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Research article

The pandemic effect on GHG emission variation at the sub-national level and translation into policy opportunities

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ABSTRACT

Greenhouse gas (GHG) emissions inventories are commonly compiled at country level to monitor national progress towards nationally or internationally agreed targets. While they can support national climate change mitigation strategies, accounting for the intra-national heterogeneity of a country can draw different conclusions directly linked to the socio-economic and environmental sub-national context. This means that more refined and accurate policies and mitigation strategies can be designed when supported by GHG inventories at sub-national scale. The differences between sub-national territorial emissive behavior can be revealed by subjecting different territories to the same stress factors. A complete GHG emissions inventory, based on the Intergovernmental Panel on Climate Change (IPCC) Guidelines, is compiled for three diverse administrative territories, in terms of scale, socio-economic contexts, and environmental conditions. By selecting three diverse sub-national contexts belonging to the same national territory – Italy – the analysis provides highly detailed information on the emissive status and behavior and delivers insights that national inventories fail to provide. The COVID-19 pandemic is considered as a stress factor; therefore, the reference years are 2019 and 2020 during which GHG emissions are detected. The study will test the capacity of sub-national GHG emission inventories, compiled by scaling the IPCC methodology to the sub-national level, to detect such differences through the lens of the pandemic. This allows obtaining detailed information and linking the pandemic effect to the GHG emissions of particular activities, which can inspire effective sub-national context-specific mitigation actions. Furthermore, we show that environmental and economic metrics are not as strictly coupled as they would appear at national level.

1. Introduction

Greenhouse gas (GHG) emission accounting and monitoring procedures are normally implemented and provide indications in different contexts and sectors, including energy (Jung and Kwon, 2014), waste (Marchi et al., 2017), mobility (Cui et al., 2011), and planning (Sporchia et al., 2023), as well as different geographical scales, like the country-scale (Lalas et al., 2021; Rugani and Caro, 2020), city-scale (Andrade et al., 2018; Arioli et al., 2020; Marchi et al., 2023; Pulselli et al., 2019; Suryati et al., 2021), or facility-scale (Sun et al., 2022). However, while useful for nation-wide actions, their potential is limited due to the large variety that can exist in terms of both environmental, social, and economic aspects within a country (Clarke-Sather et al., 2011). This implies the urgent need of a widespread and practical implementation of such environmental accounting methodologies in territorial sub-systems at the regional, local, municipal, urban, and sub-urban level (Giest and Howlett, 2013; Harker et al., 2017; Kern, 2019; Lorenzo-Sáez et al., 2022; Wolkinger et al., 2012). Though sub-national accounting experiences often focus on few activities or sectors (Cui et al., 2011; Jung and Kwon, 2014; Marchi et al., 2017), the application of an overall all-encompassing (i.e., including all sectors) accounting scheme at the sub-national level is possible. It could provide much more specific information with a larger potential to support policymakers (Chen et al., 2022; Pulselli et al., 2019; Sporchia et al., 2023; Suryati et al., 2021; Xi et al., 2011). However, the compilation of GHG inventories at sub-national level is currently not a common practice due

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to a number of reasons (e.g., lack of fundings or data), which represents a missed opportunity (Harker et al., 2017).

Sub-national accounts can capture the territorial peculiarities and provide local decision-makers with a solid basis for the design of effective local actions fine-tuned according to the socio-economic context considered (Chen et al., 2022; Huovila et al., 2022; Wiedmann et al., 2021). This approach is necessary to build a multi-level governance method that can address the challenges from a set of diverse policies that increases the overall effectiveness compared to generic national actions (Giest and Howlett, 2013; Harker et al., 2017; Kern, 2019; Lorenzo-Sáez et al., 2022; Pietrapertosa et al., 2021).

The COVID-19 pandemic was an unprecedented challenge for humanity, implying severe health issues and affecting multiple other aspects of human society, which emerged in the form of consequences in environmental, social, and economic domains (Mofijur et al., 2021). In the environmental sphere, for instance, on one hand, the annual average concentration of atmospheric pollutants (e. g., particulate matter, NOx etc.) in 2020 decreased significantly compared to 2019 levels (Khan et al., 2021; Le et al., 2020; Lovarelli et al., 2020; Mostafa et al., 2021; SanJuan-Reyes et al., 2021) whereas, on the other hand, the pandemic induced an increased production of waste (e. g., personal protective equipment such as masks and gloves, but also food delivery package) together with a reduction of the recycling rate (Zambrano-Monserrate et al., 2020) and disrupted supply chains (Pimenta et al., 2022). As an example of the social burden, the death toll directly linked to COVID-19 infection reached 18.2 million as of 31 December 2021 (Wang et al., 2022). The economic effect was striking and led to an unprecedentedly sharp fall quantified, globally, in 3.3% decrease in GDP in 2020 compared to 2019 (World Bank, 2023). This was even worse compared to the 2008 global financial crisis (World Bank, 2023).

Another immediate and direct environmental consequence concerns the global CO_2 emission which decreased by 5.4% in 2020 compared to 2019 (UNEP, 2021). However, direct emission observation at city scale showed a rebound after an initial decrease (Nicolini et al., 2022). The pandemic will also affect the future emission dynamics with decreasing trends in the short term but increasing trends in the long term (Shan et al., 2021). Besides the environmental benefits deriving from this fall, this unprecedented event represents an opportunity for understanding better and more deeply the environment-society-economy nexus and get insights into the relationships existing among these three domains and the underlying drivers (e.g., environment-human health) (Conticini et al., 2020; Sporchia et al., 2021). Accordingly, critical points and aspects about territorial sustainability can be identified, representing the basis upon which to investigate issues and design more effective actions. In particular, in the context of the current challenge posed by the shift towards the global climate neutrality, and the related comprehensive effort to achieve it – for example the Paris agreement (United Nations, 2015) – this extraordinary event could provide extremely rich information to accelerate the transition.

So far, COVID-19-related GHG emission reduction has been investigated through sub-national GHG emission inventories focusing on CO_2 (Hartono et al., 2021; Huo et al., 2022; Liu et al., 2020, 2022; Nalini et al., 2022), energy sector (Rugani and Caro, 2020; Samani et al., 2021), limited periods of time (Bolaño-Ortiz et al., 2020; Nalini et al., 2022), specific activities such as transport (Camargo-Caicedo et al., 2021; Durán-Grados et al., 2020; Gamba et al., 2021; Kareinen et al., 2022; Mannarini et al., 2022) or household consumption (Long et al., 2021; Rojas et al., 2022), or even without providing a sectoral detail, thus with limited informative potential (Hu et al., 2022). As the pandemic can represent an opportunity to strengthen the sustainability of territorial systems (Lehmann et al., 2021; Tibrewal and Venkataraman, 2022), we investigate this opportunity in terms of GHG emission, and take advantage of it to show the relevance of the territorial context in shaping the emission trends.

This paper aims to explore the capability of a complete sub-national scale GHG emissions inventory – made in line with the Intergovernmental Panel on Climate Change (IPCC) Guidelines (IPCC, 2019, 2006) – to capture the COVID-19 phenomenon and provide insightful information, identifying, qualitatively and quantitatively, the activities most affected by this unprecedented event. Such identification points out some hotspots of emission and inspire policy actions fine-tuned according to the territorial context. By analyzing different scales and contexts (geographic, demographic, administrative) within the Italian national territory, the study is aimed to:

i) confirm the feasibility of a complete GHG accounting procedure at the sub-national level;
ii) explore the sensitivity of such application to the pandemic event;
iii) identify the dependence of the effects of the pandemic on the socio-economic conditions;
iv) demonstrate that coupling the sub-national investigation of specific contexts to the more diluted country-scale view – capturing the pandemic effect too – can orient actions in terms of GHG emission monitoring and related mitigation potential;
v) provide a reference for sub-national territories willing to act in terms of climate change mitigation.

2. Methods

As intra-national heterogeneity can be large, it is necessary to consider different areal systems in order to capture the variability of their characteristics – for instance, geographical, demographic, environmental, and economic features, and also scale – and validate the method. The same applies even to larger regions or countries for which policies must consider the context heterogeneity (Sporchia et al., 2021). Accordingly, we selected three Italian territories characterized by differences in all the above-mentioned aspects: the Province of Parma, the Province of Siena, and the Municipality of Grosseto. The territories are briefly described in the following sections. They have been chosen to be representative of the possible intra-national diversity, instead of being representative for the national context itself.

2.1. *The Province of Parma*

The Province of Parma covers an area of 3′450 km^2 of which 43% mountain, 32% hill, and 25% plain (ISTAT, 2022a). The population size was around 454′000 (ISTAT, 2022b). The area is sub-divided into 44 municipalities. It belongs to the region (NUTS[1] 2) Emilia-Romagna, in turn pertaining to the NUTS 1 North East.

The area is economically well developed, with an employment rate of 68.8% in 2019 (ISTAT, 2022c). The added value of the territory indicates that agriculture only accounted for 2%, industry for 37%, and other sectors for 61% in 2019 (ISTAT, 2022d). Among manufacture activities, food and food-related sectors, together with machineries, cover together around 70% of the territorial economic industrial output (Unione Parmense degli Industriali, 2020). Besides, glass production has a remarkable position by virtue of two of the largest glass-producing plants in Italy. The area also hosts production plants for food products exported and well known all around the world, which include cheese, pasta, and cured ham. Around half of the territory is covered by forest, particularly in the areas pertaining to the Apennines Mountain range. Conscious of the urgency of moving towards carbon neutrality, multiple private and public stakeholders of the territory in late 2020 formed the "Territorial Alliance for Carbon Neutrality: Parma", with the aim of identifying and deploying strategies towards the achievement of the carbon neutrality at the territorial level.

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[1] The NUTS classification (Nomenclature of territorial units for statistics) is a hierarchical system for dividing up the economic territory of the EU and the UK for multiple statistical purposes. See https://ec.europa.eu/eurostat/web/nuts/principles-and-characteristics for further details.

2.2. The Province of Siena

The Province of Siena covers an area of 3′821 km^2, predominantly hilly (ISTAT, 2022a). The population size was around 266′000 (ISTAT, 2022b). The area is sub-divided into 35 municipalities. It belongs to the region (NUTS 2) Tuscany, in turn pertaining to the NUTS 1 Centre.

The area is particularly well developed, with an employment rate of 68.6% in 2019 (ISTAT, 2022c). The economy of the area is mainly driven by services, which cover 73% of the added value, followed by industry (22%) and agriculture (5%) in 2019 (ISTAT, 2022d). Services are mostly tourism-oriented whereas industry is composed of a few manufacture plants and several intermediate manufacturing plants, including the ones providing public services and small-scale food factories (Patterson et al., 2008). Agriculture covers a strategical role with the production of typical products (e. g., wine, cheese, and pork). Besides, agri-food production is well developed and strictly linked with touristic services such as hospitality, catering, and gastronomy (Camera di Commercio di Arezzo-Siena, 2021; IRPET, 2003). Around half of the territory is covered by forest, and it is self-sufficient in terms of energy thanks to the presence of geothermal power plants. These two features allowed the territory to become carbon neutral since 2011 (Bastianoni et al., 2014). The Province of Siena presents ISO 14064-1 validated GHG inventories calculated in time series since 2006 (Bastianoni et al., 2014). Based on these monitoring activities, in 2008 the local authorities launched a political program to achieve carbon neutrality by 2015. Ten years after the compilation of the first inventory, a group composed of both private and public stakeholders decided to create the “Territorial Alliance for Carbon Neutrality: Siena” to further strengthen the mitigation action. The good practices deriving from this initiative inspired the creation of the above-mentioned alliance for Parma.

2.3. The Municipality of Grosseto

The Municipality of Grosseto has a population of 81′440 residents (ISTAT, 2022b). Its territory covers 474 km^2 of which 57.4% is agricultural land, 19.8% is covered by forest, 7.8% by woody crops (fruit, olives and vineyards). Urban settlement accounts for just 9.5% of the territory (Comune di Grosseto, 2017). Grosseto is the capital city of the homonymous Province of Grosseto. The municipality’s economy is based on tourism along the coast, and on traditional agriculture. Besides cereals, sunflowers, vegetables, olives and grapes, the territory is characterized by the Maremmana beef production, as well as specific rice varieties. Minor relevance is covered by the industrial sector and services (Comune di Grosseto, 2017; Marchi et al., 2023). The municipal territory - much smaller compared to the other analyzed contexts - is highly urbanized and densely populated in the areas occupied by urban settlements. The local government has recently implemented a strategy based on the mitigation of the GHG emissions linked to the administrative procedures, as a first step towards a broader mitigation in the direction of the carbon neutrality of the municipality.

2.4. The general approach

The GHG inventories for the considered territories have been compiled following the 2006 IPCC guidelines (IPCC, 2006) and the subsequent 2019 refinement (IPCC, 2019) in order to achieve the largest comprehensiveness. All the activities that generate emissions are grouped into 4 sectors: Energy, Industrial processes and product use (IPPU), Agriculture, Forestry and Other Land Use (AFOLU), and Waste. In line with the IPCC Guidelines, emissions are calculated and assigned to the system according to the geographic criterion. In some cases, we adopted a responsibility approach in order to attribute the impacts to the analyzed context, including those that are created outside the administrative borders of the considered territories. The typical case is electricity consumption. Whenever the territorial electricity demand exceeds the territorial production, imported electricity from national grid must cover the demand gap. Since imported electricity is produced elsewhere, the related emission is created outside the boundaries of the area considered and would not be accounted for when a geographical approach is applied strictly. In our case, however, this emission was considered in the accounting procedure since a responsibility criterion was used, i.e., the assigned GHG emission is proportional to the actual consumption of imported electricity.

The guidelines provide a basic equation that allows to calculate the emissions, multiplying each activity data (i.e., human actions) by the specific emission factor per unit activity. Both should be specific for the process or territory considered. However, while activity data can be collected directly or derived indirectly through disaggregation or proximation, emission factors are much less variable and are commonly found in literature when specific ones are unavailable.

Whenever possible, activity data was collected through a bottom-up approach. However, in some cases a top-down approach was used, and national or regional information was disaggregated to reach the desired resolution or scale, following the schematic general decision process synthetized in Fig. 1.

More specific flow-charts are available in the supplementary material (1) to illustrate the decision-making process followed for the data selection and collection at the sub-national level. They not only apply to the territorial contexts analyzed in the present study, but also to any other sub-national territorial contexts, being designed from a general perspective.

The complete list of the sources of activity data and emission factor by activity type is provided in the supplementary material (2) (Tables S1, S2, S3). In order to highlight the immediate direct effects of the pandemic we focused on 2019 and 2020.

The analysis is limited to the three main GHG that are significant for the contexts analyzed: Carbon dioxide (CO_2), Methane (CH_4), and Nitrous oxide (N_2O). The emission flows of the different gases have been expressed in a common unit, i.e., tons of carbon dioxide equivalents (t CO_2eq) in order to allow an overall assessment. The conversion into CO_2eq is made by means of the Global Warming Potential (GWP), provided by the IPCC Sixth assessment report (IPCC, 2021). Specifically, we used the 100 years GWP values, specific for each GHG (see Table S4 in the supplementary material (2)). National data have been expressed accordingly.

To assess the sensitivity of the methodology we compared the results for the sub-national analyses with the national context. National GHG emission for 2019 and 2020 were retrieved from the data submitted to the United Nations Framework Convention on Climate Change (UNFCCC) by the single countries following the Common Reporting Format (CRF) (UNFCCC, 2022). However, to ensure a meaningful comparison between the national and sub-national contexts, only data referring to the three GHG considered were considered.

3. Results

The three analyzed territorial contexts are characterized by different results both in terms of total emission and in the variation over time (Fig. 2). Hereafter, for the sake of brevity and clarity, we refer to the Province of Parma as Parma, to the Province of Siena as Siena, and to the Municipality of Grosseto as Grosseto. As expected, the largest, most industrialized, and most populated area, that is Parma, reached the highest level of emission in both years, with a decrease of 12.5% – from 5′267 kt $CO_{2\text{-eq}}$ in 2019 to 4′608 kt $CO_{2\text{-eq}}$ in 2020. The smallest territory, Grosseto, accounted for 407 and 334 kt $CO_{2\text{eq}}$ in 2019 and 2020, respectively, though recording the largest reduction – 15.4%. Finally, Siena generated 1′300 kt $CO_{2\text{-eq}}$ in 2019 and 1′200 kt $CO_{2\text{-eq}}$ in 2020 showing a 7.7% fall.

The recorded decrease for all the territories considered (Fig. 3a, b, c) was larger than the reduction documented at the national scale (−8.7%) (Fig. 3d). While it is evident that at national level the activities associated to the biggest amounts of emissions were the ones affected by the

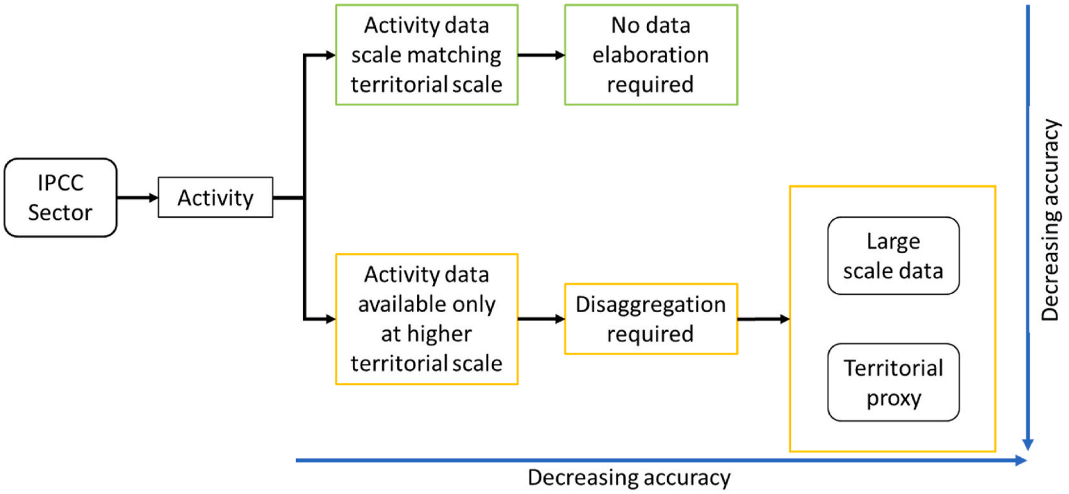


Fig. 1. Schematic representation of the decision process followed to deal with missing data or data gaps. Squares with green edges indicate the most preferable option, while squares with yellow edges indicate the least preferable one. The options are sorted from left to right and from the top to the bottom following the level of accuracy obtainable by opting for them. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

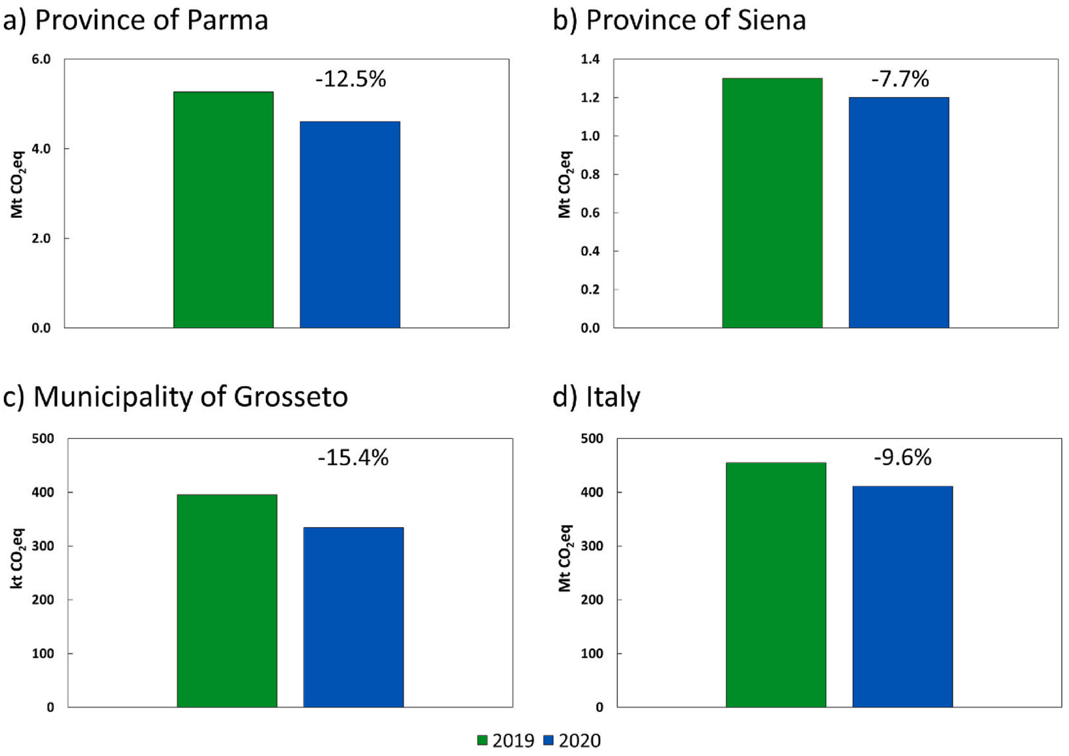


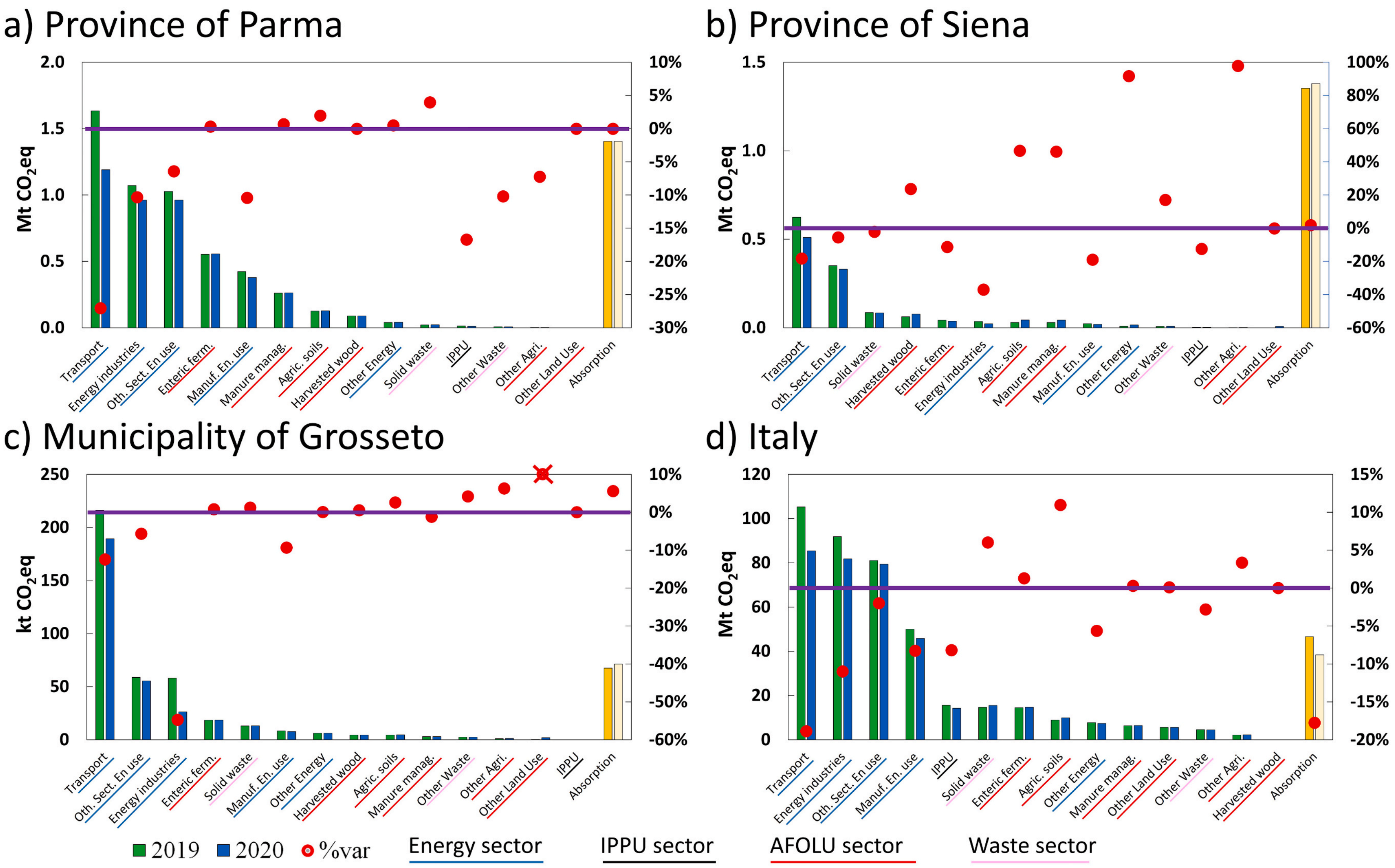
Fig. 2. Total gross GHG emissions in 2019 and 2020 for a) Parma, b) Siena, c) Grosseto, d) Italy. Results are expressed in terms of CO_2-eq, together with the percentage variation between the two years on top of the blue column. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

largest fall (i.e., transport, energy industries, and energy production in manufacturing activities – see Fig. 3d), the results are much more heterogeneous for the sub-national contexts (Fig. 3a, b, c).

Being capable to account for the CO_2 absorption from the atmosphere – aside from the emissions – the method captures the capacity of a territory to compensate the GHG released by the human activities within its boundaries – typically through natural ecosystems uptake. Parma abated around 1′405 kt $CO_{2\text{-eq}}$ (Fig. 3a) compensating 27% and 30% of the gross emissions in 2019 and 2020, respectively. Grosseto abated around 70 kt $CO_{2\text{-eq}}$ (Fig. 3c) allowing to compensate 17% and 21% of the gross territorial emissions in 2019 and 2020, respectively. Finally, Siena absorbed a quantity of emissions that is larger than the gross territorial ones – around 1′400 kt $CO_{2\text{-eq}}$ (Fig. 3b) – which accounted for 104% and 115% of the gross emissions.

To ease the comprehension, hereafter we refer to the emissions as to the activity from which they originated.

Our analysis showed that the pandemic induced most GHG emission reduction for the transport sector in Parma, in both absolute (Mt CO_2eq) and relative terms (%), and Siena (Fig. 3a and b). Here, energy industries were the most affected in relative terms, but they were less relevant in absolute terms, while in Grosseto energy industries were the most affected in both terms (Fig. 3c). This indicates the large potential that



a) Province of Parma

b) Province of Siena

c) Municipality of Grosseto

d) Italy

Fig. 3. Gross GHG emissions in 2019 and 2020 for a) Parma, b) Siena, c) Grosseto, d) Italy. Results are expressed in terms of CO$_2$-eq (left axis), together with the percentage variation between the two years (right axis). The purple horizontal line indicates 0% variation. To allow an easy comparison the absorption values are expressed as positive, colored in orange shades, and placed at the right side of the charts. Activities accounting for a marginal share have been aggregated by sector. The crossed dot indicates a variation out of scale (+343%). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

mitigating actions addressing these sectors could attain in each territory. Energy activities showed the largest fall in terms of emission for all the territories considered (Fig. 3). The highest variation was recorded for the energy industries in Grosseto (−55%) (Fig. 3c). In general, energy activities recorded a negative or marginally (<1%) positive variation, except for fugitive emission for Siena (included in "other energy"). Consider that energy industries include waste-to-energy and biogas plants besides traditional power plants – whether renewable or not.

IPPU sector followed the energy activities, recording a negative variation in all cases, in line with the national trend (−8%). Parma recorded the largest decrease (−17%), followed by Siena (−13%).

Activities belonging to the AFOLU sector showed a less definite trend, with mostly marginal variations (either slightly positive or slightly negative). However, cases of significant reduction were detected, especially for Siena, where the emission from enteric fermentation recorded a reduction of 11%, whilst other agricultural activities almost doubled their emission (+98%) (Fig. 3b). It is also noteworthy that the emission from other land use in Grosseto grew by 343% (Fig. 3c).

Waste activities showed contrasting results, with solid waste (i.e., landfill, composting and selection plants) following the growing national trend (6%) in Parma (4%) and Grosseto (1%) but decreasing in Siena (−2%). Other waste activities (i.e., wastewater treatment) significantly decreased in Parma (−10%), in line with the national trend (−3%) but increased sharply in Siena (17%) and moderately in Grosseto (4%).

Finally, the absorption increased marginally in the three territories, showing an opposite trend compared to the national context (−18%).

The pandemic reshaped the composition of the emission inventory in a different way in each territory (Fig. 4). While the overall contribution of the energy sector decreased, it maintained a central role, accounting for more than half of the total emissions (Fig. 3). However, despite the reduction in energy activities being proportionally similar for Parma and Siena, there was a contrasting pattern observed for Grosseto (Fig. 4). In Grosseto, the significance of the energy industry declined while other energy activities gained greater importance. This trend also contradicts the national scale, indicating that smaller-scale territories can experience distinctive impacts.

While energy activities generally decreased, AFOLU activities recorded moderate variations showing a more stable trend (Fig. 3). This is clearly visible for manure management, agricultural soils, and harvested wood in Siena (Fig. 4). Waste activities showed a similar behavior. Instead, IPPU activities decreased comparably in the three territories, as well as at a national scale. We refer the reader to Table S5 in the supplementary material (2) for a complete and detailed list of the disaggregated activities and related emissions for both years and for the four territories.

4. Discussion

The pandemic had remarkably different consequences on the activities of territories where manufacturing plays a primary role. The restrictions directly affected the industrial activities falling in the IPPU categories such as glass and ceramic production. This was directly reflected in the emissions levels for IPPU sector for both Parma (−17%) and Siena (−13%), with a trend in line with the national figure (−8%). However, the results for Parma are illustrative in this sense since a large part of Parma's manufacturing activities (aside from the ones falling in the IPPU sector) are directly involved in the food supply chains and were spared from the restrictions by virtue of that (DPCM 8 marzo 2020, 2020; DPCM 9 marzo 2020, 2020). Indeed, the pandemic affected remarkably the transport activities too in Parma, especially in terms of diesel fuel combustion (−30%). This can be partly linked to reduced transport of the heavy raw materials for the mineral industry (and related finished products) and to the reduced general heavy traffic through the territory, facilitated by the presence of two branches of the most trafficked national highways. On the other hand, since food-related activities were not suspended, the related energy demand was not affected. In turn, this reflected in a limited reduction of the emissions from the energy industries, partly based on energy recovery from their waste (−10%, Table S5 in the supplementary material (2)). These findings are supported by the results for Siena and Grosseto, where the suspension of the manufactory activities (except for a marginal number, involved in food supply chains) drove the fall of the energy industry, while transport was less affected for the absence of heavy industries (Fig. 3) as the largest reduction was due to gasoline – mostly private passenger cars. The unaffected energy demand and waste generation due to the uninterrupted operation of activities involved in food-supply chains in Parma can explain even the absence of a significant reduction

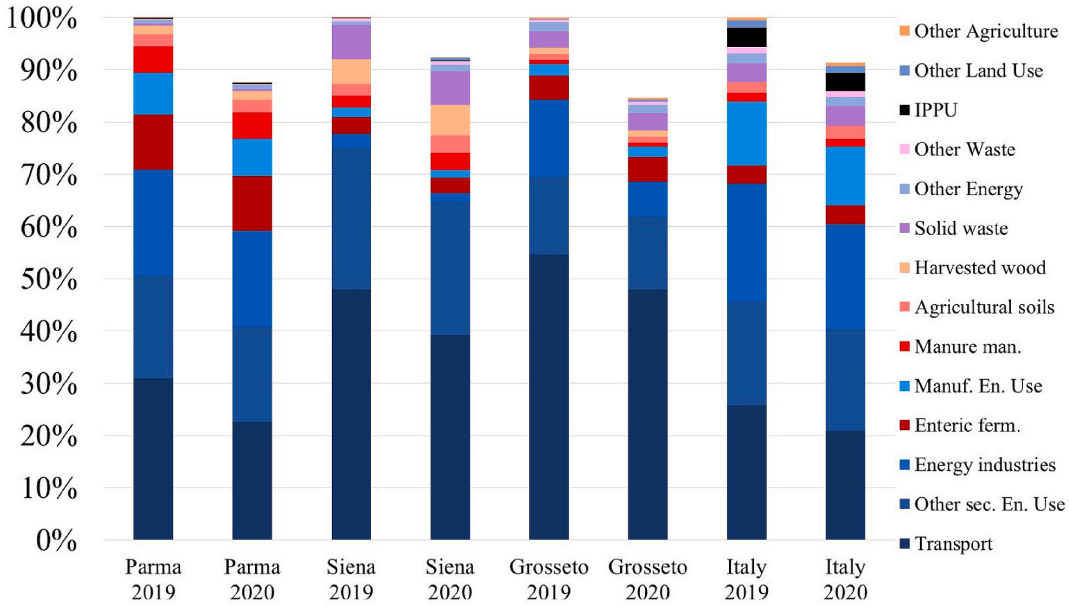


Fig. 4. The relevance of each activity over the gross total emission for the three studied territories and for the national Italian context for 2019 and 2020. Both 2019; 2020 figures are indexed on the basis of the values for 2019 to show the proportional overall variation over the two years. Activities belonging to the same sector have different shades of the same color. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

for the waste-to-energy activity. This is a key finding indicating that most of the variation is due to activities not involved in food supply chains. This quantification provides an estimation of the large mitigation potential that can be achieved through actions on activities that might be less relevant for the territory too (e.g., in terms of industrial output) and support policymaker in designing specific measures.

The pandemic significantly affected waste generation and treatment with consequences on multiple sides in territories where tourism plays a central economic role. First, a reduced presence of tourists resulted in lower quantities of waste generated and collected. Second, the emergence of a new type of domestic waste (e.g., disposable sanitary equipment such as personal protective equipment – PPE) coupled with reduced organic waste from food-serving activities (e.g., bars and restaurants) directly affected the composition of waste both landfilled and sent to energy recovery. Third, emergency measures were temporarily adopted to cope with the difficult moment, allowing waste collecting companies to landfill waste as collected without undergoing any selective previous treatment. Considering that emissions from landfilled waste are generated over a long period of time – even several years after the landfilling due to anaerobic activities – these multiple factors resulted in marginal change of emissions from solid waste disposal between 2019 and 2020 (4% in Parma, −2% in Siena, and 1% in Grosseto). However, this trend should be further investigated on a long-term basis to fully capture the peculiar type of emissions, characterized by a multiannual generation. Conversely, an immediate effect has been captured in terms of waste-to-energy activity for the territories relying on tourism, where a sharp fall was recorded (−65% in Grosseto, and −37% in Siena, Table S5 in the supplementary material (2)). Despite the pandemic curtailed the tourists presence in Parma comparably with respect to the other territories – −59% from 717′000 tourists in 2019 to 294′000 in 2020 for Parma (ISTAT, 2022e), −58% from 2′076′000 to 872′000 for Siena (Camera di Commercio di Arezzo-Siena, 2021), and −32% from 253′000 to 172′000 for Grosseto (Camera di Commercio della Maremma e del Tirreno, 2021) – the related decrease in waste generation was more than exceeded by the generation of unprecedented amounts of sanitary equipment, generally made of plastic. Indeed, in Parma – where tourism plays a significantly less relevant role compared to Siena and Grosseto – the waste-to-energy emission significantly intensified (11%), due to an increase in the plastic fraction, directly linked to disposed sanitary PPE. This confirms the strong relationship between the economic structure of the territory and the effect of the pandemic.

These results highlight the large mitigation potential that interventions on tourism-related waste generations can play in areas where tourism is well developed. Indeed, while touristic activities are already known for being a noteworthy source of large amounts of waste (Martins and Cró, 2021; Mateu-Sbert et al., 2013), the application shown in the present study provides quantitative and qualitative insights on the relationship between the tourism-waste production (examined in the waste sector) and the energy sector too. In this sense, the lack of electricity generated through waste could potentially result in a shift towards the use of non-renewable resources. These findings can support decision-makers in designing mitigation actions in both short- and long-terms in areas where tourism is pivotal in economic terms (Burlakovs et al., 2020).

The pandemic effect appears to be irrelevant in terms of heat production for heating private and public infrastructures. The marginal increase in Parma was linked to a slightly colder year as well as the marginal decrease in Siena and Grosseto was linked to a slightly warmer one (Eurostat, 2022). However, due to a shift of workers from the usual workplace (e.g., production plant, office, shops) to their private houses while the restrictions were in force, it is evident that the pandemic only shifted the emissions from the workplaces to residential buildings. This could mean that mitigation strategies focusing on heating might have comparable potential regardless of the type of building – provided that the shift of workers will become permanent.

Agricultural activities too were substantially unaffected. First, they were part of the food supply chain. Second, production simply cannot be abruptly interrupted, especially livestock rearing. Indeed, most variations related to a change in the number or species of animals present in the territories, a different type of annual crop cultivation, the use of different fertilizer products, or their use in different quantities. As such, while the pandemic does not offer particular insights in this case, the study can provide estimates on the relevance of the territorial agricultural activities, and can inspire mitigation related actions, such as reforestation, better grassland management, and alley cropping (Fargione et al., 2018).

The pandemic did not significantly affect the CO_2 absorption by the territories. Nevertheless, the inclusion of such estimation in the inventory provides insightful information too. For instance, by considering the proportion of territory actively absorbing CO_2 – typically forest – it is possible to estimate the extent of reforestation required to absorb a targeted quantity of emissions. In this sense, by virtue of its forests, Siena already absorbs enough CO_2 to compensate for the emissions generated within the same territory. Instead, considering that forests cover around 50% of the territory of Parma, it is evident that even if the whole territory was to be (hypothetically) reforested it would still be insufficient to compensate for its emissions (much larger than in Siena), despite being around the same size and having comparable absorption capacity compared to the forest of Siena. This reveals the relevance of a comprehensive assessment of both emission and absorption if and how effective reforestation could be as a mitigation strategy.

A last consideration is about the relationship between economic and environmental metrics. Over the analyzed period, Italian GDP decreased by 9% (World Bank, 2023), basically matching the simultaneous gross emission decrease (−9.6%; Fig. 1, Table S5). This would suggest a positive relationship between the economic and the environmental metrics. However, in 2020 the value added (similar to the Gross Domestic Product – GDP – at sub-national scale) decreased differently in the three territories, with Siena recording the largest variation (−9.3%), followed by Parma (−4.2%). For Grosseto there is no data at municipal level, but only provincial data, which corresponds to a decrease of 4.2% (Centro Studi delle Camere di commercio Guglielmo Tagliacarne, 2021). Comparing the economic trend with the environmental one shown in Fig. 4, these appear to be opposite. Indeed, GHG emissions decreased the most in Grosseto (−15.4%), followed by Parma (−12.5%) and Siena (−7.7%) (Fig. 2). This indicates that the apparent correlation deriving from national figures is not matched by sub-national results.

The discrepancy could be partly explained by comparing the relevance of territorial economic sectors within the territorial value added and the relevance of the emission sector within the territorial emission inventory. However, there is no direct match between the economic and environmental categories, hampering the possibility of conducting a robust analysis. The relevance of energy activities in driving GHG emissions (and their variation) is evident, but it is not possible to directly link it with the overall economic output (Szustak et al., 2021), or with any economic sector since the emission sectors reflect the physical source of the emission (the kind of physico-chemical reaction regardless of the human activity) whereas the economic sectors reflect the user-side information about the emission (the primary economic objective of production activities), regardless of the physico-chemical reaction involved. Our findings support the need to further explore the linkages between economy and environment by going beyond the existing “emission sectors” or “economic sectors”. For the purpose of the present study, our findings are particularly relevant as they reveal the capacity of sub-national applications of the GHG emission inventory to capture dynamics that national accounts would fail to grasp. The present work illustrates a possible application of environmental accounting, focusing on carbon accounting, at the sub-national level. Decision-makers wishing to apply sustainable policies cannot prescind from relying on solid science-based data, next to economic data – which too often represent the sole basis upon which policies are drawn. This general cultural shift in territorial governance is strongly needed, but still not highly diffused. To facilitate this shift, it is necessary to undertake systematic data collection campaigns, possibly at different scales and detail levels – allowing to aggregate data in terms of both emissive categories and economic categories. Integrating such kind of procedure in territorial governance can even facilitate the diffusion of the approach in other territories, not only in terms of good practices to follow, but also by providing a source of initial approximation. Territorial decision-makers willing to start a transition towards sustainability by implementing mitigation strategies could use the inventories compiled for territorial contexts with similar characteristics (in both economic and geographic terms) as a reference to draw a rough estimate of the emissive status of their jurisdiction. With such preliminary approximation, policy makers, and the population of the administered system, can gain awareness on the urge to act and start to implement a mitigation process, clearly based on a specific GHG emission inventory for such territory. Such type of initiative can facilitate the process to join alliances for the mitigation of climate change at municipality scale as in the case of the Covenant of Mayors,[2] but also at higher level, such as it already happened for the “Territorial Alliance for Carbon Neutrality: Parma”, the creation of which was inspired by the experience of the “Territorial Alliance for Carbon Neutrality: Siena”. Furthermore, other sub-national scale inventories can help practitioners to fill data gaps while compiling inventories for territories with similar contexts.

4.1. *Context-specific hotspots and mitigating actions towards the carbon neutrality goal*

The pandemic affected territorial and sectoral emission in different ways, driven by the socio-economic context. By identifying the emission reduction hotspots at a sub-national level and the related context-based drivers it is possible to generate information that can support mitigation strategies to guide the territories towards the achievement of the carbon neutrality goal. Furthermore, the mere territorial context imposes specific tailored actions. For example, since Siena has a surplus of energy generation (250 GWh in 2019) mainly thanks to the geothermal renewable energy power plants, it has attained a negative balance (i.e., CO_2 absorption larger than GHG emission). While no credit is currently assigned for this achievement, the surplus of electricity generated within the territory is consumed beyond the territorial borders. Such a surplus could be used to address the identified emission hotspot. For instance, it could be used to power up electric mobility substituting traditional fossil fuel-based mobility. Considering the current efficiency levels of 16 kWh/100 km for electric vehicles and 0.172 kg CO_2eq/km for gasoline cars (Pulselli et al., 2019), the energy surplus could avoid 269 kt CO_2eq, abating 21% of the territorial gross emission – thus almost 3 times the reduction due to the pandemic.

Instead, considering the well-developed dairy and pork industry in Parma, coupling a change in manure management practices with renewable energy production could be a win-win solution. If the manure from all stationary stabled dairy cattle and pig farms were sent to anaerobic digestion for electricity production (passing to 100% from the current 21% and 4% for cattle and pig, respectively), it could generate around 140 GWh (CRPA, 2012). On one hand, this would reduce the import of electricity from the national grid, on the other hand, a large part of the emission from manure management would be avoided. Considering that the digestate could be efficiently used as fertilizer (Sporchia and Caro, 2023), thus assuming that direct and indirect N_2O emission would be unaffected, methane emission would be avoided as the manure would be digested and the produced biogas used to generate electricity. Such solution could have avoided 222 kt CO_2eq in total (deducting emission from the anaerobic digestion), corresponding to 4% of 2019 gross territorial emission – almost one third of the reduction recorded in 2020. Of course, the methane in the biogas could also be purified and fed into the grid, or the generated electricity could be used to power electric vehicles as in Siena. However, most of the emission was generated by diesel – thus likely heavy trucks – meaning that electrification of the transport in Parma might not be as effective as in Siena. Nevertheless, the avoided inorganic fertilizer production and the heat generation from biogas would also contribute, but an accurate quantification was not feasible.

Grosseto benefits from a maritime port whose structure includes two breakwaters that could be used to generate blue energy. The dimensions of the breakwaters and the sea level are suitable for the installation of an embedded Oscillating Water Column device such as the one in Mutriku (Spain) which could reduce the import of electricity from the grid by generating around 250 MWh/year – estimation after Ibarra-Berastegi et al. (2018) hypothesizing the same depth and wave energy potential. This could avoid 89 kt CO_2eq emission, i.e., 27% of the 2019 territorial emission – almost twice the reduction recorded in 2020. The electricity could power the coastal touristic activities located in proximity to the port. The proposed solutions are based on existing technologies and are meant to not affect the territorial specific activities in any way.

For more details about these mitigation policies refer to Table S6 in the supplementary material (2).

5. Conclusions

By exploring the COVID-19 pandemic, we showed that a sub-national scale application of the GHG inventory captures the context-specificity providing information that can better support mitigation actions at local scale. This is necessary for territories aspiring to achieve carbon neutrality and supports the adoption of multi-level governance frameworks for the achievement of targets even at a broader scale – national or international. A systematic application of sub-national inventories as monitoring tool is informative not only for supporting local policymakers, but also to verify the effectiveness of the implemented measures. Furthermore, we observed that the economic and environmental metrics are not so strictly correlated. This highlights the capacity of subnational GHG inventory applications to provide complementary information that national accounts would fail to capture. The study revealed that the pandemic affected the sustainability level of countries, regions, communities, and activities heterogeneously. The emissive dynamics followed this heterogeneity strictly driven by the variety of the considered territorial contexts, depending on economic, social, and environmental features as well as on the scale. We showed and quantified how the pandemic affected different kinds of activities in different ways in different territories. The drivers that underpinned these diversified dynamics have been discussed revealing the existence of interconnections between activities belonging to different sectors. The results allowed to propose context-specific mitigation strategies that on the one hand, can support the studied territories towards the achievement of the carbon neutrality, and on the other hand, can be a proxy to facilitate similar territorial contexts toward the achievement of the same goal. The capacity of the methodology to deliver in this sense can be further increased through a close collaboration between the local administrations and the researchers for the provision of in-depth data that would allow an even higher resolution in the results.

Author contributions

Conceptualization, F.S., M.M. and F.M.P.; methodology, F.S., M.M and F.M.P.; validation, A.P., N.M. and F.M.P.; formal analysis, F.S. and M.M.; investigation, F.S. and M.M.; data curation, F.S., M.M. and A.P; visualization, F.S.; writing—original draft preparation, F.S. and M.M.; writing—review and editing, F.S., M.M., A.P., N.M. and F.M.P. All authors have read and agreed to the published version of the manuscript.

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[2] https://www.globalcovenantofmayors.org/.

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The article respects ethical responsibilities, proposed by the Publishing Ethics Resource Kit, approved by authors.

Consent to participate

All authors have agreed to participate and collaborate in elaborating the manuscript.

Consent for publication

All authors have agreed to the final version of the manuscript.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.119539.

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