Energy Efficiency (2025) 18:36
https://doi.org/10.1007/s12053-025-10325-1

ORIGINAL ARTICLE

CO_2 emission changes in two Italian regions: progress toward 2050 climate neutrality under the Covenant of Mayors

Paolo Maria Congedo · Luca Colazzo · Marina Bonomolo · Cristina Baglivo

Received: 10 June 2024 / Accepted: 7 April 2025

Abstract In 2008, the European Commission established the Covenant of Mayors (CoM), a voluntary initiative to involve and support local authorities in pursuing the European Union's climate change mitigation and adaptation goals. This study proposes a methodology to evaluate the effectiveness of Sustainable Energy Action Plans (SEAPs) and Sustainable Energy and Climate Action Plans (SECAPs) in terms of reducing carbon dioxide emissions in the regions of Apulia and Sicily. The CO_2 emissions are analyzed at the provincial level, before and after the approval of the plans by the municipal council, using homogeneous consumption data from national sources, rather than from data declared by the CoM signatories themselves. The methodology adopted combines the analysis of variance and compound annual growth rate (CAGR) of emissions, both total and per capita, with an assessment of the level of involvement of municipalities and the population in CoM plans. Through Pearson's coefficient, the correlation between the spread of plans and emissions at the provincial level was also assessed. The main results show that Apulia and Sicily, with a share of approved plans of 45.5% and 87.7%, respectively, experienced a reduction in total emissions of 12.1% and 21.2%, and per capita of 9.3% and 18.7%, in the period after municipalities submitted their SEAPs or SECAPs. A greater effectiveness of the plans is denoted in Sicilian provinces than in Apulian ones. These findings underscore the importance of emissions monitoring by signatory local governments, particularly through a uniform methodology, as well as monitoring at the provincial and regional levels, implemented by the Covenant Territorial Coordinators (CTCs), to assess the implementation of the action plans and ensure that regional and national emission reduction targets are met.

Keywords Covenant of Mayors · Sustainable Energy and Climate Action Plan · Mitigation · Energy consumption · CO2 emissions · Climate neutrality

P. M. Congedo · L. Colazzo · C. Baglivo (✉)
Department of Engineering for Innovation, University of Salento, 73100 Lecce, Italy
e-mail: cristina.baglivo@unisalento.it

P. M. Congedo
e-mail: paolo.congedo@unisalento.it

L. Colazzo
e-mail: luca.colazzo@unisalento.it

M. Bonomolo
Department of Engineering, University of Palermo, 90128 Palermo, Italy
e-mail: marina.bonomolo@unipa.it

Introduction

Since the early 1990 s, the European Union (EU) has taken a central role in the fight against global climate change. One of its most notable contributions was the ratification of the Kyoto Protocol on

Published online: 17 April 2025

May 31, 2002, which set binding targets for member states to reduce greenhouse gas (GHG) emissions. Subsequently, the EU has implemented increasingly ambitious policies and legislation to combat climate change, most notably the 2015 Paris Agreement. Through the adoption of a series of targeted programs, the EU has committed to reducing energy dependence, improving energy efficiency (Bertoldi, 2018a, 2022) and promoting the extensive use of renewable energy sources.

In order to fully achieve the EU's targets, they must be adopted and implemented at the sub-national level, where local authorities can become key players in the fight against climate change by taking sustainable energy and climate initiatives in their territories (Broto, 2017; Congedo & Baglivo, 2021; Congedo et al., 2021). In this context, cities can be the answer.

In Europe, more than 12,000 cities and local governments have joined the Covenant of Mayors Climate and Energy (CoM) initiative (https://www.eu-mayors.ec.europa.eu/it/key_figures), achieving significant progress, often with greater speed and ambition than national and regional governments. This has made local authorities privileged partners in developing and implementing policies consistent with the goal of limiting temperature rise to 2 °C and 1.5 °C above pre-industrial levels by mid-century, demonstrating their ability to lead climate action (Kona et al., 2018).

Figure 1 shows the evolution of EU energy and climate policies compared with the evolution of the CoM.

The introduction of the CoM can be seen as an important step in the evolution of European policy,

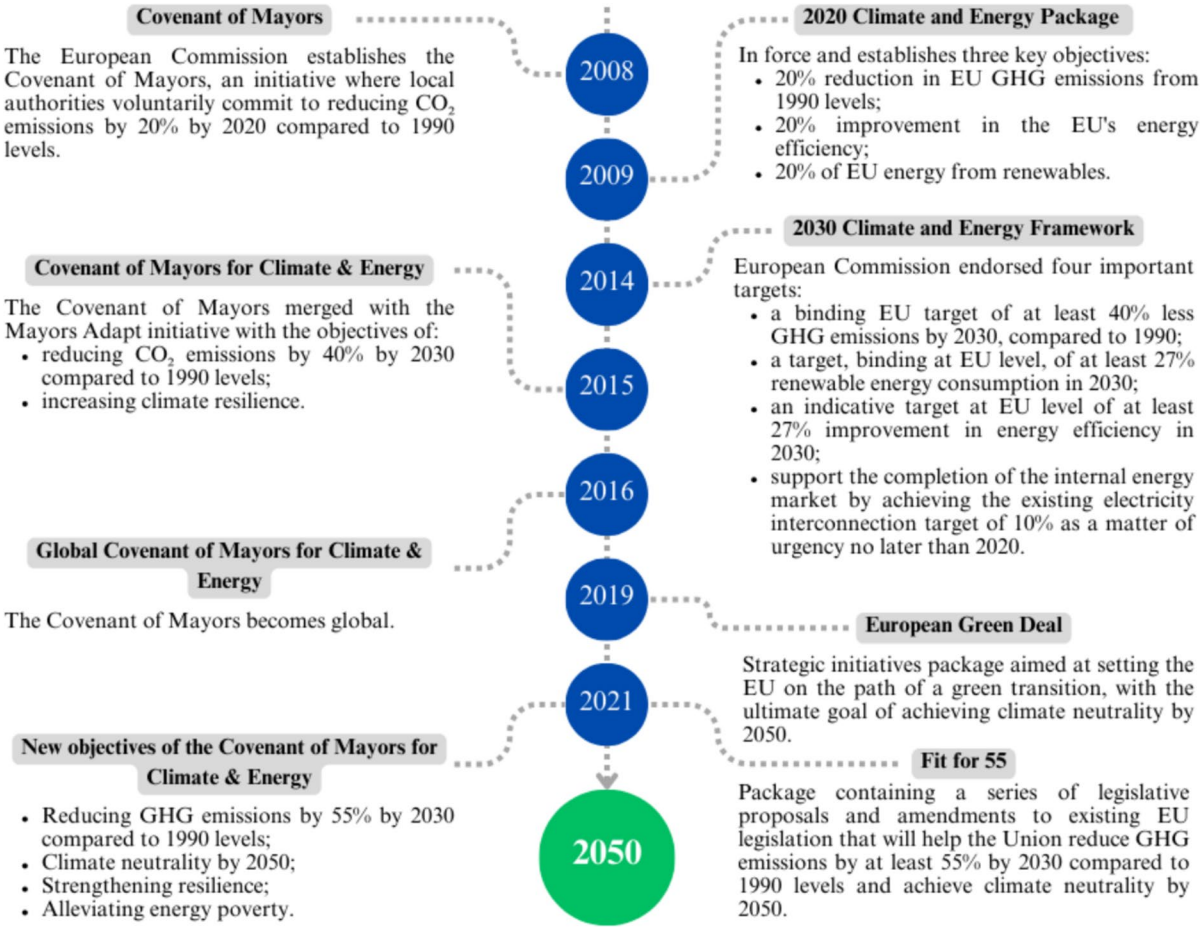

Fig. 1 Comparison between the evolution of European policies to combat climate change and the development of the CoM

as it gives municipalities a more proactive role in pursuing European energy and climate goals (Pablo-Romero et al., 2015, 2016).

CoM signatories demonstrate their commitment by developing Sustainable Energy and Climate Action Plans (SECAPs) for their respective territories, in accordance with the CoM Guidelines (Bertoldi, 2018b, c, d).

In this context, the European Commission's Joint Research Center (JRC) is tasked with evaluating the Plans developed by cities, monitoring the progress of local actions toward their respective targets, and assessing the final results. The monitoring system consists of a comprehensive assessment every four years (Andreanidou et al., 2018), including an update of the emissions inventory, known as the Monitoring Emissions Inventory (MEI). However, there is no final monitoring report at the end of the initiative.

In supporting local authorities, especially smaller ones, in energy and climate planning, regions and provinces play a key role. By joining the initiative as Covenant Territorial Coordinators (CTCs), they assist municipalities not only in drafting emission inventories and developing action plans but also in promoting investments in energy efficiency projects and renewable energy sources (Melica et al., 2018).

Literature overview

The development of action plans presents several challenges. Marinakis et al. (2017) pointed out that lack of technical expertise and limited resources are significant obstacles to implementing Sustainable Energy Action Plans (SEAPs) and promoting renewable energy or energy efficiency measures in some regions. These difficulties have spurred numerous studies aimed at developing methodologies that provide local governments with analytical support tools to facilitate energy and climate planning decisions (Bjelic & Ciric, 2014; Kyriakarakos et al., 2014; Mirakyan & De Guio, 2013). For example, Scorza and Santopietro (2021) proposed a methodology to optimize the use of SECAPs in the EU by integrating a systemic strategic planning approach to enhance urban resilience and sustainability, while also providing an overview of relevant EU energy policies and best practices.

Other studies have analyzed technical aspects related to the drafting of action plans. For instance, Lombardi et al. (2016) outlined the methodology adopted for formulating these plans and reported the results obtained in 36 municipalities in Apulia, particularly in the province of Foggia (Italy).

Meanwhile, Santopietro et al. (2024) analyzed the economic impact of the CoM by examining how adherence influenced public investments, with a focus on education expenditures. Using a sample of 81 SEAPs approved in Basilicata between 2008 and 2021, their study compares expenditures before and after approval to assess the effect of the CoM initiative on municipal policies.

In addition to planning, monitoring plays a crucial role in the CoM methodology, as it allows signatories to verify the implementation of the measures outlined in the action plans, track progress toward GHG emission reduction targets, and identify any gaps that might hinder the achievement of those targets. This phase has recently received considerable attention in the literature: some studies have examined the reduction in CO_2 emissions reported in monitoring reports (Pazienza, 2014), while others have developed tools and methodologies to support the implementation and advancement of MEI (Battista et al., 2021; Cinocca et al., 2018; Palermo et al., 2021).

However, as interviews conducted by Basso and Tonin (2022) have shown, some municipalities exhibit little political interest in the implementation and monitoring of their plans. They merely sign the covenant for political visibility, regarding the implementation and monitoring tasks as bureaucratic burdens.

The scientific literature offers a limited number of studies that unequivocally demonstrate the effectiveness of CoM adherence in reducing emissions through energy savings or promoting renewable energy. Santopietro and Scorza (2021) evaluated the effectiveness of the CoM in Italy by analyzing the performance of Italian signatories in terms of SEAPs and Monitoring Reports. Croci et al. (2017) analyzed 124 CoM signatory cities, showing the correlation between baseline emissions and reduction outcomes. Palermo et al. (2020) examined the policies of 315 CoM cities, highlighting how factors such as population, Gross Domestic Product (GDP), and climate conditions influence policy choices. Lastly, Franco et al. (2025) recently developed an innovative approach based on Machine Learning and Structural Topic Modeling to analyze the effectiveness of local climate policies in achieving emission reduction targets by 2030. Using

a dataset updated to 2023, their study identifies the most relevant policy themes and assesses their impact on the likelihood of meeting emission reduction commitments, providing a replicable methodology for evaluating climate mitigation policies.

Larger studies, such as those by Hsu et al. (2020) and Rivas et al. (2021), assessed the progress of CoM cities, noting that cities with high baseline emissions tend to set less ambitious targets. Lucchitta et al. (2024) investigated factors influencing the outcomes of measures planned in the SEAPs of CoM signatories, with a focus on policy instruments and sectors; regression analysis revealed that policies implemented in specific sectors have a significant impact on emission reductions.

Pablo-Romero et al. (2016) evaluated whether CoM membership and the development of related SEAPs contributed to reducing electricity consumption in municipalities in Andalusia, and consequently, their emissions. Their study, conducted from 2001 to 2012, examined trends in electricity consumption and determined whether CoM adherence and SEAP development had impacted these trends. For this purpose, total electricity consumption, household consumption, and government consumption were analyzed in relation to municipal income using panel data econometric techniques.

Rivas et al. (2022a) analyzed the progress made by European cities participating in CoM 2020 toward meeting their specific GHG emission reduction targets, representing the first statistical analysis of monitoring practices based on a large dataset comprising more than 5,000 European municipalities, of which over 1,600 adhere to the CoM monitoring system. Their analysis of plans developed in Europe from 2008 to 2020 (Rivas et al., 2022b) showed that 85.6% of GHG reduction targets were achieved before 2020. However, reduction patterns vary: some local governments have exceeded their targets, while 12% have increased emissions. The involvement of stakeholders and government support emerged as crucial factors.

The research by Salvia et al. (2021) analyzed the climate mitigation targets of 327 European cities, representing more than 25% of the EU population. Their study explored how plan type, city size, membership in climate networks, and regional location are associated with levels of ambition in GHG emission reduction. Although 78% of cities aim for reductions, the average reduction target of 47% is insufficient to meet the Paris Agreement, although some cities are targeting carbon neutrality. Notably, city size emerged as the strongest predictor.

Other studies have proposed methodologies to predict GHG emissions in cities. Franco et al. (2023), using data from the GCoM, analyzed 6,231 EU- 27 cities and municipalities by considering factors such as energy consumption, population, and trends in per capita emissions. Their methodology assessed the expected outcomes and performance of cities, aiming to support those seeking significant emission reductions.

Finally, the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), through a survey designed to develop a methodology to assess the additional potential for GHG emission reductions by Italian municipalities participating in the CoM, observed that these reductions increase with the population size of municipalities. The study, completed in 2019, utilized data provided by the JRC and the CoM public platform (ISPRA, 2019).

The Italian case: the contribution of Apulia and Sicily to the GCoM initiative

In Italy, through the CoM, 5,811 cities and local authorities, representing a population of 73,175,671 people (European Commission et al., 2024), have committed to addressing the causes and effects of climate change, as well as promoting energy access and combating energy poverty. In particular, two Italian regions, the focus of this study, stand out for their commitment and involvement: Apulia and Sicily. These regions are the only ones in Southern Italy to have taken on the role of CTC—officially recognised by the European Commission—and committed to providing strategic guidance as well as technical and financial support for the development and implementation of the signatories' plans in their respective geographical areas through a series of key activities. Thanks to the assumption of this role, a greater number of municipalities have been engaged in the initiative, thereby contributing to the achievement of regional objectives in terms of GHG emission reduction, energy savings, and renewable energy production.

With regard to financial support, it is important to highlight that both Regions have initiated

specific programs aimed at covering eligible expenses incurred by signatory municipalities for the development of action plans and the implementation of energy efficiency measures in local authority buildings. These contributions represent a significant form of support for municipalities, many of which face complex economic and financial challenges, enabling them to engage specialized professionals in the preparation of the Plans. The amount of financial support is adjusted based on the demographic size of the municipalities, determined by the number of inhabitants.

In terms of technical support, both Regions have developed dedicated web portals that provide access to all the necessary documentation for joining the CoM, as well as technical assistance tools to facilitate participation in the initiative.

In this context, ENEA, as national coordinator of the CoM, has entered into an agreement with the Apulia Region and the Sicily Region, providing an IT platform to support municipalities in the drafting and monitoring of SECAPs. This platform is particularly relevant for the implementation of GHG mitigation actions.

The Sicilian Government has played a pivotal role in the implementation of the CoM initiative (Famoso et al., 2015). On November 9, 2009, it signed a partnership agreement with the Directorate-General for Energy and Transport (DG TREN) of the European Commission, which was subsequently approved by Regional Government Resolution No. 164 of June 15, 2010. Through this agreement, the Sicilian Region was officially recognized as a Supporting Structure for local administrations within the framework of the CoM.

Following this, Regional Government Resolution No. 460 of November 30, 2012, established a Steering Committee responsible for coordinating and monitoring the implementation of the commitments undertaken by municipalities adhering to the CoM, ensuring compliance with programmatic objectives set forth for both the European Community and local citizens.

Subsequently, Regional Government Resolution No. 478 of December 11, 2012, titled"Guidelines for the Reprogramming of the PO FESR 2007–2013 and Adherence to the Cohesion Action Plan"allocated financial resources for the creation of a start-up dedicated to the CoM.

Finally, Decree No. 413 of October 4, 2013, issued by the General Director of the Department of Energy and published in the GURS (Part One) No. 55 of December 13, 2013, Ordinary Supplement No. 1, approved the Resource Allocation Program for the Municipalities of Sicily, aimed at promoting energy-environmental sustainability through the CoM.

With the aim of revitalizing the CoM initiative at the regional level and supporting local authorities in the coordinated planning of actions to address both the potential impacts of climate change and mitigation policies through a common strategy, the Apulia Region has embarked on a significant path toward climate neutrality.

By means of Resolution No. 1154 of July 13, 2017, the Regional Council approved the candidacy of the Apulia Region as a CTC to the European Commission and established the Regional Coordination Structure, and, in April 2018, formally assumed the role.

Subsequently, with Resolution No. 1575 of September 17, 2020, the Apulia Region initiated the process of defining the Regional Strategy for Climate Change Adaptation (SRACC). This strategy aims to systematize existing knowledge and experiences related to climate phenomena and to identify appropriate measures to enhance territorial resilience, thereby improving the capacity to respond effectively to climate-induced stress. Furthermore, within the framework of its role as a CTC, this strategy will provide local authorities with detailed information to support the adaptation and development of action plans.

Finally, through Resolution No. 349 of March 14, 2022, the Apulia Region adopted an initiative that provides financial support in the form of vouchers to assist CoM signatories in drafting their action plans.

Despite significant support from the two regions, however, the action plans encounter several critical issues. These include difficulties in the quality of emission inventories, effective implementation of planned measures, and completion of monitoring by signatories. The analysis of the experiences of these two regions made it possible to assess the similarities and differences in local progress towards achieving the CoM goals.

Problem statement

Most of the previously mentioned studies evaluated the effectiveness of the CoM using the GCoM—MyCovenant dataset, containing the target emission reductions declared by signatories for the target years

2020 or 2030 and their self-reported emission inventories for the base year and the monitoring year. The present work used this dataset exclusively to analyze the actual participation of municipalities in the Apulia and Sicily regions in the submission of action plans. To assess cities' progress in mitigating CO_2 emissions in the regions examined, actual energy consumption data, at the provincial scale, was used. These data are provided by the national datasets of the Ministry of Environment and Energy Security (MASE) and TERNA, the company that operates Italy national electricity transmission grid. The choice not to use the dataset from the MyCovenant reporting platform for emission assessment was made to ensure uniformity and consistency in the overall data analysis. Since the emission inventories provided by CoM signatories are based on heterogeneous sources and methodologies, it was deemed more appropriate to adopt single and standardized datasets at the provincial level. This avoids discrepancies due to methodological differences and ensures comparable and consistent results across the different areas examined.

After data collection, the effectiveness of CoM in terms of emission reduction was analyzed. Specifically, the changes and the annual growth rate in total and per capita CO_2 emissions at the provincial level were calculated, before and after the approval of the action plans by the municipalities. Correlation coefficients were then calculated to look for possible linear relationships between the factors described and the actual participation in CoM by municipalities, at the provincial level, measured in terms of percentage of municipalities and population covered.

The objective of the analysis is to verify whether the policies and measures implemented at the local and regional levels have actually contributed to the achievement of the initiative objectives.

Materials and methods

This section outlines the methodology and procedures adopted to assess the efficacy of the CoM in the regions of Apulia and Sicily.

Table 1 specifies the datasets employed in this study, with a brief description and bibliographic reference. Each dataset has been carefully selected to ensure the reliability and representativeness of the information used in the study. The description provided for each dataset includes essential information on the content and origin of the data, while the bibliographic reference allows readers to easily trace the source from which the data have been obtained.

Table 2 lists the specific sections pertaining to the analyses conducted within the study are listed. Each section is accompanied by a brief description of its content, providing the reader with a clear and concise overview of the topics covered in the document.

To support the analyses presented in the preceding sections and summarized in the tables, specific methodologies have been adopted. The following sections describe the statistical and analytical techniques employed in data processing.

In "Analysis of Apulian and Sicilian GCoM signatories" section, the year in which the highest number of SEAPs or SECAPs approvals was recorded is estimated for each province. These data made it possible to divide the examined time interval (2005–2022) into two distinct periods: one before and one after the approval of the plans. This analysis used the concept of mode, which is a statistical measure that identifies the most frequent value or values within a data set.

In "Analysis of CO2 emissions in Apulia and Sicily" section, provincial energy consumption data are converted into CO_2 emissions (in tonnes) through a simple multiplication operation (1).

$$CO_2\ emissions\left(tons\ of\ CO_2\right) = consumption(MWh) \cdot emission\ factor\left(\frac{tons\ of\ CO_2}{MWh}\right) \quad (1)$$

The JRC provided a dataset containing GHG Emission Factors for local energy use of non-renewable energy sources (Bastos et al., 2024a) and for national electricity (NEEFE) (Bastos et al., 2024b), first published in Bertoldi et al. (2010) and later updated in Koffi et al. (2017), Lo Vullo et al. (2022) and Bastos et al. (2024c). This dataset has been processed using two approaches: the activity-based approach (IPCC) (IPCC, 2006) and the life-cycle approach (LC). In this paper, the first approach is taken, considering CO_2 emissions (t CO_2/MWh).

In "Assessment of the CoM effectiveness" section, the CAGR is used to estimate the annual growth rate of CO_2 emissions because it provides

Table 1 Datasets used in the present study

Data source	Description of the source	Dataset	Reference	Content
JRC	Joint Research Centre	GCoM—MyCovenant, 5th Release – January 2024	(Baldi et al., 2024; Franco et al, 2024)	The dataset includes a collection of action plans and monitoring reports, provided by local authorities via the MyCovenant platform
TERNA	Company that manages, maintains, and develops the high-voltage electricity transmission network in Italy	Consumption: electricity by sector	(https://www.terna.it/it/sistema-elettrico/statistiche/evoluzione-mercato-elettrico/consumi-energia-elettrica-settore)	The dataset comprises information on electricity consumption by sector, segmented by region and province, spanning from 2000 to 2022, covering the residential, industrial, agricultural, and service sectors
MASE	Ministry of Environment and Energy Security	Provincial sales (consumption) of gasoline, diesel, and fuel oil; provincial sales of LPG (liquefied petroleum gas) and lubricants; provincial consumption of natural gas	(https://www.sisen.mase.gov.it/dgsaie)	The dataset includes consumption related to petroleum products and natural gas via SISEN platform. (years 2003–2024)
ISTAT	National Institute of Statistics	Reconstructed resident population—Years 2001–2019; Resident population as of January 1 st—Years 2019–2023	(http://www.dati.istat.it/Index.aspx)	ISTAT provides datasets on the resident population as of January 1 st from 2001 to 2023. Data on the Italian resident population (years 2001–2023)

Table 2 Sections of the analyses presented in this research article

Sections	Reference chapter	Content description
3.1	Analysis of Apulian and Sicilian GCoM signatories	This section examines the status of GCoM signatories among municipalities in Apulia and Sicily, with an analysis at the provincial level. Specifically, the share of municipalities and population covered by action plans (SEAPs or SECAPs) were calculated
3.2	Analysis of CO_2 emissions in Apulia and Sicily	This section analyzes CO_2 emissions from the consumption of electricity, petroleum products, and natural gas in the provinces of Apulia and Sicily over the period from 2005 to 2022. Subsequently, trends in total and per capita emissions were achieved
3.3	Assessment of the CoM effectiveness	In this section, the changes and CAGR of total and per capita CO_2 emissions at the provincial level were calculated, both before and after the approval of the first action plan (SEAP or SECAP) by municipalities. Subsequently, a possible correlation between the spread of these plans and the corresponding emissions was evaluated

a representative measure of the average annual growth rate of a value over time, taking into account variations between the initial and final values. This method is particularly useful when analyzing data with fluctuations over a long period because it provides a stable value that describes growth on an annual basis in a uniform manner. The CAGR provided a simplified and understandable view of emission trends, which is useful for comparing different periods, such as those before and after municipalities submitted their action plans. The CAGR Eq. (2) is as follows:

$$CAGR = \left(\frac{V_f}{V_i}\right)^{\frac{1}{n}} - 1 \tag{2}$$

where

V_f is the final value of emissions;
V_i is the initial value of emissions;
n is the number of years between the initial and final value.

Also, in "Assessment of the CoM effectiveness" section, Pearson's correlation coefficient is used to establish the existence of a correlation between the examined variables. This coefficient measures the linear relationship between two continuous variables on scales of intervals or ratios, indicating both the strength and direction of the relationship between them. The Eq. (3) reports the Pearson correlation coefficient (r):

$$r = \frac{\sum (x_i - \overline{x}) \cdot (y_i - \overline{y})}{\sqrt{\sum (x_i - \overline{x})^2 \cdot \sum (y_i - \overline{y})^2}} \tag{3}$$

where

x_i and y_i are the individual observations of the two variables;
$\overline{x}$ and $\overline{y}$ are the respective means of the variables;

The Pearson correlation coefficient ranges from − 1 to 1 (values near − 1 or 1 signify strong correlations). Table 3 shows the possible results in relation to the type of correlation.

Table 3 Possible outcomes of the Pearson correlation coefficient

Value	Type of correlation	Description of the result
$0 < r \leq 1$	Positive	Direct proportional relationship between the two variables
$-1 \leq r < 0$	Negative	Inverse proportional relationship between the two variables
$r = 0$	No linear	No correlation between the two variables

Results and discussion

Analysis of Apulian and Sicilian GCoM signatories

This section analyzes the fifth edition of the GCoM—MyCovenant released in January 2024 and updated in April of the same year. The data include an extensive collection of action plans and monitoring reports uploaded directly by local authorities to the MyCovenant platform. These datasets provide an overview of local initiatives undertaken by GCoM signatories globally to address climate change mitigation, adaptation, and energy access.

From the MyCovenant dataset, the necessary information are extracted and reprocessed as needed, ensuring that it was in line with the variables and parameters relevant to the analysis of the two regions.

The analysis reveals that Apulia and Sicily are among the regions with the highest percentage of plans submitted by municipalities and approved by the municipal council, 45.5% (117 out of 257 municipalities) and 87.7% (343 out of 391 municipalities), respectively. Specifically, the share of municipalities with at least one approved action plan (SEAP or SECAP) in the provinces of the regions examined were calculated. The results are shown in Fig. 2.

Furthermore, the population involved in the Covenant reached 46.4% (1,818,567 out of 3,922,941) and 92.8% (4,486,927 out of 4,833,329) of the total population in Apulia and Sicily respectively. At the provincial level, the share of population residing in signatory municipalities with at least one approved action plan (SEAP or SECAP) are shown in Fig. 3.

By analysing the fifth release of GCoM datasets, this study identified for each province the year in which the highest number of action plans approvals was recorded. These data are fundamental for structuring the analysis, as they allow the division of the time interval into two distinct periods: one before and one after the approval of the first plan (SEAP or SECAP) by municipal councils. Since the study is conducted at the provincial level, the most common year in which municipalities within the same province approved and adopted their first plan is considered. This approach highlights and analyzes any variations in CO_2 emissions data, enabling a more precise assessment of the plans' effectiveness and their tangible impact on the affected territories. The results are shown in Table 4.

Analysis of CO_2 emissions in Apulia and Sicily

After assessing the participation levels of Apulian and Sicilian municipalities in the CoM at the provincial level, the analysis shifted to examining CO_2 emissions. It is important to note that the initiative's member municipalities chose different base years for their Baseline Emission Inventory (BEI) and Monitoring Emission Inventory (MEI). The objective of this analysis is to examine emission trends at the provincial level, comparing the periods before and after

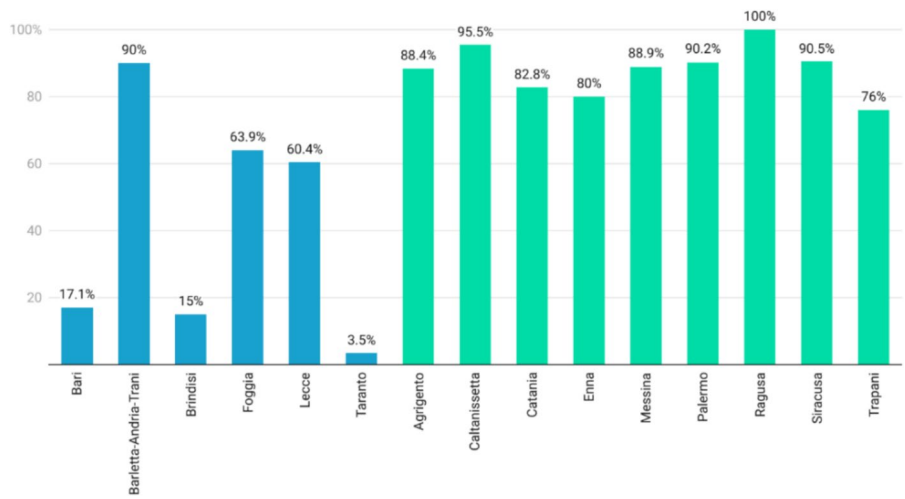

Fig. 2 Share of municipalities with at least one approved action plan per province in the Apulia and Sicily regions

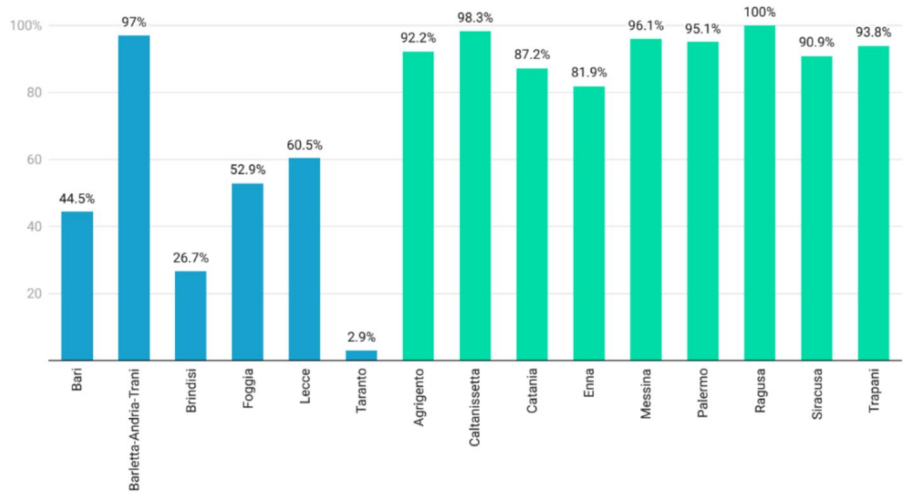

Fig. 3 Share of population covered by action plans per province in the Apulia and Sicily regions

the approval of the action plans (SEAP or SECAP), to assess whether there has been a significant change in emissions due to the benefits of the adopted plans. Specifically, the antecedent period is considered to be the interval between 2005 and the approval year of the first estimated plan (see "Analysis of Apulian and Sicilian GCoM signatories" section, Table 4), while the period after that is between the year following the plan approval and 2022. In addition, with the establishment of the new Apulian province of Barletta-Andria-Trani in June 2009, 2010 was chosen as the starting year for the period before the plan approval for this province, due to the greater quantity and uniformity of available data.

Table 4 Most common SEAP or SECAP approval year by province in the Apulia and Sicily regions

Region	Province	Most common SEAP/SECAP approval year
Apulia	Bari	2015
	Barletta-Andria-Trani	2013
	Brindisi	2014
	Foggia	2011
	Lecce	2013
	Taranto	2014
Sicilia	Agrigento	2015
	Caltanissetta	2015
	Catania	2015
	Enna	2015
	Messina	2015
	Palermo	2015
	Ragusa	2015
	Siracusa	2015
	Trapani	2015

For the analysis of CO_2 emissions associated with electricity, the source data were taken from the electricity consumption of the provinces of Apulia and Sicily from the TERNA database for the period 2000–2022, as shown in Table 1 in Chapter 2 of this article. Consumption was divided by sector: residential, industrial, agricultural and services.

Within the scope of this study, only electricity consumption in the service and residential sectors were considered, as they correspond to the key CoM sectors: tertiary, municipal and residential. These sectors are central to the actions taken by CoM local member governments to reduce CO_2 emissions.

Once electricity consumption is determined, the corresponding emissions are calculated by multiplying this consumption by the electricity-specific emission factor.

Furthermore, in this study, it was deemed appropriate to exclude local energy production from renewable sources and focus exclusively on energy consumption from nonrenewable sources. This approach provided a clearer and more direct view of GHG emissions associated with energy consumption and allows for a more accurate analysis over time. In light of the above, the emission factor for electricity consumption used to calculate the CO_2 emissions in the provinces of Apulia and Sicily for the period 2005–2022 is assumed to be equal to the NEEFE.

Specifically, the value provided by the JRC for Italy in 2005 (the starting year of the period analyzed in this study) is employed and, as recommended by the JRC, is maintained constant.

Subsequently, CO_2 emissions related to the use of natural gas and petroleum products at the provincial level in the regions of Apulia and Sicily are analyzed. In this examination, only consumption related to the sectors identified as key by the CoM guidelines are considered. These sectors include the residential sector, the service sector, public transportation, and private transportation, while sectors outside municipal jurisdiction, such as industries regulated by the Emissions Trading Scheme (ETS) and transit routes such as rural roads and highways, were excluded.

As shown in Table 1 in Chapter 2 of this article, consumption data were obtained from the archive provided by the MASE. This archive provides the Petroleum Bulletin, a dossier compiled with data collected between 2003 and 2024 on petroleum products through the SISEN platform. Specifically, datasets on provincial consumption of gasoline (ordinary network), diesel fuel (ordinary network), heating oil, fuel oil, automotive LPG, and combustion LPG documented in the regions of Apulia and Sicily from 2005 to 2022 were are used.

In addition, the MASE offers an assortment of data on imports, consumption (both provincial and regional), and natural gas balances. In this study, only consumption related to the "Distribution Network" in the regions under study is considered. This term refers to the use of natural gas as a fuel for residential, commercial or other purposes that require supply through the gas distribution network. These applications may include domestic heating, culinary uses, commercial use in restaurants and stores, and other similar uses.

Subsequently, to calculate the CO_2 emissions associated with the consumption of the above petroleum products and natural gas, simply multiply these consumptions by the corresponding emission factors related to fossil fuel combustion, according to the IPCC methodology.

In this way, it is possible to obtain the CO_2 emissions associated with the consumption of gasoline, diesel, LPG and natural gas in the provinces of the Apulia and Sicily regions during the period 2005–2022.

This analysis revealed a reduction in total emissions of 12.1% for Apulia and 21.2% for Sicily. In addition, Fig. 4 shows trends in CO_2 emissions (expressed in tons) at the provincial level (Fig. 5).

For comprehensiveness, CO_2 emissions per capita are also considered. Provincial demographic changes over the same period considered are analyzed using datasets provided by ISTAT, which report resident population as of January 1. The demographic analysis showed a slight decrease in resident population, 3.1% in Apulia and 3.0% in Sicily, respectively.

Subsequently, CO_2 emissions per capita were calculated: over the period under consideration (2005–2022), there was a reduction from 2.94 to 2.66 tons of CO_2 per capita in Apulia and from 2.71 to 2.14 tons in Sicily (a decrease of 9.3% and 21.2%, respectively). These reductions are consistent with the changes in total CO_2 emissions calculated above.

At the provincial level, trends in per capita emissions in the regions of Apulia and Sicily are shown in Figs. 6 and 7, respectively. Again, it can be seen that per capita emissions decreased in most provinces in the sectors and over the period considered, confirming what has been observed for total emissions.

Assessment of the CoM effectiveness

This section collects and compares data from the two previous analyses regarding the prevalence of action plans in the provinces of the Apulia and Sicily regions and their respective CO_2 emissions. Specifically, the first analysis determined the percentages of municipalities and population covered by at least one action plan, broken down by province. In addition, the years in which the first plan approval by municipalities occurred most frequently are identified, allowing the period 2005–2022 to be divided into two distinct phases: the one before and the one after SEAP or SECAP approval by the municipal councils. The second analysis provided data on total and per capita CO_2 emissions for the provinces considered over the 2005–2022 period. Subsequently, by implementing the results of the analysis with the pre- and post-approval periods of SEAP or SECAP, it is possible to preliminarily assess the impact of CoM in the territories of the considered regions by calculating the percentage changes related to total and per capita CO_2 emissions.

However, the periods analyzed vary by province, making the data not directly comparable in

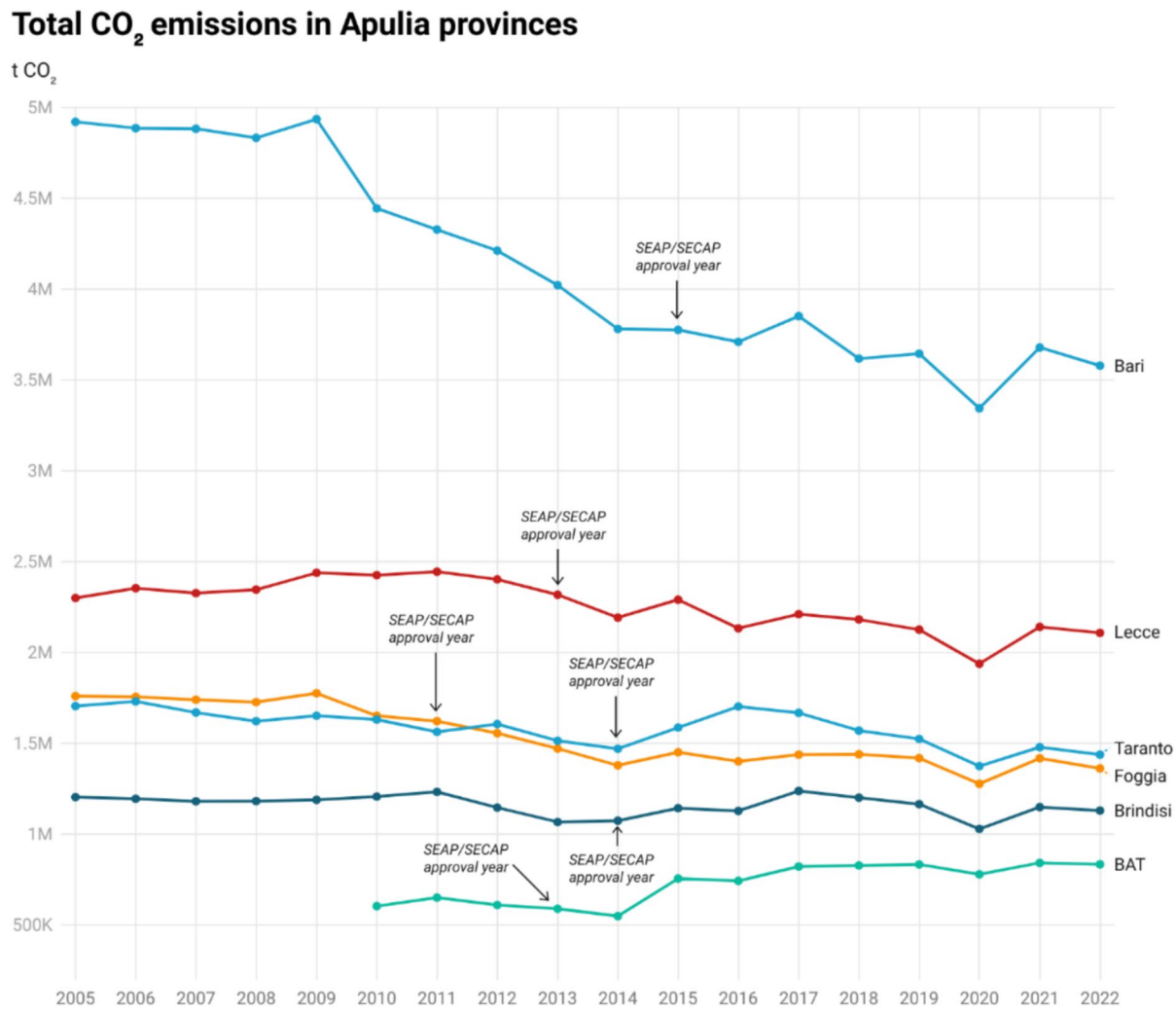

Fig. 4 Total CO_2 emissions in the province of Apulia (Unit of Measurement: t CO_2)

absolute terms. To overcome this problem and ensure a more accurate and comparable analysis across provinces, the CAGR of total and per capita CO_2 emissions is calculated. The CAGR is particularly useful in this context because it normalizes the change in emissions on an annual basis, taking into account differences in the duration of the pre- and post-SEAP/SECAP periods between provinces. This method makes it possible to analyze the average annual variation in emissions, regardless of the length of the period considered, making the data comparable. In summary, CAGR allows for a more fair and consistent assessment of the impact of plans on CO_2 emissions, avoiding distortions due to the different length of observation periods between provinces.

Table 5 summarizes the results obtained. In particular,

- **Δ (%)** is the percentage change in total and per capita CO_2 emissions between the pre-SEAP/SECAP and post-SEAP/SECAP periods;
- **CAGR (%)** is the compound annual growth rate, which measures the average annual change in CO_2 emissions over the observation period.

However, as mentioned in the previous chapters, following the establishment and activation of

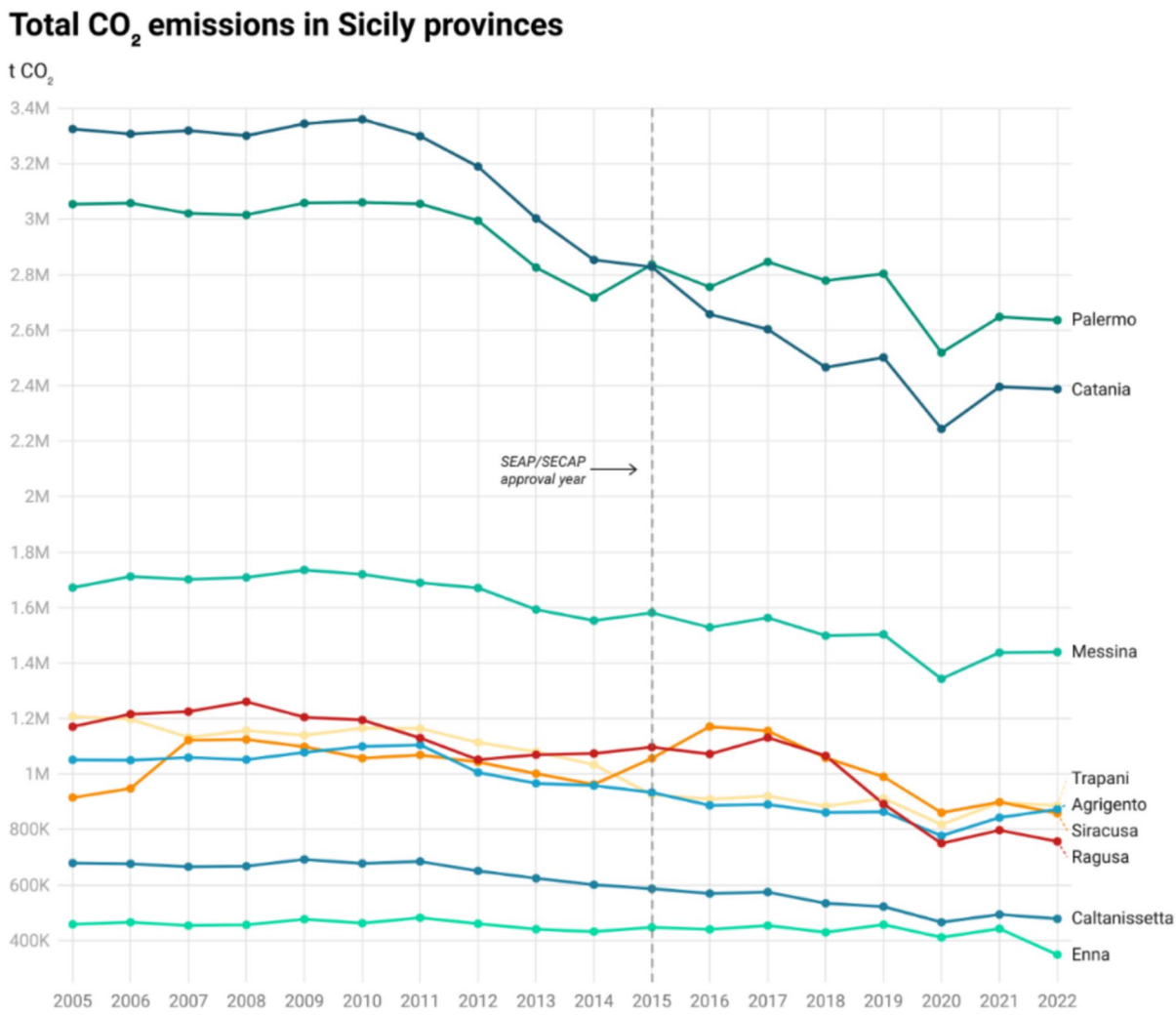

Fig. 5 Total CO_2 emissions in the province of Sicily (Unit of Measurement: t CO_2)

the new province of Barletta-Andria-Trani (BAT) in June 2009, there are anomalous values in the period following the approval of plans, both in terms of percentage changes and the annual growth rate of CO_2 emissions. For clarity, the cells in question are highlighted in red in the table above.

Analyzing the changes in emissions (Δ) resulted that:

- In Apulia, all provinces, with the exception of Lecce, experienced a significant reduction in total and per capita emissions in the pre-SEAPs/SECAPs period. However, in the period prior to the approval of the plans, apart from the anomaly observed in the Province of Barletta-Andria-Trani, a moderate decrease in total emissions is observed in all Apulian provinces and a reduction in per capita emissions only in the provinces of Bari, Foggia and Taranto. This indicates a positive impact, with a marginal improvement after the plans are approved.
- In Sicily, with the exception of the province of Syracuse, there is a substantial reduction in both total and per capita emissions in the period before the plans were approved (in this case, in addition to the province of Syracuse, the province of Enna is also included). In the period following the approval of the plans, there is a marked improvement in the reduction of total

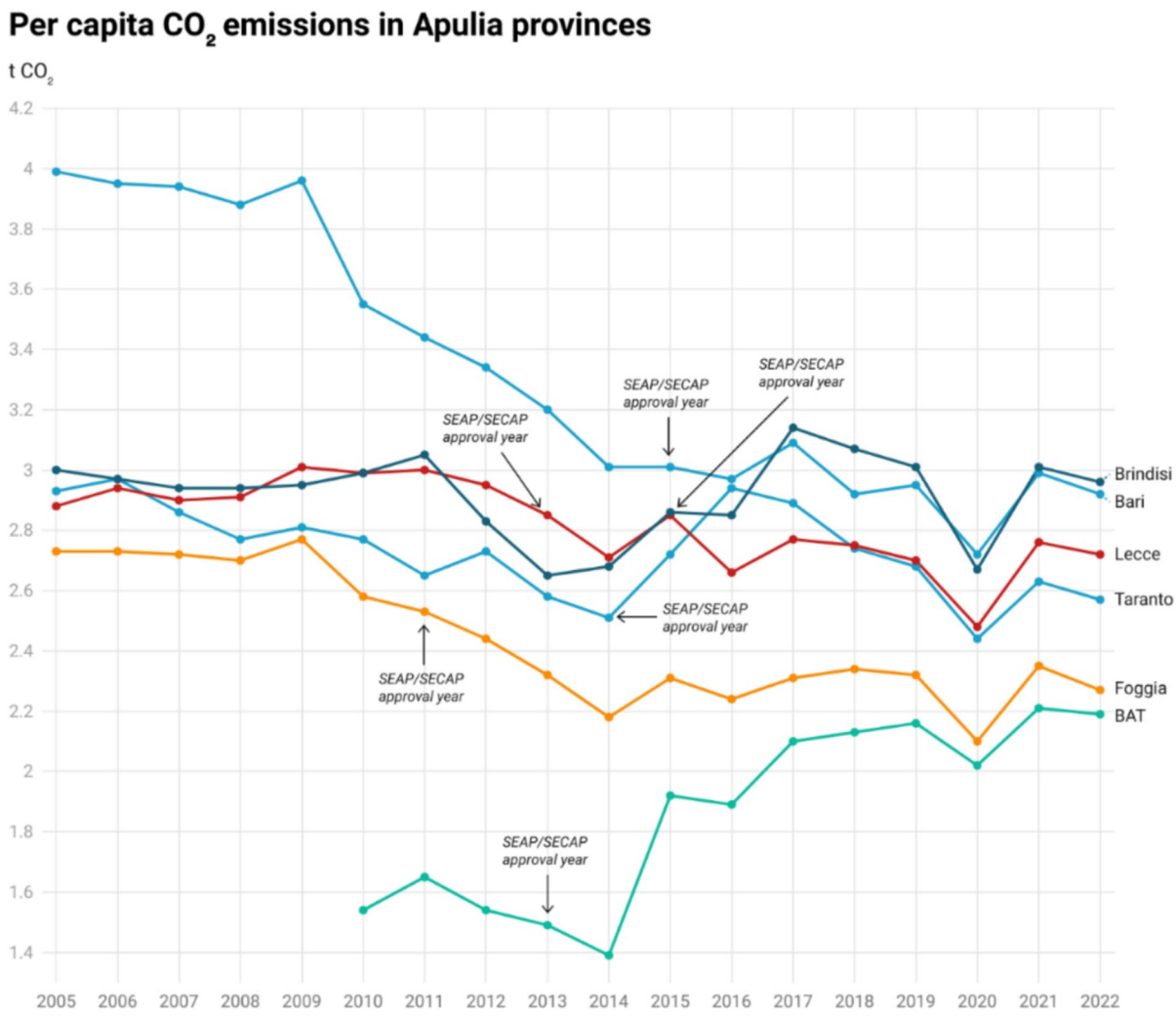

Fig. 6 Per capita CO_2 emissions in the province of Apulia (Unit of Measurement: t CO_2)

and per capita emissions in the provinces of Caltanissetta, Catania, Enna, Ragusa and Syracuse, suggesting that the implementation of the plans has led to tangible benefits. In the provinces of Agrigento, Messina, Palermo and Trapani, on the other hand, the improvement in total emissions is more moderate, with a similar trend in per capita emissions, except in the provinces of Agrigento and Trapani.

– Finally, an analysis of the compound annual growth rate (CAGR) reveals the following: in Apulia, in the period prior to the approval of the plans, there is an annual decrease in total emissions in all provinces, with the exception of Lecce, where the rate is slightly positive. As for per capita emissions, the rate is negative in all Apulian provinces. In the period prior to the approval of the plans at the provincial level, the CAGR identifies a decrease in total emissions in all provinces, with the exception of the Province of Barletta-Andria-Trani (BAT), which shows an anomaly. Similarly, a negative rate is observed for per capita emissions, with the exception of the provinces of Brindisi and Lecce, where a slight annual growth is found.
– In Sicily, in the period prior to plan approval, most provinces show an annual decrease in total and per capita emissions. Exceptions are the province of

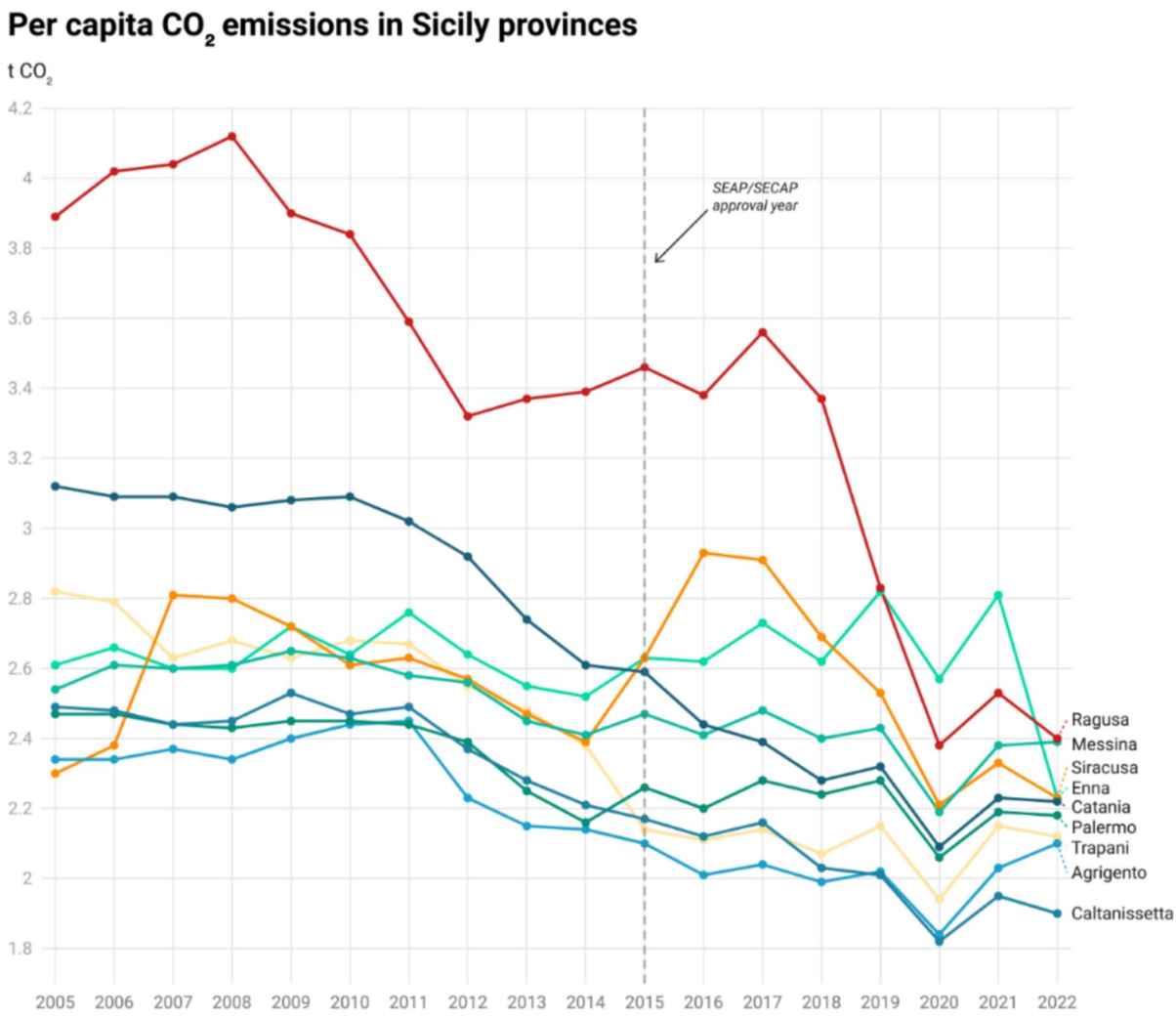

Fig. 7 Per capita CO_2 emissions in the province of Sicily (Unit of Measurement: t CO_2)

Table 5 Summary of results

Region	Province	TOTAL CO_2 EMISSIONS				PER CAPITA CO_2 EMISSIONS			
		Δ		CAGR		Δ		CAGR	
		pre-SEAP/SECAP	post-SEAP/SECAP	pre-SEAP/SECAP	post-SEAP/SECAP	pre-SEAP/SECAP	post-SEAP/SECAP	pre-SEAP/SECAP	post-SEAP/SECAP
Apulia	Bari	-23,3%	-3,5%	-2,6%	-0,6%	-24,5%	-1,7%	-2,8%	-0,3%
	BAT	-2,4%	51,8%	-0,8%	5,4%	-2,8%	57,1%	-0,9%	5,8%
	Brindisi	-10,8%	-1,1%	-1,3%	-0,2%	-10,8%	3,6%	-1,3%	0,5%
	Foggia	-7,9%	-12,5%	-1,4%	-1,3%	-7,3%	-6,7%	-1,3%	-0,7%
	Lecce	0,8%	-3,8%	0,1%	-0,5%	-1,0%	0,3%	-0,1%	0,0%
	Taranto	-13,8%	-9,4%	-1,6%	-1,4%	-14,1%	-5,7%	-1,7%	-0,8%
Sicilia	Agrigento	-11,2%	-1,6%	-1,2%	-0,3%	-10,5%	4,4%	-1,1%	0,7%
	Caltanissetta	-13,6%	-16,0%	-1,4%	-2,9%	-12,9%	-10,3%	-1,4%	-1,8%
	Catania	-15,0%	-10,2%	-1,6%	-1,8%	-17,1%	-9,0%	-1,9%	-1,6%
	Enna	-2,4%	-20,8%	-0,2%	-3,8%	0,7%	-14,9%	0,1%	-2,7%
	Messina	-5,4%	-5,8%	-0,6%	-1,0%	-3,0%	-0,8%	-0,3%	-0,1%
	Palermo	-7,1%	-4,3%	-0,7%	-0,7%	-8,5%	-1,0%	-0,9%	-0,2%
	Ragusa	-6,3%	-29,4%	-0,7%	-5,6%	-11,1%	-29,1%	-1,2%	-5,6%
	Siracusa	15,5%	-26,7%	1,4%	-5,0%	14,2%	-24,1%	1,3%	-4,5%
	Trapani	-23,3%	-2,5%	-2,6%	-0,4%	-24,1%	0,8%	-2,7%	0,1%

Syracuse, which shows growth in both total and per capita emissions, and the province of Enna, which shows an increase only in per capita emissions. In the period before the plans, a decrease in total emissions is observed in all Sicilian provinces. The same trend is seen in per capita emissions, with the exception of the provinces of Agrigento and Trapani, which show a positive growth rate.

After analytically examining total and per capita emissions through the measurement of changes and annual growth rate in the periods before and after the approval of SEAPs or SECAPs by the municipalities at the provincial level, these results are compared with the distribution of plans in the different provinces. The objective is to identify a possible correlation between the obtained variables. For this purpose, Pearson's correlation coefficient is used, which allows quantification of the relationship between the variables under consideration, providing indications of the strength and direction of that relationship. A negative correlation would suggest a significant impact of plans in reducing emissions, while a positive correlation may indicate the need to explore additional factors or methodologies to better understand the effectiveness of the plans in different provinces. In addition, outliers found are excluded from the calculation of the correlation coefficient in order to ensure a more accurate and representative estimate of the relationship between the variables analyzed.

The variables compared using Pearson's correlation coefficient are defined as follows:

- Variable 1 represents the distribution of action plans at the provincial level, expressed both in terms of the number of municipalities and the population size (population of municipalities) covered.
- Variable 2 corresponds to total and per capita emissions, measured through changes (Δ) and CAGR over the period before the plans were approved. In order to standardize this period among the different provinces, in the specific case of changes in emissions, the interval considered was set between the year after 2015, the year in which the largest number of plan approvals were recorded in Apulia and Sicily, and 2022.

Table 6 Pearson correlation coefficients for the Apulia region

Pearson correlaton coefficients (r): Apulia region		Variable 2			
		Total CO_2 emissions		Per capita CO_2 emissions	
		Δ (2016–2022)	CAGR (post-SEAP/SECAP)	Δ (2016–2022)	CAGR (post-SEAP/SECAP)
Variable 1	Municipalities with approved action plans by province [%]	0.52	− 0.08	− 0.05	− 0.02
	Population covered by action plans by province [%]	0.76	0.28	0.04	0.23

Table 7 Pearson correlation coefficients for the Sicily region

Pearson correlaton coefficients (r): Sicily region		Variable 2			
		Total CO_2 emissions		Per capita CO_2 emissions	
		Δ (2016–2022)	CAGR (post-SEAP/SECAP)	Δ (2016–2022)	CAGR (post-SEAP/SECAP)
Variable 1	Municipalities with approved action plans by province [%]	− 0.47	− 0.48	− 0.51	− 0.49
	Population covered by action plans by province [%]	0.02	0.00	− 0.06	− 0.04

As a result, eight combinations of variables are obtained, each of which produced a correlation coefficient by region (Tables 6 and 7).

Table 6 presents the correlation coefficients for the provinces in Apulia, based on the combinations of variables 1 and 2, with the following main results:

- Municipalities with approved action plans and total CO_2 emissions: A moderate positive correlation (r = 0.52) is observed for changes in emissions, while the correlation is weakly negative for CAGR (r = − 0.08). This indicates that while inducing a slight annual reduction in emissions, provinces with greater participation of municipalities in the plans experienced a moderate increase in total emissions during the period under consideration.
- Municipalities with approved action plans and per capita CO_2 emissions: The correlation is almost zero for both changes (r = − 0.05) and CAGR (r = − 0.02). This suggests that municipalities'participation in the plans did not have a significant impact on per capita emission reduction.
- Population covered by action plans and total CO_2 emissions: Here the correlation is more pronounced, with positive values for both changes in emissions (r = 0.76) and CAGR (r = 0.28). This result implies that in provinces where a higher percentage of population was covered by plans, the expected benefits in terms of annual emission reductions and decreases were not satisfactorily achieved.
- Population covered by action plans and per capita CO_2 emissions: The correlation between population covered and changes in per capita emissions is almost zero (r = 0.04), while the correlation with CAGR is weak (r = 0.23). This suggests that population participation did not have a significant impact on the reduction of per capita emissions, with limited annual growth in emissions. This could indicate that other factors, such as plan quality or local resources, have a greater influence on the results.

Table 7 shows the correlation coefficients for the provinces in Sicily, with the following main results:

- Municipalities with approved action plans and total CO_2 emissions: A significant negative correlation is observed for both changes in emissions (r = − 0.47) and CAGR (r = − 0.48). This indicates that in the provinces with greater adherence to the plans there was a more pronounced reduction and a significant annual decrease in total emissions, confirming the effectiveness of SEAPs/SECAPs in the Sicilian context.
- Municipalities with approved action plans and per capita CO_2 emissions: Again, a negative correlation is observed for both the changes (r = − 0.51) and the CAGR (r = − 0.49), indicating that greater adherence to the plans is associated with a reduction in per capita emissions and an annual rate of decrease in them.
- Population covered by action plans and total CO_2 emissions: In this case, the correlation is very weak or almost zero, both for variance (r = 0.02) and CAGR (r = 0.00). This suggests that the percentage of population covered did not show a significant correlation with total emission reduction or annual decrease, indicating the possible influence of other factors such as plan quality and local resources.
- Population covered by action plans and per capita CO_2 emissions: Again the correlation is weakly negative, suggesting a less significant relationship for both changes and annual growth rate of per capita emissions. This could indicate that the size of the population covered has little impact on the improvement in per capita emissions.

Conclusion and policy implications

This study analyzed the effectiveness of CoM in the Italian regions of Apulia and Sicily, with a focus on CO_2 emissions at the provincial level. This initiative involved local authorities in a voluntary agreement to achieve ambitious goals, including reducing CO_2 emissions and adapting to climate change. Through the CoM, the signatories engaged in a collective approach to promote energy and environmental sustainability, contributing to EU energy and climate goals.

The analysis of CoM signatories in the two regions, using data from the MyCovenant platform, showed significant results. Sicily emerged as a leading region, with 87.7% of municipalities adhering to the initative, covering 92.8% of the population, indicating a widespread participation and strong commitment of local authorities and citizens in the fight against climate change. In contrast, in Apulia, the

adherence rate is 45.5%, but still covers 46.4% of the population, demonstrating good participation, although lower than in Sicily.

Analysis of CO_2 emissions between 2005 and 2022 showed a significant reduction in both regions: Apulia (− 12.1%) and Sicily (− 21.2%). These results suggested that local policies have had a positive impact, with per capita emissions decreasing by 9.3% in Apulia and 21.2% in Sicily. Despite the decrease in emissions, Sicily showed a more effective approach, suggesting that the local context may have facilitated better results.

This research focused on energy consumption from nonrenewable sources, isolating the impact of fossil sources on emissions. The findings are based on an analysis of the period from 2005 to 2022, divided into pre- and post-approval phases of the action plans (SEAPs or SECAPs) by the municipal councils, to observe changes in emissions. In Apulia, the annual reduction in total emissions in the provinces most adherent to the plans was modest, with an overall increase in emissions. This suggests that although there was a positive effect, it was not enough to offset other factors that contributed to the increase in emissions. In Sicily, on the other hand, provinces with greater adherence to the plans experienced more significant reductions in emissions. Negative correlations between annual growth rates and changes in emissions indicate a positive impact of plans on regional environmental performance. However, population involvement, understood as a demographic dimension, did not show a strong impact, suggesting that factors such as the quality of plans or available resources are more crucial to success.

In summary, while the CoM generated improvements in the provinces analyzed, the results are variable. Some municipalities have seen significant progress, while others have seen increases in emissions. Regional differences require targeted policies to ensure that all areas benefit from the opportunities provided, highlighting the need for stronger support and coordination policies to maximize the effectiveness of climate mitigation strategies at the local level.

This paper proposed a methodological framework for developing provincial and regional CO_2 emission monitors based on the analysis of SEAPs and SECAPs. It is applied a single methodology with official and uniform databases, instead of self-declared data by municipalities, involving CTCs as key players in monitoring and evaluating the implementation of these plans. In addition to providing technical support, CTCs can conduct periodic assessments of the status of plan implementation at the provincial and regional levels, ensuring alignment between local policies and national and international emission reduction targets. The implementation of systematic and standardized monitoring of CO_2 emissions at the provincial and regional levels can be a key step toward achieving energy and climate sustainability goals. Through the use of a unified methodology and official databases, together with the active support of CTCs, it will be possible to improve the effectiveness of action plans, ensuring a significant impact in the fight against climate change. This approach will not only improve the management of environmental policies, but also help build greater public awareness and participation in decision-making processes regarding sustainability.

A further development of this study involves analyzing the impact of the role of CTCs across the entire national territory, with a detailed assessment of their influence on the implementation of technical and financial support strategies for the development and execution of signatories'plans within their respective geographical areas. Additionally, the study will examine their contribution to engaging a greater number of municipalities in the initiative, with the aim of supporting the achievement of local targets for greenhouse gas emission reduction, energy savings, and renewable energy production.

Authors'contributions Paolo Maria Congedo: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision. Luca Colazzo: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. Marina Bonomolo: Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. Cristina Baglivo: Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision.

Funding Open access funding provided by Università del Salento within the CRUI-CARE Agreement. No funding received.

Data availability All data generated or analysed during this study are included in this published article.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Human ethics Not applicable.

Competing interests No financial and non−financial competing interests.

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