scenarios. Regarding PM2.5 (first column in Fig. 5), only minor variations emerge, mainly in the southern part of the region. In contrast, NO_2 concentrations peak in the central area, where the three biggest cities are located (Milano, Bergamo, Brescia), with a more pronounced reduction observed, extending also to the western part of the region.

Reductions in pollutant concentrations are assessed in urban areas, as summarized in Table 7. The PM2.5 reductions range from 0 to 1.6% in the SOFC-PREAC scenario and from 0.3% to 3.3% in the SOFC-MAX scenario. For NO_2, the reductions are more pronounced, ranging from 0.8% to 2.0% in the SOFC-PREAC scenario and up to 4.9% in the SOFC-MAX scenario.

The differences between PM2.5 and NO_2 reductions reflect the dominant role of road transport in NO_2 emissions, while PM2.5 originates from a wider range of sources, including residential heating and secondary aerosol formation, thus limiting the effect of transport decarbonization alone.

Overall, while the percentage reductions may appear moderate, they represent meaningful improvements considering the already challenging air quality conditions in the region, where even small decreases in pollutant concentrations can lead to significant health benefits.

The sensitivity analysis indicates that the environmental results are only marginally affected by the uncertainty associated with the selected literature parameters. The best-case and worst-case scenarios slightly modify the estimated fleet size (20-19% for SOFC-PREAC and 52-49% for SOFC-MAX) and the net electricity supplied by the SOFC fleet (6-7% and 14-19%) resulting in only minor variations in emission reductions and air quality indicators. Detailed results are reported in Section S5 of the Supplementary Materials.

Table 4
Scenario development: changes in the four activities involved in SOFC scenarios.

Activity	SOFC-PREAC	SOFC-MAX
Biomethane production plants	+786 mcm	+ 2 bcm
Biomethane utilization	+770 mcm	+1.97 bcm
Substitution of ICE light-duty vehicles with SOFC fleet	+20%	+51%
Energy produced by SOFC fleet	9.1 PJ	23.2 Pj
Energy consumption of biomethane plants	2.0 PJ	5.2 PJ
Production of energy by Natural Gas power plants	−7%	−17%
Manure destined to biomethane production	+6%	+15%

5. Discussion

Although the introduction of biomethane-powered SOFC vehicles is expected to reduce emissions from the transport sector, the regional assessment shows that the overall environmental impacts also depend on interactions with the energy and agricultural sectors. These cross-sector effects can only be captured through an integrated modelling approach. The results demonstrated that replacing conventional internal combustion engine vehicles with SOFC vehicles can significantly reduce the use of fossil fuels in light-duty vehicles (20% in SOFC-PREAC and 51% in SOFC-MAX scenario) and the demand for energy by natural gas power plants (7% and 17%, respectively).

Moreover, recent reviews emphasize the unique role of SOFC electric vehicles as prosumers: by supplying electricity to the grid and supporting renewable integration and power-sector decarbonization [46] they enhance the flexibility of the energy system. This contribution supports the integration of intermittent renewables such as solar and wind, aligning with EU decarbonization strategies and national and regional energy transition targets.

The impact assessment indicates that replacing conventional internal combustion engine vehicles with SOFC vehicles can reduce emissions of $CO_{2\text{-eq}}$, but also of some air pollution precursor such as NO_x and NH_3, leading to measurable improvements in air quality, especially in densely populated urban areas. While the reduction in PM2.5 concentrations was modest due to the persistence of other emission sources, the decrease in NO_2 levels highlights the potential health benefits of this technology.

These results are aligned with recent studies that have explored the potential of SOFCs in road transport, highlighting both environmental and energy benefits. SOFC–battery hybrid vehicles can significantly reduce greenhouse gas emissions compared to conventional internal combustion engines [25], with impacts that decrease substantially when fueled with renewable fuels [47]. These findings suggest that SOFC vehicles can simultaneously decarbonize transport, enhance air quality, and contribute to a more flexible and sustainable energy system.

Although Lombardy represents a particularly relevant case study because of its severe air quality issues, the proposed methodology is transferable to other regions. The framework can be applied by replacing the regional emission inventory, transport activity data, biomass availability, and electricity generation mix with those of the target region. Nevertheless, the magnitude of the environmental benefits will depend on local characteristics. The relationship between precursor emissions and ambient pollutant concentrations depends on regional meteorological conditions, emission patterns, atmospheric transport, and the non-linear formation of secondary pollutants. Consequently, the source-receptor model adopted in this work is specifically calibrated for the Lombardy domain and cannot be directly transferred to other regions. Therefore, while the proposed methodological framework is generally applicable, the quantitative results should be interpreted as

Table 5
Emissions variation per sector and pollutant in the SOFC-PREAC scenario with respect to BC2019.

SOFC-PREAC	NO_x	VOC	NH_3	PPM10	PPM2.5	SO_2	$CO_{2\text{-eq}}$
Energy production	−0.3%	0%	0%	0%	0%	−0.1%	−1.2%
Biomethane production plants	+0.2%	0%	0%	0%	0%	0%	+1.1%
Road transport	−1.8%	0%	0%	−0.2%	−0.3%	0%	−1.2%
Agriculture	0%	0%	−3.1%	0%	0%	0%	−0.2%
Total	−1.8%	0%	−3.1%	−0.3%	−0.3%	−0.1%	−1.4%

Table 6
Emissions variation per sector and pollutant in the SOFC-MAX scenario with respect to BC2019.

SOFC-MAX	NO_x	VOC	NH_3	PPM10	PPM2.5	SO_2	$CO_{2\text{-eq}}$
Energy production	−0.6%	0%	0%	−0.1%	−0.1%	−0.1%	−2.8%
Biomethane production plants	+0.5%	0%	0%	0%	0%	0%	2.8%
Road transport	−4.5%	−0.1%	0%	−0.6%	−0.8%	−0.1%	−2.2%
Agriculture	0%	0%	−7.8%	0%	0%	0%	−0.7%
Total	−4.6%	−0.1%	−7.8%	−0.7%	−0.9%	−0.2%	−2.9%

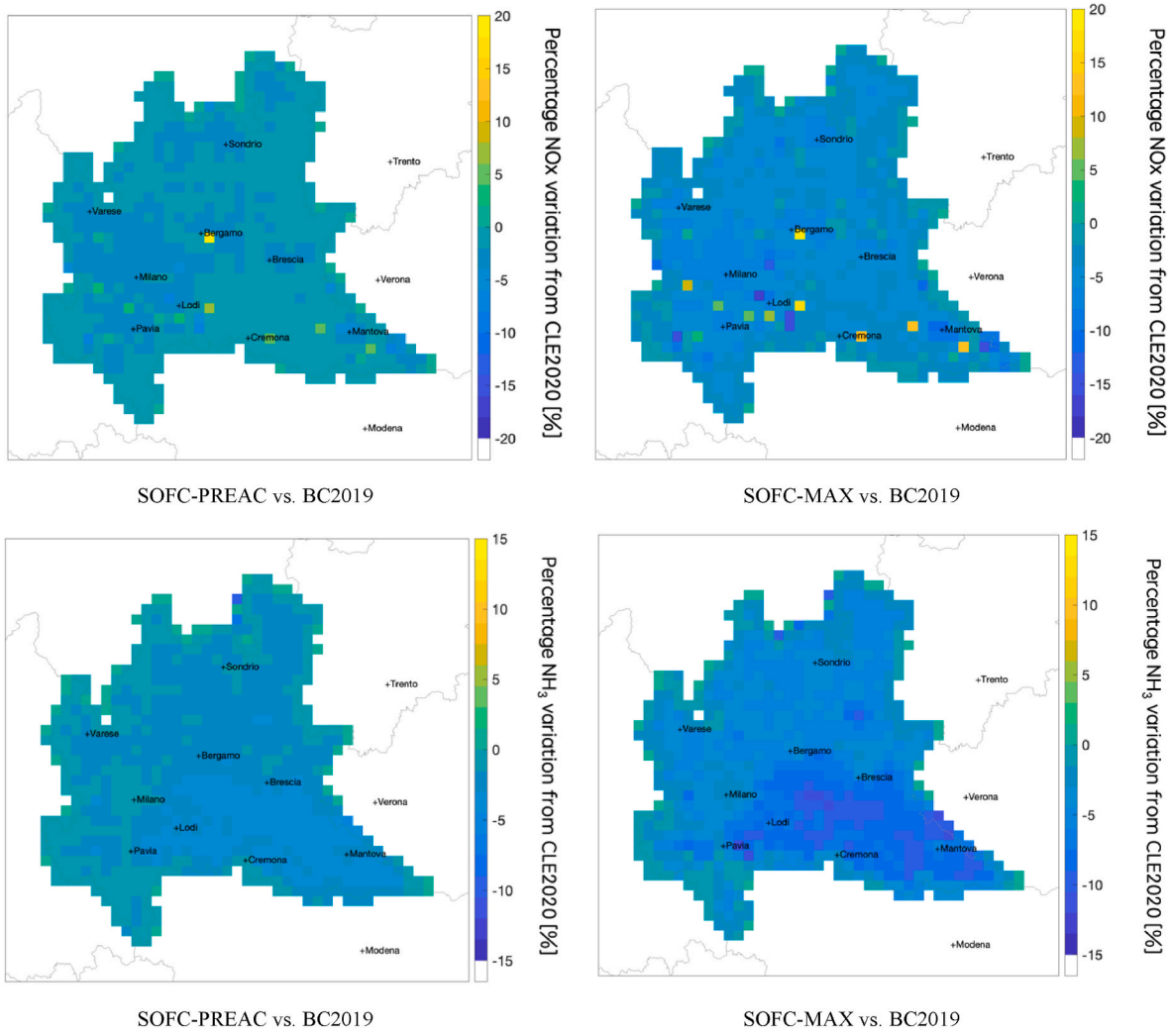


Fig. 4. NO_x and NH_3 percentage emissions variation of SOFC-PREAC and SOFC-MAX scenarios by BC2019.

representative of the Lombardy case study.

The proposed assessment should be interpreted considering several limitations. First, the fleet penetration scenarios represent policy-oriented assumptions constrained by regional biomethane availability rather than projections of market adoption, and therefore do not account for economic, behavioral, or infrastructure barriers. Second, the vehicle performance is derived from previously published simulations assuming nominal SOFC operation, without explicitly modelling degradation, thermal cycling, start-stop behavior, or long-term operational variability under real driving conditions. Finally, the study focuses on environmental impacts and does not include techno-economic indicators or a full uncertainty analysis beyond the sensitivity assessment of the main

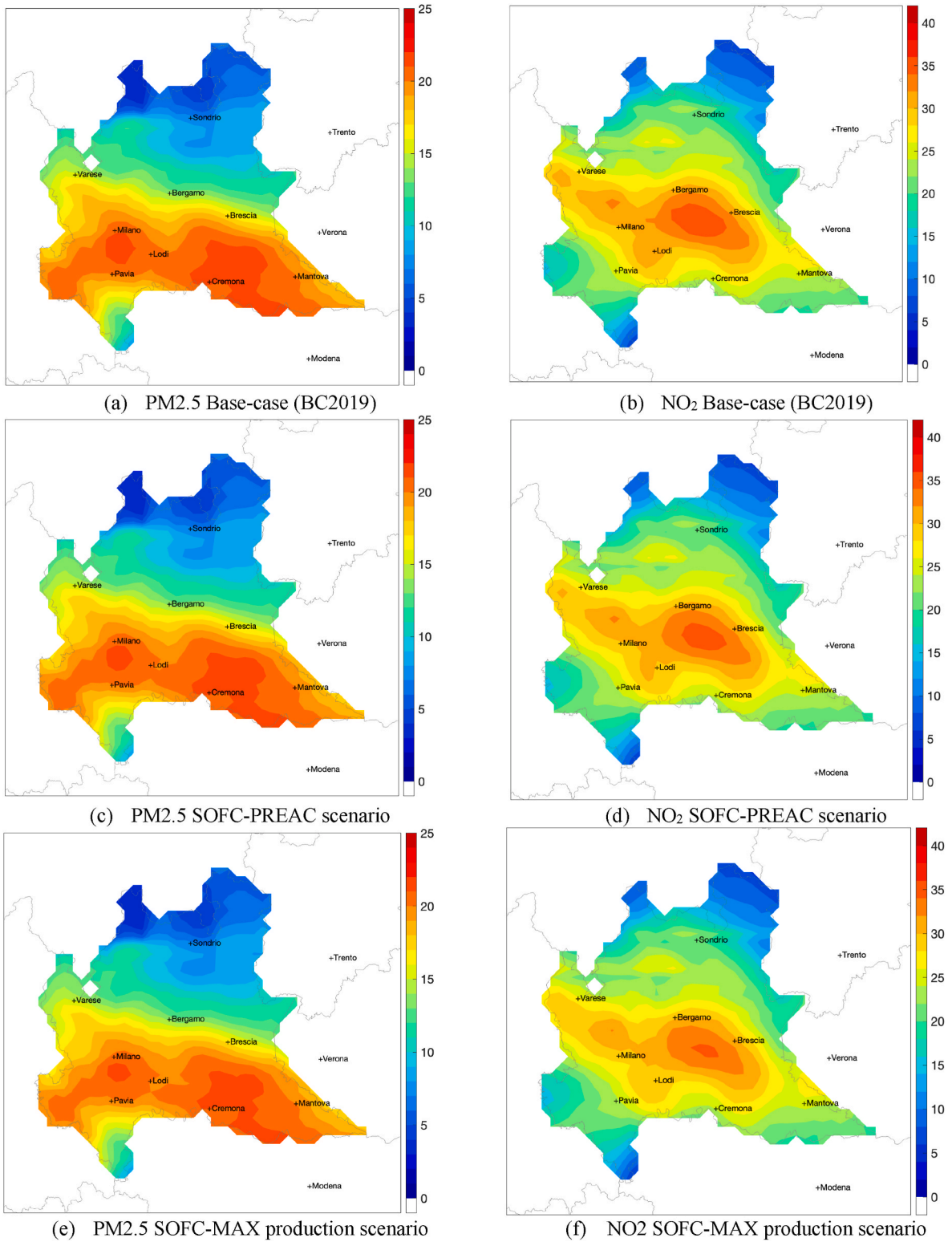


Fig. 5. Spatial yearly average PM2.5 and NO_2 expressed in $\mu g/m^3$ in the Base-case, SOFC-PREAC, and SOFC-MAX scenarios.

biomethane production parameters.

6. Conclusions

This study assessed the environmental and energy implications of introducing a fleet of biomethane-powered SOFC light-duty vehicles in the Lombardy region, considering both transport decarbonization and renewable energy integration. The SOFC vehicles are used as prosumers; therefore, they consume energy for traction but also generate energy for the grid during the stop time.

The method used consists of applying an integrated assessment model in a scenario analysis approach. The data collected from literature by a vehicle dynamic simulation tool are elaborated to estimate the annual average consumption of biomethane and energy generated for

Table 7
Yearly average PM2.5 and NO_2 concentrations ($\mu g/m^3$) in the base-case scenario (BC 2019) and in the SOFC-PREAC and SOFC-MAX scenarios.

	PM2.5 [$\mu g/m^3$]			NO_2 [$\mu g/m^3$]		
	BC2019	SOFC-PREAC	SOFC-MAX	BC2019	SOFC-PREAC	SOFC-MAX
Milano	20.1	20.1	20.0	30.0	29.6	29.0
Bergamo	13.5	13.5	13.5	29.9	29.5	29.0
Brescia	17.5	17.4	17.2	31.8	31.4	30.9
Como	14.3	14.1	13.9	25.8	25.5	25.1
Cremona	20.1	20.0	19.8	24.9	24.5	23.9
Lecco	12.3	12.2	11.9	24.0	23.8	23.5
Lodi	20.4	20.2	19.9	30.5	30.1	29.3
Mantova	18.8	18.5	18.2	25.0	24.7	24.3
Pavia	21.6	21.4	21.1	24.7	24.2	23.5
Sondrio	6.9	6.9	6.8	21.8	21.7	21.4
Varese	14.9	14.8	14.5	27.5	27.0	26.4

the grid by a single vehicle. Two different hypotheses are implemented: the production of a quantity of biomethane equal to that projected by the regional energy plan PREAC (778 mcm) and the maximum biomethane production estimated from the organic waste available (2 bcm).

The quantity of biomethane is used to estimate the number of vehicles that could be shifted to SOFC. Therefore, the scenarios involve the energy production, road transport, and agriculture sectors.

The scenario analysis indicates that available regional biomethane resources could support a substantial penetration of SOFC vehicles, resulting in a reduction in fossil fuel consumption, greenhouse gas emissions, and key air pollutants.

Beyond the quantified emission reductions, the study demonstrates the importance of adopting an integrated regional assessment. The proposed framework captures interactions among the transport, energy, and agricultural sectors, showing that the environmental benefits of biomethane-powered SOFC deployment arise from multiple interconnected processes rather than from vehicle substitution alone. This systems-level perspective provides additional insight compared with conventional vehicle-scale assessments.

Future work should extend the present assessment by integrating techno-economic evaluations, infrastructure requirements, uncertainty analysis, and degradation-aware vehicle modelling. Furthermore, the methodology should be applied to additional regions using local emission inventories and air quality models to evaluate the influence of different electricity mixes, biomass availability, and atmospheric conditions on the resulting environmental benefits.

CRediT authorship contribution statement

Laura Zecchi: Writing – original draft, Software, Methodology, Investigation, Data curation. **Giulia Sandrini:** Writing – review & editing, Methodology, Data curation. **Michele F. Arrighini:** Writing – review & editing, Software, Methodology. **Daniel Chindamo:** Writing – review & editing, Supervision, Conceptualization. **Marco Gadola:** Writing – review & editing, Supervision, Conceptualization. **Marialuisa Volta:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Data availability

Data will be made available on request.

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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.

Glossary:

Variables
$m_{digester}$: mass of manure directed to biomethane production in the scenario
V_{CH4_gross}: volume of biomethane produced in a year in the scenario
V_{CH4_net}: volume of biomethane delivered to SOFC vehicles in a year in the scenario
N_{SOFC}: number of light-duty vehicles that are converted to SOFC vehicles
A_{SOFC_grid}: quantity of energy generated by the SOFC fleet in the stationary mode and delivered to the grid
A_{bCH4}: total energy consumed for biomethane production
A_{AD}: energy consumed for anaerobic digestion in biomethane production plants
A_{UP}: energy consumed for biomethane upgrading
ΔA_{PP}: relative variation in energy generation
ΔA_{LDV}: relative variation in fossil fuel energy consumption by the light duty vehicle fleet
ΔA_{BP}: variation in the biomethane production activity sector
ΔAR_{CS_LNA}: application rate of manure management measures
Parameters
t_{trac}: total time used for traction by the SOFC light-duty vehicles
t_{grid}: total time spent to generate power for the energy grid by the SOFC light-duty vehicles
a_{trac}: energy consumed in two weeks of operation by a single SOFC vehicle
a_{grid}: energy delivered to the grid in two weeks by a single SOFC vehicle
γ_{CH4}: average biomethane consumption
v_{CH4}: volume of biomethane required for a single SOFC vehicle for a year
λ: methane leakage factor
V_{CH4}^{BC}: volume of biomethane in the base-case scenario
m_{total}: total mass of manure produced on the domain
N^{BC}: number of light-duty vehicles in the base-case scenario
A_{PP}^{BC}: base-case energy generation
A_k^d: activity level of emission source k cell d
ef_k^p: emission factor of precursor p for activity k
eff_m^p: removal efficiency for pollutant p of measure m
AR_m^{BC}: application rate of measure m in base-case scenario

Appendix A. Supplementary data

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