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Article

Municipal Carbon Footprint and Water Infrastructure: A Comparative Assessment of Emission Reduction Plans in Three Greek Municipalities

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Abstract

This study comparatively assesses the Municipal Emission Reduction Plans (MERPs) of Spetses, Platania, and Souli, emphasizing the role of water infrastructures in shaping municipal carbon footprints. Using secondary data extracted from the officially approved MERPs, a descriptive inter-municipal comparative analysis was conducted based on demographic variables and sectoral and total greenhouse gas emissions for the base year 2019 and the reference year 2023. Percentage changes in population and sector-specific emissions were calculated at the municipal level and subsequently compared across the three municipalities. The analysis covers municipal buildings and lighting, transport, waste and wastewater management, water and irrigation distribution systems, while also presenting the emission reduction actions and projected 2030 targets documented in the respective plans. The results reveal substantial inter-municipal variations, driven primarily by water supply models, geomorphology, altitude differences, network extent, and the distribution of service responsibilities. In Platania and Souli, water supply and irrigation constitute among the most energy-intensive sectors, contributing significantly to total emissions, whereas in Spetses the externalized water supply model alters the emission structure. The findings indicate that water infrastructure can represent a significant emission source and that effective mitigation depends on spatially tailored strategies considering geomorphological, operational, and administrative characteristics.

Keywords: water infrastructure; water-energy nexus; climate neutrality; municipal emission reduction plans; municipal carbon footprint

1. Introduction

One of the most important challenges that modern societies must face is the climate crisis; both the European Union and its Member States are committed to ambitious greenhouse gas emissions reduction targets over the coming decades. The European goal of achieving climate neutrality by 2050 defines a holistic framework of action with interim goals for reducing net anthropogenic greenhouse gas emissions in comparison to the 1990 levels. On a national level, having incorporated the European goal, Greece with the National Climate Law attempts to fulfill the interim targets of reducing greenhouse gas emissions by 55% by 2030 and by 80% until 2040 [1,2].

The National Climate Law (L. 4936/2022) aims to establish a coherent framework to improve adaptive capacity and climate resilience in Greece and ensure a gradual transition to a climate-neutral society by 2050, in an environmentally sustainable, socially equitable, and economically efficient manner. The mitigation and adaptation strategies developed in L. 4936/2022 address all levels of

governance and economic sectors. Notably, Article 16 introduces the so-called Municipal Emission Reduction Plans (MERPs). The article requires each local authority (municipality) in Greece to develop a MERP and prepare yearly technical progress reports on the implementation progress of the plan. This obligation is reinforced by the strategic role assigned to municipalities through the National Energy and Climate Plan (NECP), as well as by the participation of many municipalities in the European Covenant of Mayors for Climate and Energy. Local Climate and Energy Plans aim to develop integrated strategies for mitigating greenhouse gas emissions, enhancing energy efficiency, and transitioning toward resilient and sustainable urban and regional systems. Under this framework, Municipal Emission Reduction Plans (hereafter MERPs) are being drawn up, through which each municipality submits reports and monitors greenhouse gas emissions on an annual basis, planning and anticipating minimum reduction goals of 10% by 2025 and 30% by 2030, taking 2019 as the base year [1,2].

In this context, municipalities manage critical infrastructure and services that directly shape their carbon footprint. These include municipal buildings, lighting, transport, solid waste and wastewater management, as well as water supply and irrigation systems [3–6]. While existing climate planning often prioritizes buildings and transport as dominant emission sectors, attention is being given in this study to water-related infrastructure, recognizing that water supply, irrigation, and wastewater systems can be highly energy-intensive due to pumping requirements, treatment processes, pressure regulation, and network losses [7–12]. The energy demand of such systems is strongly influenced by geomorphology, altitude differences, spatial dispersion of settlements, and the technical organization of services, resulting in significant variability between municipalities [12,13].

This study, using official records and data from three Greek municipalities, the Municipalities of Spetses, Platania, and Souli, proceeds to a comparative assessment of their characteristics, their carbon footprint, and its reduction between the base year 2019 and the reference year 2023, as well as a comparative assessment of the proposed actions to reduce emissions and increase greenhouse gas removals by 2030. Emphasis is placed on examining the contribution of water infrastructure to total municipal emissions and on evaluating how local structural characteristics influence the energy intensity of water-related services.

The inventory and comparative assessment of the carbon footprint, along with the proposed mitigation actions, provide the basis for targeted interventions and rational energy management. Highlighting the diversity of proposed actions among municipalities emphasizes the need to approach climate neutrality through spatially adapted and evidence-based measures. The findings indicate that water supply and irrigation systems, often underestimated in local climate discourse, may constitute significant emission sources, especially in municipalities with pumping-dependent networks. Consequently, integrating water infrastructure into municipal climate planning emerges as a prerequisite for achieving climate neutrality, strengthening local resilience, and ensuring coherence between environmental, energy, and spatial policies [2,3,5,6].

2. Materials and Methods

2.1. National Regulatory Framework for Municipal Emission Reduction Plans in Greece

At the national level, Greece has incorporated the European objective of climate neutrality into its legal framework through the National Climate Law (Law 4936/2022). The law establishes binding interim greenhouse gas (GHG) emission reduction targets of 55% by 2030 and 80% by 2040 compared to 1990 levels, with the long-term objective of achieving climate neutrality by 2050 [1,2].

Law 4936/2022 establishes an integrated policy framework for climate change mitigation and adaptation that applies across governance tiers and economic sectors. Its objective is to strengthen adaptive capacity and resilience while facilitating a phased transition to climate neutrality in a way that is environmentally sustainable, socially equitable, and economically efficient. Within this

legislative framework, Article 16 introduces the Municipal Emission Reduction Plans (MERPs) as a mandatory instrument of local climate governance [1,2].

According to Article 16, each first-level Local Government Organization (municipality) is required to prepare a Municipal Emission Reduction Plan and to submit annual technical progress reports documenting the implementation of the plan and the evolution of GHG emissions. The MERPs must include a quantified emissions inventory using 2019 as the base year and define minimum emission reduction targets of 10% by 2025 and 30% by 2030 [1,2].

The preparation, implementation and monitoring of MERPs are functionally linked to the National Energy and Climate Plan (NECP) and are consistent with commitments undertaken by municipalities participating in the European Covenant of Mayors for Climate and Energy. In addition, MERPs must take into consideration the municipal Building Energy Renovation Plan (BERP) as introduced with Article 7 of L. 4342/2015 [1,2,14]. The institutional framework prescribes standardized sectoral categorization, a uniform reporting structure, and fixed temporal reference points, ensuring methodological consistency and comparability of municipal emission inventories across the national territory.

2.2. Emission Accounting Framework Applied in the Municipal Emission Reduction Plans in Greece

The carbon footprint of First-Level Local Government Organizations, within the framework of the preparation of Municipal Emissions Reduction Plans (MERPs), was calculated in accordance with the provisions of Article 16 of the National Climate Law (Law 4936/2022, Government Gazette 105A)[2].

The methodology designed for the quantification of greenhouse gas (GHG) emissions and for the preparation of the Municipal Emissions Reduction Plans was based on the following standards:

1. ISO 14064-1:2018 Greenhouse gases – Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals.
2. Greenhouse Gas Protocol, WRI: Global Protocol for Community-Scale Greenhouse Gas Inventories (GPC): An Accounting and Reporting Standard for Cities, Version 1.1.
3. Guidelines of the Intergovernmental Panel on Climate Change (IPCC) for National Greenhouse Gas Inventories.

ISO 14064-1:2018 is a standard developed by the International Organization for Standardization (ISO) and provides guidelines for the quantification, monitoring, and reporting of greenhouse gas emissions. The standard establishes the framework for measuring the carbon footprint and tracking the temporal evolution of emissions. The GHG Protocol is a set of internationally recognized standards and guidelines for the calculation and reporting of greenhouse gas (GHG) emissions. The guidelines of the Intergovernmental Panel on Climate Change (IPCC) constitute a set of internationally recognized methodologies for estimating greenhouse gas (GHG) emissions and removals, as well as for compiling emission inventories from various sectors and sources. The IPCC guidelines provide a standardized and transparent approach for countries to report greenhouse gas emissions and removals and to monitor progress toward climate change mitigation targets. These guidelines are regularly updated to reflect advances in scientific knowledge, changes in national circumstances, and evolving policy needs[2].

To enable comparability among different greenhouse gases, emissions are expressed as carbon dioxide equivalent (CO₂eq). For this purpose, specific coefficients—Global Warming Potentials (GWPs)—are used to convert other greenhouse gases into CO₂eq, reflecting the amount of heat each gas can absorb relative to CO₂[2].

For the calculation of the municipalities' carbon footprint, the computational tool developed by the Ministry of Environment and Energy (YPEN) was used, and total carbon dioxide equivalent emissions (CO₂eq) were calculated for the years 2019 (base year) and 2023 [2].

2.3. Description of the Analytical Dataset

The present study is based exclusively on secondary data extracted from the officially approved Municipal Emission Reduction Plans (MERPs) of three Greek municipalities, the Municipalities of Spetses, Platania, and Souli.

From each MERP, both descriptive and quantitative data were collected. The dataset includes descriptive territorial and socio-economic variables for each municipality in order to support the comparative assessment. These comprise territorial extent (km²), geomorphological characteristics (lowland, semi-mountainous, mountainous areas; altitude ranges), climatic classification, and economic profile (primary, secondary, and tertiary sector dominance). Demographic data were also extracted, including permanent population figures from the 2011 and 2021 Hellenic Statistical Authority (ELSTAT) censuses and the corresponding percentage change in population. Information regarding infrastructure organization was included, such as the structure of water supply systems (boreholes, pumping stations, reservoirs, tanker supply where applicable), wastewater treatment facilities, landfill arrangements, and the size and fuel type of municipal vehicle fleets.

In addition to the above contextual variables, the quantitative dataset includes total municipal greenhouse gas emissions expressed in CO₂ equivalent (CO₂eq) for the base year 2019 and the reference year 2023, as well as sectoral emissions corresponding to: municipal buildings and lighting, municipal transport and fleet, solid waste and wastewater management, and water supply and irrigation systems.

Furthermore, the emission reduction actions and the projected percentage reduction targets for 2030, as documented in the respective MERPs, were presented as reported in the official plans. No recalculation, adjustment, or independent evaluation of the proposed measures were performed.

All variables were directly derived from the MERPs and related official statistical sources referenced therein. No additional external datasets were incorporated for the purposes of this study.

2.4. Descriptive Comparative Analysis

A descriptive comparative analysis was conducted based on the demographic variables, sectoral and total greenhouse gas emission data, and the officially documented emission reduction actions and projected 2030 reduction targets included in the Municipal Emission Reduction Plans (MERPs) of the three municipalities.

Initially, demographic evolution was examined through the calculation of percentage population change between the 2011 and 2021 census years for each municipality. The resulting values were subsequently compared in order to present inter-municipal demographic variation.

Percentage changes in sectoral greenhouse gas emissions, expressed in tn CO₂eq, were calculated for each municipality by comparing the base year 2019 with the reference year 2023. This calculation was performed separately for each sector of activity, including municipal buildings and lighting, municipal transport and fleet, solid waste and wastewater management, and water supply and irrigation systems.

Following the estimation of sector-specific percentage changes at the municipal level, the resulting variations were comparatively examined across the three municipalities in order to identify differences in emission dynamics and sectoral contribution patterns between 2019 and 2023.

In addition, total municipal carbon footprint variation was calculated by determining the percentage change in overall emissions between 2019 and 2023 for each municipality. These aggregate percentage changes were then compared across the three municipalities.

All calculations were based exclusively on officially reported values, and no modification of the original emission accounting methodology was undertaken.

3. Results

3.1. Comparative Overview of the Characteristics of the Municipalities Under Study

This chapter will provide a comparative presentation of the characteristics of the municipalities under study in terms of their extent, their geomorphological, economic, climatic and population

characteristics. The differences between municipalities are explained by the overall assessment of gas emissions, which, as this study shows, varies significantly. Factors that also influence greenhouse gas emissions include the morphology of the urban fabric, altitude, the size of the road network and the presence or absence of areas and tools that consume significant amounts of energy, but these are taken into account in the carbon footprint calculation process [2,4–6].

The Municipality of Spetses covers an area of 22.5 square kilometers, with a maximum length of 4 miles and a maximum width of 2.5 miles. In the case of the Municipality of Spetses, the geomorphology of the island is mainly characterized as flat to gently hilly, as it is crossed by mountain ranges with the highest peak being Profitis Ilias at 245 meters. The limited variations in altitude affect both the spatial development of the settlement and the patterns of transportation and energy consumption. As a particularly popular and frequent tourist destination, the local economy relies heavily on tourism, which is the main source of income for the municipality's residents. Economic activity is complemented by shipping, fishing, and small-scale commercial and craft activities.

The climate of the Municipality of Spetses is classified as Mediterranean, with mild, wet winters and hot, dry summers. According to the 2011 census by ELSTAT, the permanent population of the Municipality of Spetses was 4,027, while in the 2021 census, the permanent population decreased to 3,748 [15,16]. This decline resulted in a negative change of 6.93%.

Table 1. Alteration of population in the Municipality of Spetses between 2011 and 2021.

Municipality	Population 2011	Population 2021	Percentage Change
Municipality of Spetses	4,027	3,747	-6.93%

The Municipality of Platania in Crete covers a much larger area than the Municipality of Spetses, reaching 495.43 square kilometers. There is a striking variety of geomorphology, as lowland, semi-mountainous, and mountainous areas coexist, while the municipality has an extensive coastline along northern Crete. The local economy is mainly based on agriculture, trade, and tourism, with the latter playing a particularly important role due to the intense tourist development of the coastal zone and its seasonality.

The climate of the Municipality of Platania is also characterized as Mediterranean, with mild and wet winters and hot, dry summers. However, due to the presence of mountain masses in the southern part of the municipality, local climatic variations are observed, with lower temperatures and increased rainfall in the semi-mountainous and mountainous areas. According to the 2011 ELSTAT census, the permanent population was 16,874, while in 2021 it was 15,299 [15,16], meaning that the population decreased by 9.3%, as shown in the table below.

Table 2. Alteration of population in the Municipality of Platania between 2011 and 2021.

Municipality	Population 2011	Population 2021	Percentage Change
Municipality of Platania	16,874	15,299	-9.3%

The Municipality of Souli belongs to the Region of Epirus and is located at the southeastern end of the Regional Unit of Thesprotia. With a total area of 502.8 square kilometers, the Municipality of Souli is characterized by rugged and complex terrain, with a clear distinction between lowland, semi-mountainous, and mountainous areas. In its central and southern part lies the fertile plain of Paramythia, which is bordered to the south by the Acheron River and to the northwest by the area of Neochori, while to the east stands the Koryla mountain range, with a maximum altitude of 1,658 meters. The presence of the mountain masses has resulted in the formation of closed valleys and small drainage basins, which in some cases have limited drainage, leading to the formation of lakes and marshy areas. The economic profile of the Municipality of Souli is mainly characterized by the

primary sector. Agricultural activity dominates the lowland area of the Paramythia plain, while livestock farming is also important. The unique natural beauty of the area also creates conditions for mild tourism development, mainly of a natural and cultural nature.

The climate of the Municipality of Souli is classified as Mediterranean with continental influences, varying according to altitude. The lowland areas are characterized by hot summers and relatively mild winters, while the semi-mountainous and mountainous areas have lower temperatures and increased rainfall. The presence of mountain ranges contributes to the intensification of precipitation and the formation of microclimatic conditions. The total population of permanent residents in the municipality in 2011 was 10,063, while the 2021 census recorded a total of 8,759 permanent residents [15,16], i.e. a population decline of approximately 13.04%, as shown in the table below.

Table 3. Alteration of population in the Municipality of Souli between 2011 and 2021.

Municipality	Population 2011	Population 2021	Percentage Change
Municipality of Souli	10,063	8,759	-13.04%

In conclusion, it can be observed that the Municipality of Spetses has the smallest area compared to the Municipalities of Platania and Souli, which are significantly larger and more spatially extensive. The limited extent of the Municipality of Spetses is associated with relatively mild geomorphological characteristics and small altitudinal variations, in contrast to the Municipality of Platania and especially the Municipality of Souli, where there is intense geomorphological diversity, with the coexistence of lowland, semi-mountainous, and mountainous areas. The Municipality of Platania is characterized by the coexistence of coastal and mountainous zones, while the Municipality of Souli has a rugged terrain with closed valleys and mountain ranges that create unique natural and spatial conditions.

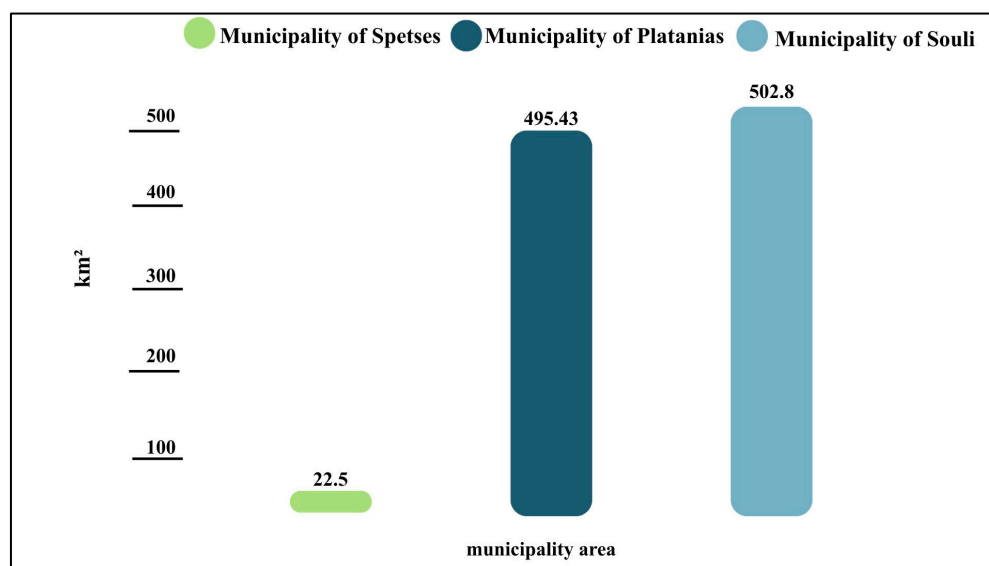


Figure 1. Comparative presentation of the area of the municipalities under study.

In terms of economic activity, the Municipality of Spetses is highly dependent on the tertiary sector, particularly tourism, while the Municipality of Platania has a mixed economic model, in which the primary sector, trade, and tourism coexist, mainly in the coastal zone. In contrast, the primary sector dominates in the Municipality of Souli, with agriculture and livestock farming as its main pillars, while tourism is mild and on a smaller scale.

Climatically, all three municipalities are classified as Mediterranean, but there are variations directly related to altitude and geomorphology. The Municipality of Spetses is characterized by mild

temperature fluctuations and dry, hot summers, while the Municipality of Platania experiences local climatic variations due to the presence of mountain ranges. In the Municipality of Souli, continental influences and rugged terrain lead to lower temperatures and increased rainfall in mountainous and semi-mountainous areas.

Finally, in terms of population characteristics, all three municipalities saw a decline in their permanent population between 2011 and 2021, with the decline being less pronounced in the Municipality of Spetses and more pronounced in the Municipality of Souli. Despite the significant differences between the municipalities, it is worth noting that the decline observed in all three is not greatly divergent, ranging from 7% to 13%, as shown in the diagram below.

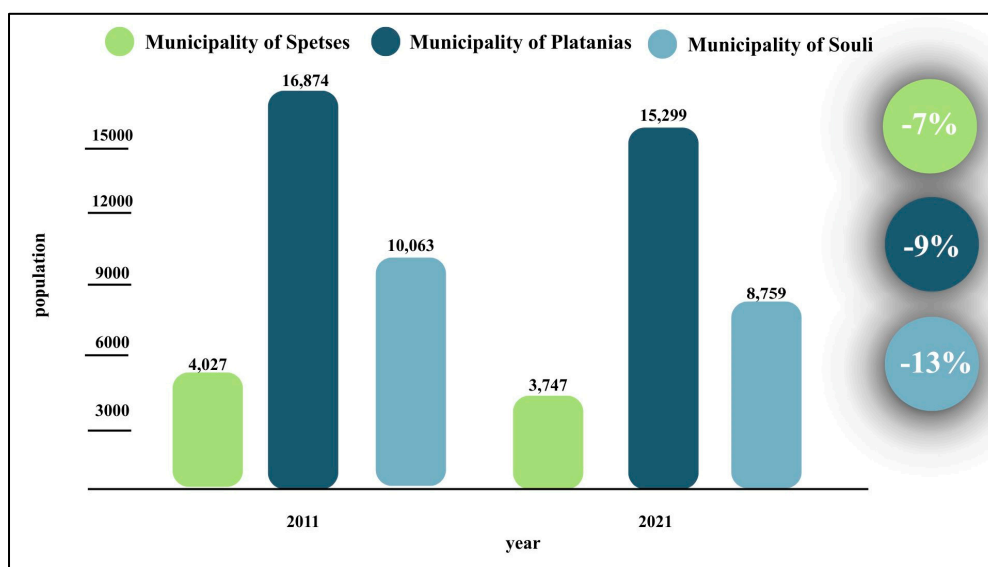


Figure 2. Comparative presentation of the alteration of the population between 2011 and 2021 of the municipalities under study.

3.2. Comparative Sectoral Carbon Footprint Analysis

3.2.1. Municipal Buildings and Lighting

According to the European Environment Agency, municipal lighting and buildings largely determine the overall carbon footprint of urban centers [4,14,17–20]. Therefore, the energy consumption of municipal buildings and lighting is one of the most critical sources of direct and indirect emissions at the local level, as municipalities manage many infrastructures with significant thermal and electrical requirements. The number, spatial distribution, and size of buildings all have an impact on the overall assessment of greenhouse gas emissions. More specifically, in order to achieve a significant reduction in energy consumption and, consequently, greenhouse gas emissions, as well as to provide the best possible experience for consumers, calculating the carbon footprint of municipal buildings and lighting is a cornerstone for achieving climate neutrality goals [4,5,14,17,19]. This chapter provides a comparative presentation of the analysis of data relating to municipal buildings and lighting in the Municipalities of Spetses, Platania and Souli, respectively, as well as the total greenhouse gas emissions produced during the base year 2019 and the reference year 2023, in tons of carbon dioxide equivalent (tn CO₂eq).

In the Municipality of Spetses, the heating of municipal buildings, but also municipal lighting, as was to be expected, was carried out exclusively using electricity, for the years 2019 and 2023. Total emissions for the base year 2019 were estimated at 138.13 tons of CO₂eq, while for 2023 the total amount increased to 160.26 tons of CO₂eq. Consequently, there was a 16.02% increase in total greenhouse gas emissions due to an increase in the use of electricity for municipal heating and lighting.

Table 4. Change in total CO₂eq emissions from municipal buildings and lighting in the Municipality of Spetses between 2019 and 2023.

Municipality	Base Year 2019	Reference Year 2023	Percentage Change
Municipality of Spetses	138.13 tn CO ₂ eq	160.26 tn CO ₂ eq	+16.02%

In the Municipality of Platania, the heating of municipal buildings for the years 2019 and 2023 was carried out using electricity and liquid diesel fuel, while municipal lighting, as expected, was carried out using electricity. Total emissions for the base year 2019 were estimated at 3,414.12 tons of CO₂eq, while for 2023 the total amount increased to 3,214.00 tons of CO₂eq. Consequently, there was a 5.86% reduction in total greenhouse gas emissions due to a decrease in the use of liquid diesel fuel and electricity for heating municipal buildings and lighting in the Municipality of Platania

Table 5. Change in total CO₂eq emissions from municipal buildings and lighting in the Municipality of Platania between 2019 and 2023.

Municipality	Base Year 2019	Reference Year 2023	Percentage Change
Municipality of Platania	3,414.12 tn CO ₂ eq	3,214.00 tn CO ₂ eq	-5.86%

In the Municipality of Souli, the heating of municipal buildings for the years 2019 and 2023 was carried out using both electricity and liquid diesel fuel, while municipal lighting, as expected, was carried out using electricity. Total emissions for the base year 2019 were estimated at 1,304.9 tons of CO₂eq, while for 2023, the total amount decreased to 955.18 tons of CO₂eq. Consequently, there was a 26.80% reduction in total greenhouse gas emissions due to a decrease in the use of liquid diesel fuel and electricity for heating municipal buildings and lighting in the Municipality of Souli.

Table 6. Change in total CO₂eq emissions from municipal buildings and lighting in the Municipality of Souli between 2019 and 2023.

Municipality	Base Year 2019	Reference Year 2023	Percentage Change
Municipality of Souli	1,304.90 tn CO ₂ eq	955.18 tn CO ₂ eq	-26.80%

The final total emissions between the three municipalities differ significantly, reflecting several distinct factors. These include the different sizes of each municipality's building stock and the varied characteristics of each location, such as population size and geography, which directly influence the final greenhouse gas emissions result. In the Municipality of Spetses, heating and lighting are provided exclusively by electricity, while in the Municipalities of Platania and Souli, electricity and liquid diesel fuel are used. In the Municipality of Spetses, the increase in electricity consumption led to an increase in total CO₂eq emissions. In the cases of the Municipalities of Platania and Souli, where the use of electricity and liquid diesel fuel decreased significantly, there was also a decrease in total CO₂eq emissions in the reference year 2023. This difference almost exclusively determines the reduction in total emissions. The Municipality of Spetses has the lowest total CO₂eq emissions. In contrast, the Municipality of Platania has the highest total CO₂eq emissions among the three municipalities in both the base year and the reference year.

Table 7. Presentation of the change in total CO₂eq emissions from municipal buildings and lighting in the municipalities under study between 2019 and 2023.

Municipality	Base Year 2019	Reference Year 2023	Percentage Change
Municipality of Spetses	138.13 tn CO ₂ eq	160.26 tn CO ₂ eq	+16.02%
Municipality of Platania	3,414.12 tn CO ₂ eq	3,214.00 tn CO ₂ eq	-5.86%
Municipality of Souli	1,304.90 tn CO ₂ eq	955.18 tn CO ₂ eq	-26.80%

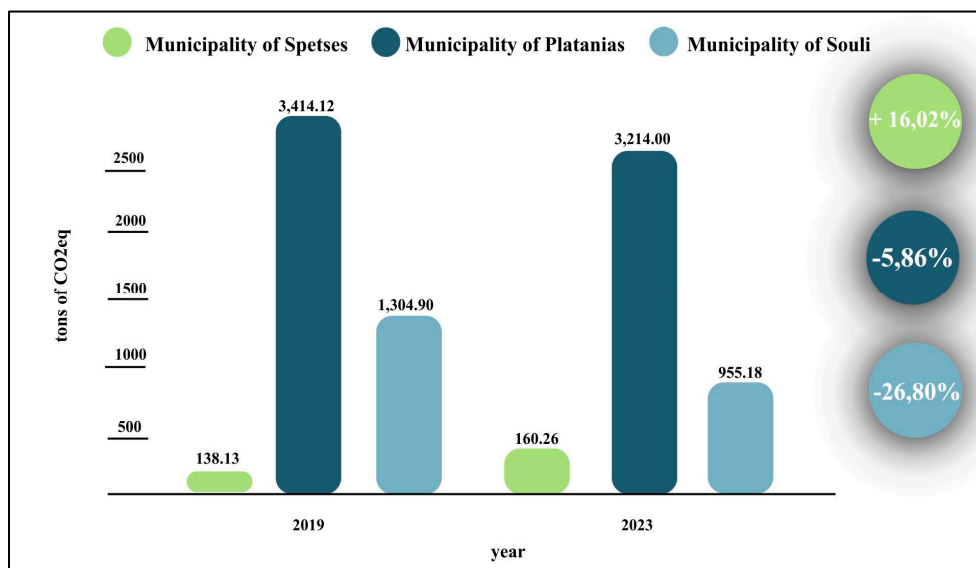


Figure 3. Comparative presentation of the change in total tn CO₂eq emissions from municipal buildings and lighting in the municipalities under study between 2019 and 2023.

3.2.2. Municipal Transport/ Municipal Fleet

Another activity that contributes to greenhouse gas emissions is the transport fleet of each municipality, including passenger vehicles, commercial vehicles, and construction machinery. More specifically, the type of fuel used to power vehicles causes corresponding gas emissions, as the combustion of diesel and gasoline produces significant amounts of carbon dioxide, methane, and nitrogen oxides [4,5,21]. Taking into account the data in the vehicle fleet available to each of the three municipalities, in combination with the type of fuel used, the total equivalent greenhouse gas emissions can be calculated. This chapter provides a comparative presentation of the analysis of the data on municipal vehicles in the Municipalities of Spetses, Platania and Souli, respectively, as well as the total greenhouse gas emissions produced during the base year 2019 and the reference year 2023, in tons of carbon dioxide equivalent (tn CO₂e).

The Municipality of Spetses, due to its small, picturesque and extremely narrow road network, which is mainly pedestrianized within the settlement, has very few vehicles in circulation. As a result, the Municipality of Spetses has only 6 vehicles that are used exclusively for waste collection. Since all of them are waste collection vehicles, it was considered appropriate in the context of this study to present them in the next section, which deals exclusively with solid waste and wastewater management.

The Municipality of Platania has 47 municipal vehicles that run on diesel, gasoline, and LPG. Total emissions for the base year 2019 were estimated at 449.05 tons of CO₂eq, while for 2023 the total amount decreased to 269.95 tons of CO₂eq. Consequently, there is a 39.88% reduction in total greenhouse gas emissions due to the use of liquid fuels by the municipal vehicles of the Municipality of Platania.

Table 8. Change in total CO₂eq emissions from the municipal fleet of the Municipality of Platania between 2019 and 2023.

Municipality	Base Year 2019	Reference Year 2023	Percentage Change
Municipality of Platania	449.05 tn CO ₂ eq	269.95 tn CO ₂ eq	-39.9%

The Municipality of Souli has 23 municipal vehicles that use diesel and gasoline. Total emissions for the base year 2019 were estimated at 117.36 tons of CO₂eq, while for 2023 the total amount

increased slightly to 149.60 tons of CO₂eq. Consequently, there is a 27.5% increase in total greenhouse gas emissions due to the use of liquid fuels by the municipal vehicles of the Municipality of Souli.

Table 9. Change in total CO₂eq emissions from the municipal fleet of the Municipality of Souli between 2019 and 2023.

Municipality	Base Year 2019	Reference Year 2023	Percentage Change
Municipality of Souli	117.36 tn CO ₂ eq	149.60 tn CO ₂ eq	+27.5%

The results of total emissions in each municipality demonstrate the significant differences between the size of the vehicle fleet available to each municipality, its composition, and its functionality. As a result, there is an increased amount of total greenhouse gas emissions in the Municipality of Platánias compared to the Municipality of Souli, partly due to the larger fleet available to the Municipality of Platánias. However, the increase in the use of LPG by municipal vehicles in the Municipality of Platánias contributes to a 39.9% reduction in total CO₂eq emissions, while the increase in the use of diesel and petrol in the Municipality leads to a 27.5% increase in total CO₂eq emissions in the reference year 2023.

Table 10. Presentation of the change in total CO₂eq emissions of the municipal fleet of the municipalities under study between 2019 and 2023.

Municipality	Base Year 2019	Reference Year 2023	Percentage Change
Municipality of Spetses	-	-	-
Municipality of Platánias	449.05 tn CO ₂ eq	269.95 tn CO ₂ eq	-39.9%
Municipality of Souli	117.36 tn CO ₂ eq	149.60 tn CO ₂ eq	+27.5%

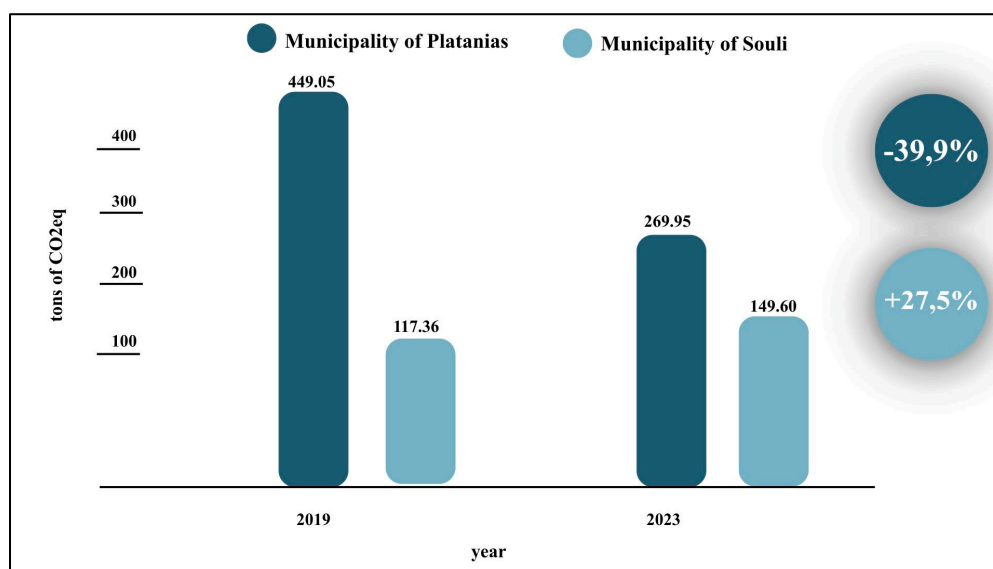


Figure 4. Comparative presentation of the change in total CO₂eq emissions of the municipal fleet of the municipalities under study between 2019 and 2023.

3.2.3. Solid Waste and Wastewater Management

Solid waste and wastewater management is a distinct and critical area in calculating the total carbon footprint of a municipality, as it is linked to greenhouse gas emissions from both the treatment and disposal processes, but also from the supporting collection and transport functions. In particular, the disposal of biodegradable waste in anaerobic conditions (e.g. in sanitary landfills sites) leads to the production and emission of methane (CH₄), a gas with a high climate impact, while wastewater

treatment and disposal can cause emissions of both CH₄, under certain conditions, and nitrous oxide (N₂O), mainly through nitrogen-related processes. This subsection reflects the total emissions in terms of CO₂eq from wastewater treatment and management, as well as from the use of the fuel by the fleet of refuse collection vehicles that support waste collection and transport [4,5,22–27].

The Municipality of Spetses does not have an organized sanitary landfill site, so waste is transferred from collection vehicles to larger vehicles equipped with press containers and transported for disposal to the Integrated Waste Management Facility (IWMMF) in Western Attica. The Municipality of Spetses has 6 waste collection vehicles that run on diesel fuel. Total emissions for the base year 2019 were estimated at 133.30 tons of CO₂eq, while for 2023 the total amount increased slightly to 154.89 tons of CO₂eq. Consequently, there is a 16.2% increase in total greenhouse gas emissions due to the use of liquid fuels by the waste collection vehicles of the Municipality of Spetses.

Table 11. Change in total CO₂eq emissions from solid waste and wastewater management in the Municipality of Spetses between 2019 and 2023.

Municipality	Base Year 2019	Reference Year 2023	Percentage Change
Municipality of Spetses	133.30 tn CO ₂ eq	154.89 tn CO ₂ eq	+16.2%

The Municipality of Platania has a wastewater treatment plant and 9 waste collection vehicles, which use diesel and gasoline. Total emissions for the base year 2019 were estimated at 1,209.94 tons of CO₂eq, while for 2023, the total decreased to 812.73 tons of CO₂eq. Consequently, there is a 32.8% reduction in total greenhouse gas emissions due to wastewater treatment and the use of liquid fuels by the waste collection vehicles of the Municipality of Platania.

Table 12. Change in total CO₂eq emissions from solid waste and wastewater management in the Municipality of Platania between 2019 and 2023.

Municipality	Base Year 2019	Reference Year 2023	Percentage Change
Municipality of Platania	1,209.94 tn CO ₂ eq	812.73 tn CO ₂ eq	-32.8%

The Municipality of Souli has a waste collection network that covers most villages. More specifically, it has 3 waste collection vehicles that run on diesel. In the Municipality of Souli, there is a sanitary landfill site in the area of Karvounari. However, it is managed by a private company and therefore, the emissions resulting from the disposal of waste in it are not included in this study. There is also a biological treatment plant in the municipality, which began operating in June 2024, so no data is currently available. Total emissions for the base year 2019 were estimated at 86.11 tons of CO₂eq, while for 2023, the total amount increased slightly to 90.32 tons of CO₂eq. Consequently, there has been a 4.9% increase in total greenhouse gas emissions due to the use of liquid fuels by the Municipality of Souli's waste collection vehicles.

Table 13. Change in total CO₂eq emissions from solid waste and wastewater management in the Municipality between 2019 and 2023.

Municipality	Base Year 2019	Reference Year 2023	Percentage Change
Municipality of Souli	86.11 tn CO ₂ eq	90.32 tn CO ₂ eq	+4.9%

The significant differences between the three municipalities are directly related to the way in which solid waste and wastewater management are organized and, above all, to the range of activities included in the inventory. The municipality of Platania has the highest total CO₂eq emissions, which is attributed, on the one hand, to the existence and operation of a wastewater treatment plant and, on the other hand, to the use of fuel by waste collection vehicles. However, in the reference year 2023,

there is a significant reduction of 32.8%, indicating an improvement in either fuel consumption or treatment efficiency. In contrast, in the municipalities of Spetses and Souli, the inventory mainly concerns emissions from the collection and transport of waste by waste collection vehicles, as either there is no organized disposal facility within the boundaries of the Municipality of Spetses, or disposal emissions are not included in the study due to private management of the sanitary landfill and the absence of available data on wastewater, as in the case of the Municipality of Souli. Consequently, the total emissions in these two municipalities appear to be significantly lower, while showing small increases, which are attributed to the increased use of liquid fuels by the garbage truck fleet. Overall, the comparison shows that the differences in results reflect not only the size or needs of each municipality, but also the availability of data and systemic limitations of the inventory, which largely determine the final footprint.

Table 14. Presentation of the change in total CO₂eq emissions from solid waste and wastewater management in the municipalities under study between 2019 and 2023.

Municipality	Base Year 2019	Reference Year 2023	Percentage Change
Municipality of Spetses	133.30 tn CO ₂ eq	154.89 tn CO ₂ eq	+16.2%
Municipality of Platania	1,209.94 tn CO ₂ eq	812.73 tn CO ₂ eq	-32.8%
Municipality of Souli	86.11 tn CO ₂ eq	90.32 tn CO ₂ eq	+4.9%

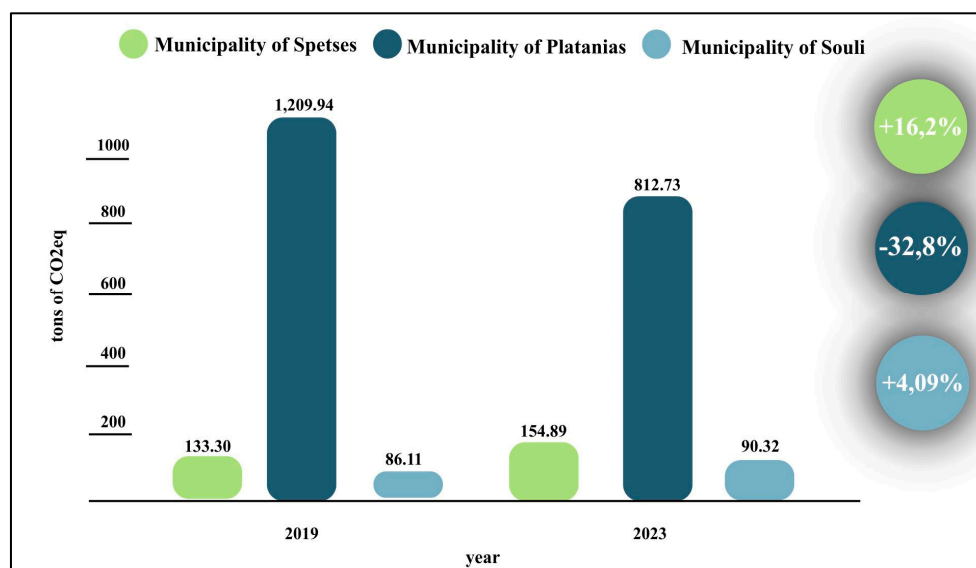


Figure 5. Comparative presentation of the change in total tn CO₂eq emissions from solid waste and wastewater management in the municipalities under study between 2019 and 2023.

3.2.4. Water Supply and Irrigation

Water supply and irrigation are basic municipal services that contribute directly and indirectly to the overall carbon footprint of municipalities, as their operation is inextricably linked to significant energy requirements. In particular, the pumping, transport, storage, and distribution of water - both for domestic use and for irrigation purposes - require the continuous operation of pumping stations, electrical and mechanical equipment, which consume electricity and therefore lead to indirect greenhouse gas emissions. The level of emissions is influenced by factors such as the geomorphology of the area, altitude differences, the length and age of the networks, as well as pressure and supply requirements, which vary significantly between urban, rural and mountainous municipalities [11,12,28–31]. In the context of this study, this subsection reflects the total consumption at the water supply and irrigation pumping stations of the Municipalities of Spetses, Platania, and Souli for the base year 2019 and reference year 2023. Water supply and irrigation activities are supported by

springs, boreholes and pumping stations, which require electricity to operate, while tanks and chlorinators are used for water storage and treatment [4,5].

The water supply network of the Municipality of Spetses is not supplied by boreholes, but by water transported by a water tanker. The water is pumped from the tanker through a DN250 pipe, to a tank at an altitude of approximately 60 meters. From the tank, a pumping unit transfers part of the water to another tank located at an altitude of 93 meters. The two tanks supply water to two independent zones that have been designated by the municipality as the Upper and Lower zones, respectively. Due to the current situation, the electricity used doesn't fall under the jurisdiction of the Municipality of Spetses, and therefore, no data on greenhouse gas emissions are available.

In the case of the Municipality of Platanias, the Municipal Water Supply and Sewerage Company of Northern Chania (DEYABA) owns the water maintenance, operation, administration and management. Water is pumped and transported from the boreholes and pumping stations, which consume electricity. Water is stored and treated in tanks and chlorinators. Total emissions for the base year 2019 were estimated at 1,852.01 tons of CO₂eq, while for 2023 the total amount increased slightly to 1,880.86 tons of CO₂eq. Consequently, there is a slight increase of 1.6% in total greenhouse gas emissions due to the use of electricity for water supply and irrigation in the Municipality of Platanias.

Table 15. Change in total CO₂eq emissions from water supply and irrigation in the Municipality of Platanias between 2019 and 2023.

Municipality	Base Year 2019	Reference Year 2023	Percentage Change
Municipality of Platanias	1,852.01 tn CO ₂ eq	1,880.86 tn CO ₂ eq	+1.6%

The Municipality of Souli owns the water supply networks and is responsible for their design, construction, maintenance, exploitation, administration and operation. More specifically, the Municipality is responsible for the operation of seventy-five pumping stations, reservoirs and boreholes. There are ten boreholes. Eighteen of the reservoirs have a pumping station and forty-seven do not. Total emissions for the base year 2019 were estimated at 1,112.01 tons of CO₂eq. Consequently, there is a slight decrease of 6.9% in total greenhouse gas emissions due to the use of electricity for water supply and irrigation in the Municipality of Souli.

Table 16. Change in total CO₂eq emissions from water supply and irrigation in the Municipality of Souli between 2019 and 2023.

Municipality	Base Year 2019	Reference Year 2023	Percentage Change
Municipality of Souli	1,112.01 tn CO ₂ eq	1,035.21 tn CO ₂ eq	-6.9%

The results of this subsection show that the water supply and irrigation sector can be one of the most energy-intensive municipal activities and, as a result, contribute significantly to the overall carbon footprint, especially in municipalities with extensive networks, significant altitude differences, and increased pumping needs. In the case of the Municipality of Spetses, no emissions are recorded in this sector, as water supply is based on transported water and electricity consumption for pumping does not fall under the jurisdiction of the Municipality. The municipality of Platanias has the highest total CO₂eq emissions in this sector, which is linked to the extensive use of boreholes and pumping stations and the size of the network served, but shows a marginal change between 2019 and 2023, indicating relatively stable energy consumption. Similarly, in the Municipality of Souli, despite the large number of pumping stations, reservoirs, boreholes and the rugged terrain of the area, there is a slight decrease in emissions, indicating a slight improvement in the operation or energy management of water infrastructure. Overall, the comparison shows that emissions from water supply and irrigation depend to a large extent on the water supply model, geomorphology and

the scope of municipal responsibilities, confirming the need for spatially adapted interventions to reduce energy consumption and corresponding emissions in this sector.

Table 17. Presentation of the change in total CO₂eq emissions from water supply and irrigation in the municipalities under study between 2019 and 2023.

Municipality	Base Year 2019	Reference Year 2023	Percentage Change
Municipality of Spetses	-	-	-
Municipality of Platánias	1,852.01 tn CO ₂ eq	1,880.86 tn CO ₂ eq	+1.6%
Municipality of Souli	1,112.01 tn CO ₂ eq	1,035.21 tn CO ₂ eq	-6.9%

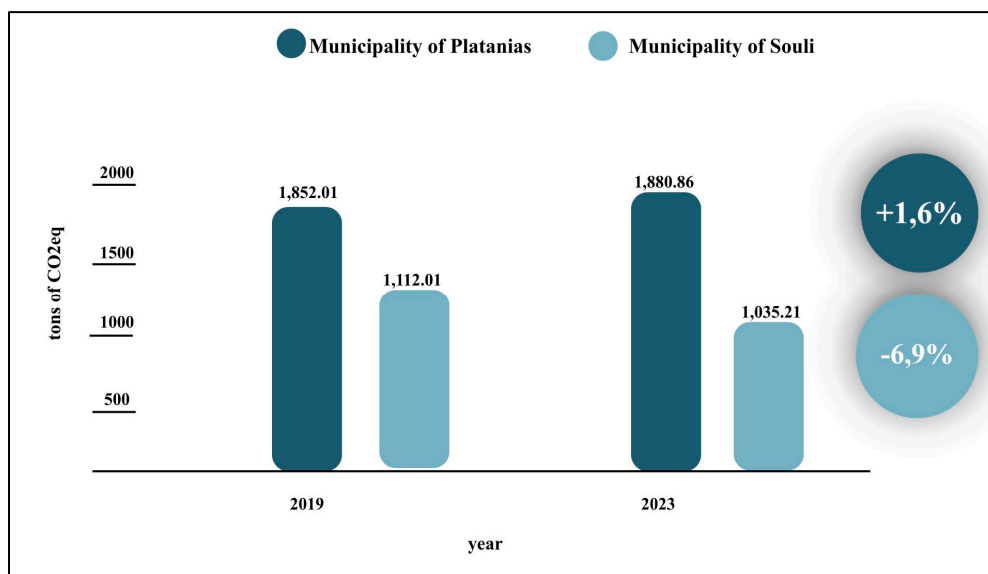


Figure 6. Comparative presentation of the change in total tn CO₂eq emissions from solid waste and wastewater management in the municipalities under study between 2019 and 2023.

3.3. Comparative Total Municipal Emission

The summary of the carbon footprint at the municipal level is a critical stage of this analysis. While the individual analysis per sector of activity highlights specific sources of emissions and differences between operations, the aggregate footprint in terms of CO₂eq provides an understanding of each sector's relative contribution to the overall footprint and the total energy and environmental impact of each municipality. This overall picture is essential for the hierarchical identification of priority sectors, the evaluation of the effectiveness of existing practices and the targeted formulation of proposed emission reduction actions tailored to the specific characteristics and actual needs of each municipality. In this context, this subsection collects and presents the total CO₂eq emissions of the Municipalities of Spetses, Platánias and Souli for the base year 2019 and the reference year 2023.

The carbon footprint of the Municipality of Spetses for the base year 2019 was 271.43 tons of CO₂eq, while for the reference year 2023, it increased to 315.15 tons of CO₂eq. Consequently, total CO₂eq emissions increased by 16.1%. In the case of the Municipality of Platánias, the carbon footprint for the base year 2019 was 6,925.55 tons of CO₂eq, while for the reference year 2023 it decreased to 6,177.54 tons of CO₂eq. Consequently, total CO₂eq emissions decreased by 10.8%. Finally, the carbon footprint in the Municipality of Souli for the base year 2019 was 2,620.38 tons of CO₂eq, while for the reference year 2023 it decreased to 2,230.32 tons of CO₂eq. Consequently, total CO₂eq emissions decreased by 14.9%.

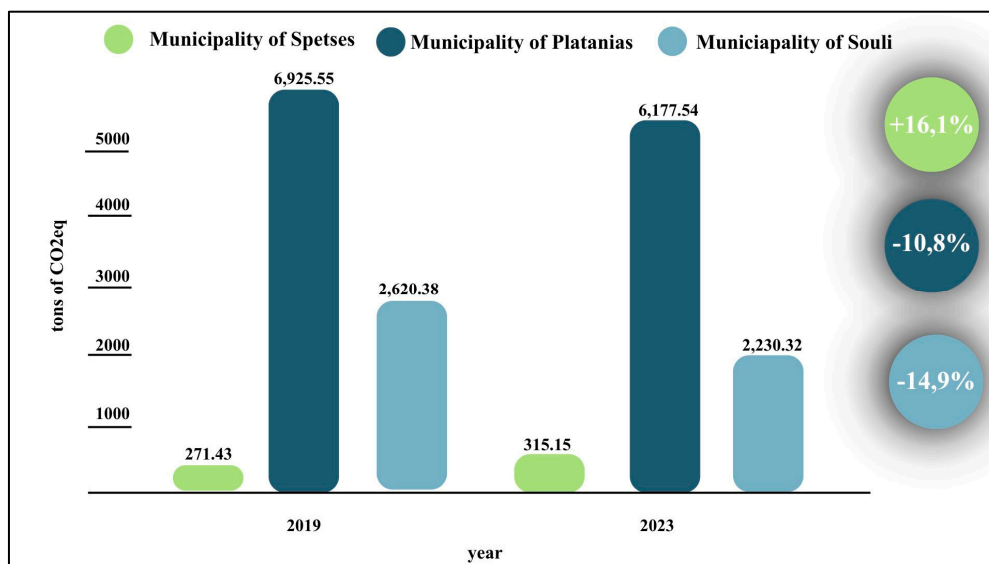


Figure 7. Comparative presentation of the change in the total carbon footprint of the municipalities under study between 2019 and 2023.

The rates of change in the total carbon footprint observed in the reference year 2023 for the three municipalities under study are the result of the combined effect of individual changes in key areas of municipal activity. In the case of the Municipality of Spetses, the 16.1% increase in total CO₂eq emissions is mainly attributable to increased electricity consumption in municipal buildings and lighting, but also to the electricity consumption in municipal buildings and lighting, but also to the increased use of liquid fuels for the movement of waste collection vehicles. No emissions are recorded from water supply and irrigation, due to the specific water supply model and the limits of the Municipality's responsibilities, nor from the municipal fleet, as they correspond to the solid waste and wastewater management sector. In contrast, the Municipality of Platania has seen an overall reduction in CO₂eq emissions of 10.8%, which is linked, on the one hand, to the significant reduction in emissions from the municipal fleet and solid waste and wastewater management, and on the other hand, to the relative stability of emissions in the sectors of municipal buildings, lighting, water supply and irrigation. In the Municipality of Souli, the 14.9% reduction in the total carbon footprint is mainly due to the significant reduction in emissions from municipal buildings and lighting, as well as improvements in the water supply and irrigation sector, despite the increase in emissions from the municipal fleet and solid waste management. The increase in emissions in an island municipality such as Spetses is related to the intense seasonality of tourism and its operational peculiarities [32–34]. Greek tourist municipalities face overloaded waste management systems and difficulties in implementing integrated treatment infrastructure [24,25,27,33–35]. At the same time, the absence of organized local treatment facilities and the dependence on the transport of mixed waste to regional facilities and the dependence on the transport of mixed waste to regional facilities is another significant reason for the deterioration of emissions, as waste management is limited to collection and sanitary landfill due to inadequate infrastructure [5,33].

Overall, the results show that variations in the total carbon footprint are not due to a single sector, but to the different dynamics and weight of individual activities in each municipality, as well as to their specific operational, geographical and organizational characteristics, which determine both emission trends and the potential for targeted reduction interventions.

3.4. Comparative Overview of Emission Reduction Actions and 2030 Targets

Within the framework of Municipal Emission Reduction Plans (MERPs), documented actions are identified and prioritized with the aim of reducing greenhouse gas emissions and increasing absorption at the local level by 2030. The selection of actions is based both on the results of the emissions inventory and on the specific operational, geographical and socioeconomic characteristics

of each municipality. This study aims to formulate realistic and feasible interventions that can contribute to achieving a reduction in emissions of at least 10% by 2025 and 30% by 2030, compared to the base year 2019, in line with the national and European framework for climate neutrality. At the same time, the analysis seeks to highlight the role of targeted adaptation of actions to the needs and capabilities of each municipality, avoiding the adoption of uniform approaches that do not consider local particularities [1,2].

For the Municipality of Spetses, the proposed actions are estimated to lead to an overall reduction in greenhouse gas emissions of 35.34% by 2030 compared to 2019. The interventions focus on the bioclimatic upgrading of public spaces and municipal lighting, the improvement of solid waste management and the gradual transition to an energy-efficient and low-emission model through the establishment of an energy community, the use of renewable energy sources and new plantings. In the Municipality of Platania, the proposed actions will lead to an estimated 37.79% reduction in emissions, with an emphasis on energy upgrades and the use of RES in 4 municipal buildings, improving the energy efficiency of water supply and irrigation infrastructure, specifically pumping stations and boreholes, adopting sustainable transport for waste collection and enhancing natural absorption through new plantings. The Municipality of Souli is expected to achieve a particularly high reduction in emissions of around 77% resulting from a combination of extensive energy efficiency interventions in street lighting and municipal school buildings, the use of renewable energy sources through photovoltaic installations and virtual energy offsetting in agricultural facilities and municipal buildings, the systematic optimization of water supply infrastructure through smart systems for monitoring energy consumption, leaks, and water quality the use of sustainable transport for waste collection and the enhancement of natural absorption through new plantings.

Table 18. Presentation of proposed actions per municipality with estimated emission reduction by 2030.

Municipality	Proposed Actions	Estimated Emission Reductions by 2030
Municipality of Spetses	Upgrading of street lighting New plantings Sustainable transport for waste collection RES installation in existing municipal infrastructure Public space redevelopment Smart waste collection Development of a modern waste management network	35.34%
Municipality of Platania	New plantings Sustainable transport for waste collection Energy upgrade & use of RES in municipal buildings Improvement of the energy efficiency of boreholes and water pumping stations	37.79%
Municipality of Souli	Upgrading street lighting New plantings Sustainable transport for waste collection Installation of RES in existing municipal infrastructure Installation of a photovoltaic park in an agricultural facility Installation of a system to monitor the energy consumption of the municipality's water distribution network Energy upgrade of the municipality's school buildings Installation of a smart green system to control leaks and monitor water quality in the water distribution network	77.0%

* The emission reduction actions and the projected percentage reduction targets for 2030, are presented as reported in the official MERPs. No recalculation, adjustment, or independent evaluation of the proposed measures were performed.

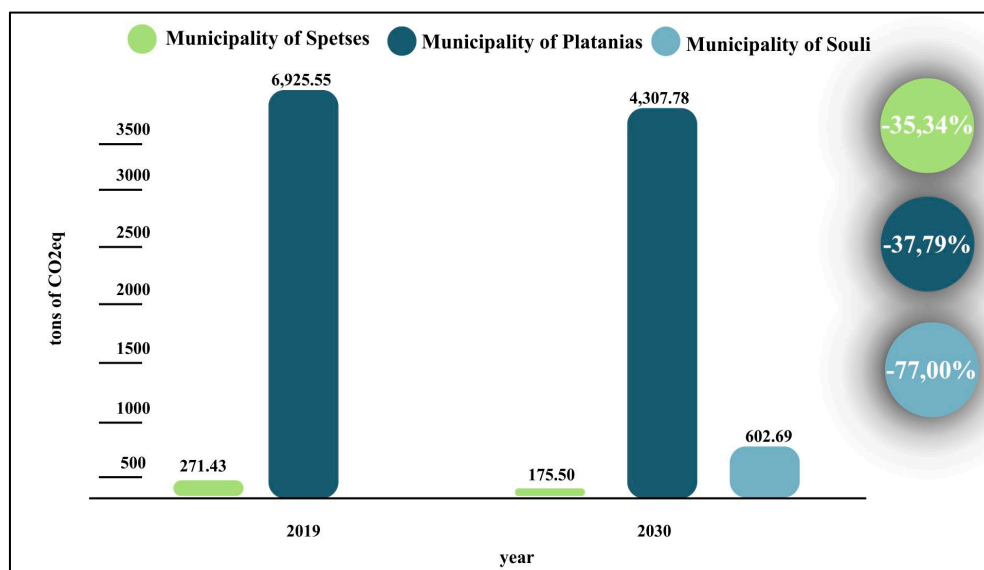


Figure 8. Comparative presentation of the change in proposed actions per municipality with estimated emission reduction by 2030.

The comparative assessment of the proposed actions shows that the effectiveness of emission reduction interventions depends to a large extent on the specific characteristics of each municipality. Factors such as geographical location, extent, climatic and economic characteristics, population size and spatial distribution, level of urbanization, the nature of municipal infrastructure and the relative contribution of individual sectors of activity to total emissions, shape different needs, priorities and possibilities for intervention. All three municipalities seek to reduce their carbon footprint through renewable energy sources, sustainable interventions in solid waste and wastewater management and new plantings. However, there are differences in the way the interventions are implemented [36].

In the case of the Municipality of Spetses, intense tourist activity and the island's characteristics make it crucial to upgrade public spaces with the aim of reducing electricity consumption and increasing absorption in public spaces, energy autonomy through RES and optimization of solid waste management, areas that contribute disproportionately to the overall carbon footprint.

In contrast, in the Municipality of Platania, the significant contribution of water supply infrastructure and building energy consumption to total emissions makes more effective the targeted energy upgrades of buildings and improvements in the energy efficiency of water supply and irrigation facilities, combined with mild interventions in the transport fleet and the enhancement of natural absorption.

In the Municipality of Souli, where the highest emissions are recorded in municipal buildings, municipal lighting and the water supply and irrigation sector, the proposed actions focus on drastically reducing electricity consumption through energy upgrades in all school buildings, upgrading the street lighting system, optimizing the operation of water supply infrastructure, utilizing renewable energy sources in every intervention where possible, while also including interventions in other areas of activity [7,10,11,36].

4. Conclusions

This study highlighted the decisive role of local government in the transition to climate neutrality. The assessment of each municipality's carbon footprint, both at the level of individual

sectors of activity and overall, showed that greenhouse gas emissions are greatly influenced by the specific characteristics of each municipality, confirming the need for tailored mitigation policies. Municipal Emission Reduction Plans (MERPs) are emerging as critical strategic planning tools, but their meaningful contribution to achieving national and European targets for 2030 and 2050 require strengthening the technical capacity of municipalities.

A comparative analysis of emissions for the base year 2019 and the reference year 2023 revealed divergent trends. The Municipality of Spetses, despite its low absolute level of emissions, showed an increase in its total carbon footprint, which is mainly attributed to increased electricity consumption in municipal buildings, lighting and waste management. This finding underscores that even small, island-based and tourist-developed municipalities are not exempt from the need for systemic energy planning and targeted interventions, especially in areas where electricity is the only source of energy.

In contrast, the municipalities of Platania and Souli showed a reduction in total CO₂e emissions, which is linked to the reduction in the use of liquid fuels, improved energy efficiency in selected sectors and in some cases reduced electricity consumption. In the municipality of Platania, despite the high absolute carbon footprint, significant reductions were recorded in the areas of municipal transport and waste and wastewater management. Similarly, in the municipality of Souli, the significant reduction in emissions in municipal buildings and lighting offset the increases recorded in the municipal fleet, reflecting the potential impact of targeted intervention even in municipalities with rugged terrain and extensive networks.

Of particular importance is the finding that sectors such as water supply and irrigation, often underestimated in public debate, can be significant sources of emissions, especially in municipalities with large altitude differences and energy-intensive pumping systems. The differences observed between the three municipalities confirm that the water supply model, the distribution of responsibilities and the technical organization of the networks largely determine the final carbon footprint, reinforcing the need to integrate these sectors into the core of mitigation strategies.

Overall, the study documents that the comparison of MRPs cannot be limited to a simple quantitative comparison of emissions, but require interpretation of the results considering local conditions, available data and the systemic limitations of the inventory. The differences recorded do not solely reflect the environmental performance of municipalities, but also institutional maturity, data availability and organizational capacity. The outsourcing of public activities by municipalities to private individuals often leads to fragmented recording of emissions and deprives the municipality of the ability to comprehensively assess its carbon footprint, limiting the ability to design comprehensive and targeted mitigation measures.

The results of the comparative analysis confirm that there is no universally applicable set of actions for all municipalities. Instead, a successful transition to low carbon emissions requires the design and implementation of tailored strategies that consider local geomorphological, operational and administrative characteristics and maximize both the environmental effectiveness and long-term sustainability of the interventions.

A typical example is the Municipality of Souli, where the proposal for parallel and targeted actions in all areas, with an emphasis on those areas with the highest emissions, without neglecting action in other areas, has led to an extremely high expected overall emission reduction rate by 2030. This finding demonstrates that a holistic approach and the avoidance of fragmented interventions can yield disproportionately high environmental benefits, even in municipalities with spatial and operational challenges.

Finally, this comparative analysis shows that Municipal Emission Reduction Plans can serve not only as tools for monitoring progress toward climate neutrality, but also as leverages for territorial restructuring. The findings indicate that water infrastructure can represent a significant emission source and that effective mitigation depends on spatially tailored strategies considering geomorphological, operational, and administrative characteristics, enhancing environmental performance and long-term sustainability. The integration of climate targets into local development planning enhances sustainable development, the resilience of local systems and the coherence

between environmental, energy and spatial policies. Achieving climate neutrality is therefore a multidimensional process that requires decentralized, evidence-based and tailored interventions, with local authorities playing an active role.

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