Urban Climate 42 (2022) 101125

Contents lists available at ScienceDirect

Urban Climate

journal homepage: www.elsevier.com/locate/uclim

Development of sectorial and territorial information system to monitor GHG emissions as local and regional climate governance tool: Case study in Valencia (Spain)

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ARTICLE INFO

Keywords:
Climate change monitoring
Decision making
GHG
Climate governance

ABSTRACT

Regional and local decision-makers need high quality GHG emission inventories to invest efficiently available resources in climate change mitigation measures. Nevertheless, decision-makers lack of tools to achieve GHG emissions inventories with enough rigor, accuracy and completeness. Thus, a territorial and sectorial information system (SITE) has been developed to monitor GHG emissions as local and regional climate governance tool. This system combines the advantages of both, top-down and bottom-up approaches, to achieve an innovative hybrid approach to account and manage efficiently GHG emissions. The implementation of SITE in Valencia region (Spain) as a case study has quantified 163 indicators in 542 municipalities. Regional gross GHG emissions in 2019 were 30 Mt. CO_2 while the fixation was 6 Mt. CO_2 eq. 1.8% municipalities emit 34% of total emissions. 34% municipalities fix more than they emit. Finally, sectoral analysis demonstrates that only 20% indicators are responsible for 85% of total emissions.

1. Introduction

The current atmospheric CO_2 concentration is the highest in history reaching a worldwide average of 421 ppm in April 2021 (NOAA, 2021). This circumstance, in addition to high concentrations of other greenhouse gases (GHG) like CH_4 or N_2O cause the global warming to which natural and human systems are sensitive.

Continued GHG emissions will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems (IPCC, 2014). Effective decision-making to implement additional mitigation pathways is crucial to limit global warming below 2 °C in comparison to pre-industrial levels (European Commission, 2020). These pathways require environmental innovations to achieve future greener economies (Mongo et al., 2021) and substantial emissions reductions over the next few decades to be able to achieve near GHG zero emissions by the end of the century (European Commission, 2019).

With this aim, the European Commission published the European Green Deal Communication in which GHG emission reduction target for 2030 is increased to 50% and toward 55% compared with 1990 levels (European Commission, 2019). To monitor the

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https://doi.org/10.1016/j.uclim.2022.101125
Received 11 November 2021; Received in revised form 18 January 2022; Accepted 4 February 2022

accomplishment of this target, signatories of the United Nations Framework Convention on Climate Change (UNFCC) must report their GHG emissions annually through GHG inventories (European Commission, 2021).

All these international and European commitments are focused on a national level where there is still room to increase national policy efficiency in terms of GHG emission reductions (Niedertscheider et al., 2018). But local/regional authorities should also contribute to Nationally Determined Contributions (UNFCCC, 2016). Furthermore, at the local level, the signatory cities of the Covenant of Mayors for Climate and Energy (or simply "Covenant of Mayors") are committed to support the implementation of the EU 40% GHG emission reduction target by 2030 and the adoption of a joint approach to tackle mitigation and adaptation measures (Covenant of Mayors, 2021). Moreover, Covenant signatories commit to submitting a Sustainable Energy and Climate Action Plan (SECAP) outlining the key actions they plan to undertake (Kona et al., 2016) to reduce their GHG emissions.

The planning and execution of SECAPs must be based on Baseline Emission Inventories (BEI) (JRC, 2018). This means that any strategy to commit resources aimed at climate change mitigation at local level is affected by the quality of the GHG emission inventories. Despite this stringent need, public decision-makers lack tools to quantify GHG emissions with enough rigor, accuracy and completeness, including all existing emission sources in the city. Simplified inventories with low-quality and incomplete scope are often used to define this BEI.

This shortcoming is due to the lack of adaptation to local/regional context of the two main existing approaches to GHG emissions quantification, the top-down approach and the bottom-up approach.

Top-down approach consists of disaggregating a global value using specific variables available on a smaller scale to obtain the disaggregated values (Fiorillo et al., 2020). Taking as example the cement industry, total national emissions assigned to this sector could be disaggregated for a municipality by using an attributive variable such as the number of cement factories in this municipality. The key advantage of this approach is that it requires few data and is therefore cost efficient. However, the accuracy of top-down approaches depends on both the accuracy of the global value used and the quality of the attributive variable used. In the example described, it can be assumed that the number of cement factories is important, but what determines their emissions is the fuel consumed and the flow of the material introduced into the process in each of them. Therefore, the quality of the top-down approach is lower compared to the bottom-up approach (Jing et al., 2016; Mateo Pla et al., 2020). Furthermore, this approach does not allow to monitor mitigation measures taken in SECAPs since mitigation measures undertaken by local emitters will normally have a small impact on the national GHG aggregate. Consequently, there is no possible impact assessment of SECAPs with top-down data.

Alternatively, bottom-up approach consists of aggregating the results calculated to obtain the global result on a larger scale (Fiorillo et al., 2020). Following our example, it means the emissions' aggregation of every cement factories in the municipality to obtain total emissions of the cement industrial activity in this municipality. The key advantage is the greater accuracy allowing for monitoring the mitigation measures conducted by each agent individually. On the other hand, it requires much higher amount of data, computational effort, and resources (Mateo Pla et al., 2020). There are experiences where a bottom-up approach has been applied at the sub-national level like in Siena province in Italy (Bastianoni et al., 2014). However, bottom-up approaches entail two major disadvantages: they do not allow obtaining disaggregated values at the local level to develop local SECAPs and they require a big effort and resources to collect the region-specific data.

Baseline Emission Inventories on which SECAPs from municipalities are based, are typically found with the following features:

1. Top-down approach-based inventories with only a few attributive variables (population, number of cars etc.) that result in low-quality inventories that do not allow adequate monitoring of the mitigation measures implemented in their SECAPs. These characteristics are very often found when analysing Baseline Emission Inventories (Dai et al., 2016).
2. Bottom-up approach-based inventories limited to few agents from which municipalities have easily available data, leaving most indicators unquantified due to the difficulty of access to the needed data. This approach entails the risk of misdiagnosis of real emissions. Thus, SECAPs planned based on these inventories are inefficient and lead to an investment of available resources in low-impact measures as can be observed by comparing the efficiency of the different key action defined. For example, in the SECAP of the city of Palermo, a measure taken on car and bike sharing had an implementation cost per tonne of CO_2 reduced of 2587 € (Covenant of Mayors, 2015), while a similar measure of the SECAP of the city of Valencia (a bike sharing service) has a ratio of 34 € per tonne of CO_2 reduced (Covenant of Mayors, 2019).

To overcome these critical shortcomings of nowadays SECAPs, the general aim of this study is to develop a sectorial and territorial information system (SITE) able to monitor GHG emissions as a local and regional climate governance tool. In the following, the acronym SITE refers both to the calculation methodology and to the digital platform that has been developed to handle the large volume of data involved. The research has following specific objectives:

1. to adapt the inventory structure of the Intergovernmental Panel on Climate Change (IPCC) at the local level,
2. to develop an innovative GHG quantification methodology based on a hybrid bottom-up and top-down approach and
3. to implement the SITE system for climate governance in the case study of Valencia region (Spain).

2. Material and methods

This section develops the inventory structure and quantification methodology used by SITE and the criteria followed to implement SITE in the case study. Finally, the internal actions and decision made by SITE to apply the highest efficient methodological approach in each indicator of each local implementation of the region has been systematized.

2.1. Inventory structure

The SITE inventory structure is an adaptation of the structure proposed by the International Panel on Climate Change (IPCC, 2006) to ensure standardization and the full scope for the BEI at local/regional level. The adaptation allows to improve its manageability and coherence for its implementation at local and regional level.

The adaptation consists primarily of reducing the number of disaggregation levels from seven reached by the IPCC to three by SITE inventory. Then, "Transport" and "Forestry" sectors have been disaggregated from "Energy" and "Land use", respectively. "Transport" for having great relevance at the local level, in connection with urban mobility policies, and to improve its monitoring consequently. "Forestry" for its net sink effect. Additionally, the IPCC indicator corresponding to "Emissions from Electricity Generation" has been replaced by a criterion made up of several SITE indicators corresponding to "Emissions derived from Electricity Consumption", since at the local level there is capacity to act on consumption and rarely on generation. Finally, some minor changes have been made, such as the disaggregation of public road transport from the total road transport because of its importance to local public administrations to fulfil international agreements (e.g. Covenant of Mayors).

The changes made to adapt IPCC structure to local level in SITE have been systematized using coefficients called *C,* which have been estimated from statistics (e.g. electricity generation and electricity consumption in residential, industrial, commercial, public sector (IDEA, 2019). This guarantees a complete correspondence between SITE and IPCC indicators, ensuring compatibility with standardized international reporting and allowing to shows results in both SITE and IPCC format.

SITE inventory is composed of three levels of disaggregation: sector, criterion and indicator. All existing emission sources are classified in one of the inventory indicators. Criteria are groupings of indicators and sectors are grouping of criteria (Fig. 1). Thus, all emission sources are quantified in the inventory and all of them will reach the same level of disaggregation (indicator), allowing their comparability and aggregation. In total, there are 163 indicators belonging to six Sectors:

1. Energy (without transport)
2. Transport
3. Industrial Processes and Product Use
4. Agriculture, Livestock and Other Land Use (without forestry)
5. Waste
6. Forestry

2.2. GHG emissions quantification methodology

SITE includes several distinct but complementary quantification methodologies: a top-down methodology (SITE 1.0) and a bottom-up methodology (SITE 2.0). SITE 1.0 consists of the attribution at the local level and within each indicator of emissions quantified at the national level in the IPCC inventory by using local attributive variables. Therefore, SITE 1.0 allows to quantify emissions from all sources at the local level as long as enough quality local attributive variables are available. SITE 2.0 consists of the application of the IPCC methodology (IPCC, 2006), but with specific data aggregated from the local level. Therefore, SITE 2.0 has a higher quantification accuracy and allows exhaustive monitoring of the mitigation measures implemented, but implies a high cost due to the difficulty of obtaining the necessary data with enough spatial and temporal disaggregation.

Between both there is a third hybrid strategy that allows to identify the most relevant indicators through SITE 1.0, to focus on the necessary efforts that requires a bottom-up methodology approach of SITE 2.0 on the fewest number of indicators that involve the highest number of emissions, or those indicators mainly affected by any mitigation measure implemented.

This hybrid approach is SITE 3.0. It allows improving SITE 1.0-quantification of each indicator based on patterns generated by SITE 2.0-implementation. Thus, this information processing technique supported by big data allows to generate specific coefficients (*cvL*) that offer the possibility of using new local attributive variables to improve accuracy. Hence, SITE 3.0 offers a good compromise

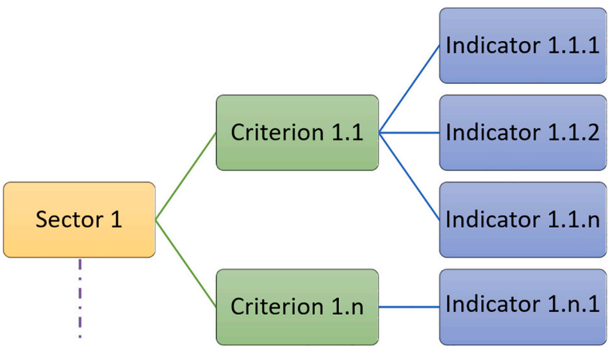

Fig. 1. SITE inventory structure scheme.
Complete SITE inventory structure can be found in the Appendix section.

between accuracy and cost.

In the following subsections, SITE 1.0, 2.0, and 3.0 quantification methodologies will be explained in detail. In addition, the sources of uncertainty are identified in each quantification methodologies, although their quantification is not the objective of this work.

2.2.1. SITE 1.0 top-down approach

SITE 1.0 methodology has been designed to combine national level information with data of local activity to attribute the results of IPCC emission inventory to a given region or municipality. SITE 1.0 methodology ensures coherence between local inventories and the IPCC national inventory in a way in which that if it is applied to all municipalities in the national territory, total GHG emissions will always sum the original value offered by the IPCC national inventory. Thus, SITE 1.0 methodology is described by following equation:

$$E_{1;i,j,k} = IPCC_{i,j,k}\frac{vL_{i,j,k}}{vN_{i,j,k}} \times C_{i,j,k} \tag{1}$$

where:

$E_{1;\, i,\, j,\, k}$: SITE 1.0 GHG emissions (t CO_2 eq.) of the local indicator k belonging to criteria j of sector i of a given municipality or local aggregate (region, province, county, etc..).

$IPCC_{i,\, j,\, k}$: GHG emissions (t CO_2 eq.) of the national indicator k belonging to criteria j of sector i of the country.

$C_{i,\, j,\, k}$: corresponding conversion coefficient from the IPCC indicator to SITE indicator.

$vL_{i,\, j,\, k}$: Value of the local attributive variable used to calculate indicator k belonging to criteria j of sector i.

$vN_{i,\, j,\, k}$: Value of the attributive variable in the country used to calculate indicator k belonging to criteria j of sector i, to which the IPCC value is referred.

i: Sector of emissions (Energy, Waste etc.)

j: Criterion of Sector (Emissions from burning fuel in manufacturing and construction industries, etc.).

k: Indicator of Criterion (Emissions from fuel burning in the steel industry, etc.).

The corresponding criterion emission for criteria *j* belonging to sector *i* is then given by:

$$E_{1;i,j} = \sum_{k=1}^{N_{i,j}} E_{1;i,j,k} = \sum_{k=1}^{N_{i,j}} IPCC_{i,j,k}\frac{vL_{i,j,k}}{vN_{i,j,k}} \times C_{i,j,k} \tag{2}$$

where:

$N_{i,\, j}$ is the number of indicators that belong to criteria *j* of sector *i*.

Finally, emissions for each sector *i* are given by:

$$E_{1;i} = \sum_{j=1}^{N_i} E_{1;i,j} = \sum_{j=1}^{N_i}\sum_{k=1}^{N_{i,j}} IPCC_{i,j,k}\frac{vL_{i,j,k}}{vN_{i,j,k}} \times C_{i,j,k} \tag{3}$$

where:

N_i is the number of criteria that belong to sector *i*.

The sources of uncertainty of SITE 1.0 estimation depend on the data obtained from bottom-up quantification at the national level ($IPCC_{i,j,k}$) and from the techniques for obtaining the attributive variables at the national level ($vN_{i,j,k}$) and local level. ($vL_{i,j,k}$). Other uncertainty source depends on the relationship that the attribute variable has with the real emissions quantified. For example, the m^3 of treated wastewater is closely related to the real emissions of the indicator “Treatment and discharge of domestic waste water” because at the national level there is a lot of uniformity in wastewater treatment technology since it does not change substantially depending on the ubication. However, in the “Cows (Manure Management)” indicator, the relationship between the number of head of cattle and the emissions derived from the management of their manure depends on the meteorological conditions and treatment technology of the territory, since it can change substantially depending on the weather.

2.2.2. SITE 2.0 bottom-up approach

SITE 2.0 methodology is obtained from (IPCC, 2006). The basic equation combines information on the extent to which a human activity takes place (named activity data, in units of energy or quantity of material) with coefficients, which quantify the emissions or removals per unit activity (named emission factors). Thus, the basic equation is:

$$E_{2;i,j,k} = AD_{i,j,k} \times EF_{i,j,k} \tag{4}$$

where:

$E_{2;\, i,\, j,\, k}$: GHG emissions (t CO_2 eq.) of the local Indicator *k* belonging to criteria *j* of sector *i* of the municipality applying SITE 2.0.

$AD_{i,j,k}$: Activity Data. For example, quantity of consumption or production of energy, material etc. that represents the total activity corresponding to local indicator *k*, belonging to criteria *j* of sector *i*.

$EF_{i,j,k}$: Emission factor that relates the produced quantity unit to GHE emissions for the corresponding sector, criteria and indicator.

Eq. (4) is in some circumstances modified to include other estimation parameters than emission factors or more than one activity datum per indicator (e.g. in complex processes comprising more than one step or fuels with different emission factors). In these cases, eq. (4) turns into a summation of products of the corresponding AD quantities and emission factors. In other cases, where time lags are involved, (i.e. material decomposition in a landfill, leakage of refrigerants from cooling devices etc.), other methods are provided (i.e. first order decay methods). Additionally, other methods as mass balance methods or more complex modelling approaches have been also applied following (IPCC, 2006).

In any case, SITE 2.0 methodology means the application of the same estimation procedure used at national level whenever enough information is available to perform the corresponding estimation with data collected or sampled at local or municipal level. It assumes the use of monitoring or sampling methods that are nowadays available in many cases with the use of sensors, communication networks and IT tools. An example is the increasingly extended availability of data of household electricity or fossil fuel consumption at municipal scale, which allows performing SITE 2.0 estimations for indicators corresponding to these consumptions.

However, very often, this type of data is available partially, only in a fraction of municipalities or in given time windows. This brought us to the idea to develop a further hybrid approach (SITE 3.0), which combines both previous methodologies in order to efficiently fill information gaps between SITE 1.0 and SITE 2.0.

In SITE 2.0 there are two sources of uncertainty. Firstly, the uncertainty due to the techniques for obtaining activity data ($AD_{i,j,k}$). Secondly, the uncertainty due to the emission factors used ($EF_{i,j,k}$). The uncertainty associated with the Emission Factor used can be consulted in IPCC (2006).

2.2.3. SITE 3.0 hybrid approach

The hybrid methodology (SITE 3.0) includes a variable amount of local attributive variables (*vL*) and its corresponding specific coefficients (*cvL*) obtained through adjustment between SITE 1.0 and SITE 2.0 results. In principle, the relationship between the local attributed variables, coefficients and SITE 2.0 emission values could have any functional form. But to illustrate the methodology, we will assume a linear relationship in the form of the following equation:

$$E_{3;i,j,k} = cvL_{i,j,k,1} \times vL_{i,j,k,1} + \ldots + cvL_{i,j,k,n_{i,j,k}} \times vL_{i,j,k,n_{i,j,k}} = \sum_{s=1}^{n_{i,j,k}} cvL_{i,j,k,s}\, vL_{i,j,k,s} \tag{5}$$

where:

$E_{3;\,i,\,j,\,k}$ GHG emissions (t CO_2 eq.) of the local indicator *k* belonging to criteria *j* of sector *i* of the municipality applying SITE 3.0.

$vL_{i,\,j,\,k,\,1}$, $vL_{i,\,j,\,k,\,2}$, …, $vL_{i,\,j,\,k,\,n_{i,\,j,\,k}}$: value of the local attributive variables 1,2, …, $n_{i,\,j,\,k}$ in the municipality used to calculate indicator *k* belonging to criteria *j* of sector *i*.

$cvL_{i,\,j,\,k,\,1}$, $cvL_{i,\,j,\,k,\,2}$, …, $cvL_{i,\,j,\,k,\,n_{i,\,j,\,k}}$: value of coefficients 1, 2, …, $n_{i,\,j,\,k}$ for the indicator *k* of criterion *j* of sector *i*.

To obtain the specific coefficient variables ($cvL_{i,\,j,\,k,\,s}$) at least as many reliable indicators quantified with SITE 2.0 from different municipalities as local attributive variables available (eq. (6)) are needed.

Hence, we assume that the quantity of SITE 2.0 emissions, $E_{3;\,i,\,j,\,k}(p)$, corresponding to *(i,j,k)* sector, criteria and indicator is available for a sufficient number of municipalities m_p, $p = 1, . . , M_{i,\,j,\,k}$. For the emission values of the chosen municipalities following vector-form has been applied:

$$\vec{E}_{2;i,j,k} = \left(E_{2;i,j,k}(1), \ldots.., E_{2;i,j,k}(M_{i,j,k})\right) \tag{6}$$

The local attributive variable vector is given by:

$$\overrightarrow{vL}\left[(m_p)\right] = \left(vL_{i,j,k,1}(m_p), vL_{i,j,k,2}(m_p), \ldots., vL_{i,j,k,n_{i,j,k}}(m_p)\right) \tag{7}$$

And eq. (5) can be written as the following scalar product:

$$E_{3;i,j,k}(m_p) = \overrightarrow{cvL}_{i,j,k} \bullet \overrightarrow{\mathrm{vL}}(\mathrm{m_p}) \tag{8}$$

The specific coefficient variables vector $\overrightarrow{cvL}_{i,j,k}$ shall statistically represents the sample of municipalities to which the methodology will be applied. It is therefore essential to ensure enough homogeneity between the $M_{i,\,j,\,k}$ municipalities used as reference set and the rest. .

We can form the corresponding vector-form for the SITE 3.0 estimators given by:

$$\vec{E}_{3;i,j,k} = \left(E_{3;i,j,k}(1), \ldots..E_{3;i,j,k}(M_{i,j,k})\right) = \left(\overrightarrow{cvL}_{i,j,k} \bullet \overrightarrow{\mathrm{vL}}(1), \ldots, \overrightarrow{\mathrm{cvL}}_{\mathrm{i,j,k}} \bullet \overrightarrow{\mathrm{VL}}(\mathrm{M_{i,j,k}})\right) \tag{9}$$

Now we can solve the following minimization problem:

Choose $\overrightarrow{cvL}_{i,j,k}$ that minimizes the Mean Square Error (MSE) corresponding to the Euclidean distance between $\vec{E}_{2;i,j,k}$ and $\vec{E}_{3;i,j,k}$.

The above procedure allows hence to obtain $\overrightarrow{cvL}_{i,j,k}$ provided the number of available SITE 2.0 estimators is larger than the number of attributive variables and coefficient we intend to adjust ($n_{i,\,j,\,k} \le M_{i,\,j,\,k}$). Now the SITE 3.0 emissions of any municipality, from which no direct SITE 2.0 emission data are available, can be calculated from their local attributive variable by means of:

$$E_{3;i,j,k}[m] = \sum_{s=1}^{n_{i,j,k}} cvL_{i,j,k,s} vL_{i,j,k,s}(m) \tag{10}$$

Thus, SITE system will self-learn as more data are processed to improve the accuracy of the *cvL* for each indicator.

Finally, GHG emissions of the installations of the EU-ETS (Emissions Trading System of European Union) described in the EU Directive 2003/87/EC (European Commission, 2003) are excluded from local commitments such as the Covenant of Mayors, which recommends not to include them in the GHG emission inventories because of their own regulatory framework conditions (JRC, 2016). However, these installations are part of the municipalities and despite having their own regulatory framework, we believe that it is necessary to quantify their environmental responsibility in the municipalities to avoid wrong diagnosis. In addition, these installations must quantify and report their GHG emissions annually according to the standards described in Commission Regulation (EU) 601/2012 (European Commission, 2012) and therefore data are easily available and accessible. Despite this fact, the treatment of these results can lead to errors because the result of their quantification corresponds to the aggregation of different emission sources within industrial chains (e.g. combustion, manufacturing processes, product use), which both in the IPCC inventory structure as in its adaptation in SITE corresponds to different indicators of different sectors. Therefore, it cannot be included in any SITE methodology to avoid double counting. In the SITE system, EU-ETS installations have been included as an independent layer associated with the municipality, but independently of the results shown using the different SITE approaches. This makes it possible to avoid errors and to maintain the methodological coherence and rigor, as well as to consider ETS emissions in the big picture of the municipal GHG emission inventories and in the climate change strategy of the municipality or region.

The main sources of uncertainty of SITE 3.0 hybrid approach depend on the three assumptions made. In addition, uncertainty also come from the techniques for obtaining attributive variables at the local level ($vL_{i,j,k}$) that are used in the model.

2.2.4. SITE implementation within a software platform aimed at commercial use

To manage the considerable amount of information, complexity and connectivity that is inherent to our methodology, it was necessary to implement the algorithms explained in this contribution into a specific data framework that was licensed to an IT company to be implemented as a commercial Software Platform. All calculations for the case study shown in the following sections, the maps and tables were stored and produced by means the aforementioned platform.

2.3. Case study: Application of the SITE framework at regional level

The developed SITE methodology has been applied and tested in a regional case study in Valencia (Spain) for the year 2019. The region of Valencia ("Comunitat Valenciana" or simply "Valencia") is located in the East of Spain at the Mediterranean Sea. The region has approx. 5 million inhabitants (more than 10% of the total population in Spain) and accounts for 542 municipalities distributed in three provinces, Castellon (135), Alicante (141) and Valencia (266 municipalities). All socioeconomic sectors are present in the region: agriculture, industry and services, especially tourism. The city of Valencia is located at the centre of the region, directly at the coast. It

Table 1
Datasets that contain local attributive variables of Valencia region.

Dataset	Main application Sector	Source
Number of inhabitants	Generic	Statistics National Institute[1]
Latest operating income by company with corresponding primary and secondary NACE code	Generic	Official Chamber of Commerce, Industry, Services and Navigation of Valencia[2]
Urban planning area catalogued as "Non-Urbanizable"	Generic	Statistics portal of Valencia region[3]
Urban planning area classified as "Endowment"	Generic	
Number of main dwellings per living area	Energy	
Number of secondary dwellings	Energy	
Number of empty dwellings	Energy	
Number of companies in the construction sector	Energy/Industry	
Number of companies in the Industrial sector	Energy/Industry	
Number of companies in the service sector	Energy/Industry	
Area by type of irrigated crop	Land Use	
Area by type of rainfed crop	Land Use	
Cereal cultivation area for irrigated grain	Land Use	
Forestry area (Wooded)	Forestry	
Volume of treated water in the Wastewater Treatment Plants	Waste	
Organic load BOD5 in Wastewater Treatment Plants	Waste	
Amount of dry sludge evacuated by Wastewater Treatment Plant	Waste	
Amount of wet sludge evacuated by Wastewater Treatment Plant	Waste	
Wetland area	Land Use	
Number of vehicles by vehicle type	Transport	Statistic portal of General Direction of Traffic[4]
Number of Gasoline vehicles by type of vehicle	Transport	
Number of Diesel vehicles by vehicle type	Transport	
Energy Performance of Buildings certificates following EU Directive 2010/31 (European Commission, 2010)	Energy	Directorate General for Industry and Energy of the Generalitat Valenciana

1 https://www.ine.es/jaxiT3/Tabla.htm?t=2903&L=1
2 https://www.camaravalencia.com/es-ES/informacion/bases-datos-informes/Paginas/bases-de-datos-empresas-espanolas-info.aspx
3 http://pegv.gva.es/va/bdt
4 https://sedeapl.dgt.gob.es/WEB_IEST_CONSULTA/subcategoria.faces

has a population size of approx. 800.000 citizens and is the third largest city and urban area in Spain, after Madrid and Barcelona.

To this aim, SITE 1.0 has quantified the GHG emissions of 163 indicators belonging to all sectors of all municipalities of the region of Valencia. Additionally, 38 Covenant of Mayors signatory municipalities were analysed in detail to apply SITE 2.0-approach to improve estimations of GHG emissions in the rest of municipalities not included in the analysis though hybrid approach.

2.3.1. Data gathering

The local attributive variables are shown in Table 1, where main application sector and data source is also described.

The datasets described in Table 1, contain the value of local attributive variables by municipality ($vL_{i,\ j,\ k,\ s}$) and value of the attributive variable at the national level ($vN_{i,\ j,\ k}$).

Specifically, the dataset "Latest operating income by company with the corresponding primary and secondary NACE code" contains the latest operating income of more than 210,000 companies and their primary and secondary NACE (Nomenclature of Economic Activities) code. Each NACE code has been associated with the indicators of SITE inventory structure to which this economic activity contributes in terms of GHG emissions.

In addition, the total of "Latest operating income by NACE code at the national level" has also been calculated corresponding to Vnn_{ijk} of this attributive variable.

Regarding the dataset "Energy Performance of Buildings," it contains more than 500,000 Building Energy Performance Certificates provided by the Directorate for Industry and Energy of Valencian.

Finally, the 174 EU-ETS reporting installations existing in Valencia have also been introduced.

Their data have been obtained from the annual report of (OECC, 2020) and introduced as an extra layer that associates each installation and its emissions with the municipality, where each of them operates.

2.3.2. Criteria for sampling representative municipalities

Baseline Emission Inventories (BEI) of 38 municipalities (Table 2) attached to the Covenant of Mayors of the Valencia region have been analysed to include their GHG emissions results obtained from bottom-up approach into SITE 2.0 to allow SITE 3.0 implementation as well as to evaluate accuracy improvement achieved.

To exemplify our approach, one indicator has been selected on the basis of prioritization resulting from the implementation of SITE 1.0.

The criteria established for sampling representative municipalities to evaluate the SITE 3.0 hybrid approach are:

1. to have an emission inventory developed through a bottom-up approach,
2. to pass an outlier's filter based on a ratio of CO_2 emissions/inhabitants, to identify possible differences in the scope applied,
3. to have quantified every fossil fuel source (Natural Gas, Diesel and LPG) in the BEI of the municipality,
4. to be quantified using a rigorous methodology (for example, avoiding methodologies based on survey sampling with too low a number of surveys).

2.3.3. Development of SITE as advanced climate governance system

SITE climate governance tool is developed as a procedure to link various quantification approaches to achieve the highest efficient GHG emissions quantification of all indicators in each municipality belonging to the region.

Fig. 2 shows the corresponding decision tree of SITE indicators, including the sequence that each indicator in each municipality must follow to apply the most efficient methodology approach.

First, the 163 indicators are calculated at local level in each municipality of Valencia through SITE 1.0 approach using the input data of IPCC national inventory and local attributive variables. Then, the indicators quantified which not have SITE 2.0 applied to any municipality are translated to the final output of SITE "Local GHG inventories".

In the third place, SITE 1.0 indicators are analysed in three aspects:

Table 2
Municipalities attached to the Covenant of Mayors of the Valencia region analysed.

Municipalities analysed to select the sample		
Alacant	Novelda	València
Alcoi	Orihuela	Alboraia
Benidorm	Alcalalí	Ontinyent
Benissa	Pego	Torrent
Callosa d'en Sarrià	Petrer	Alcúdia
Concentaina	Villena	Pobla de Vallbona
Dénia	Castelló de la Plana	Carlet
Xàbia	La Vall d'Uixó	Canals
Elda	Vinaròs	Alcúdia de Crespins
Elx	Almassora	Llaurí
Ibi	Borriana	Paterna
Vila Joiosa	Cabanes	Simat de Valldigna
Muro de Alcoy	Nules	

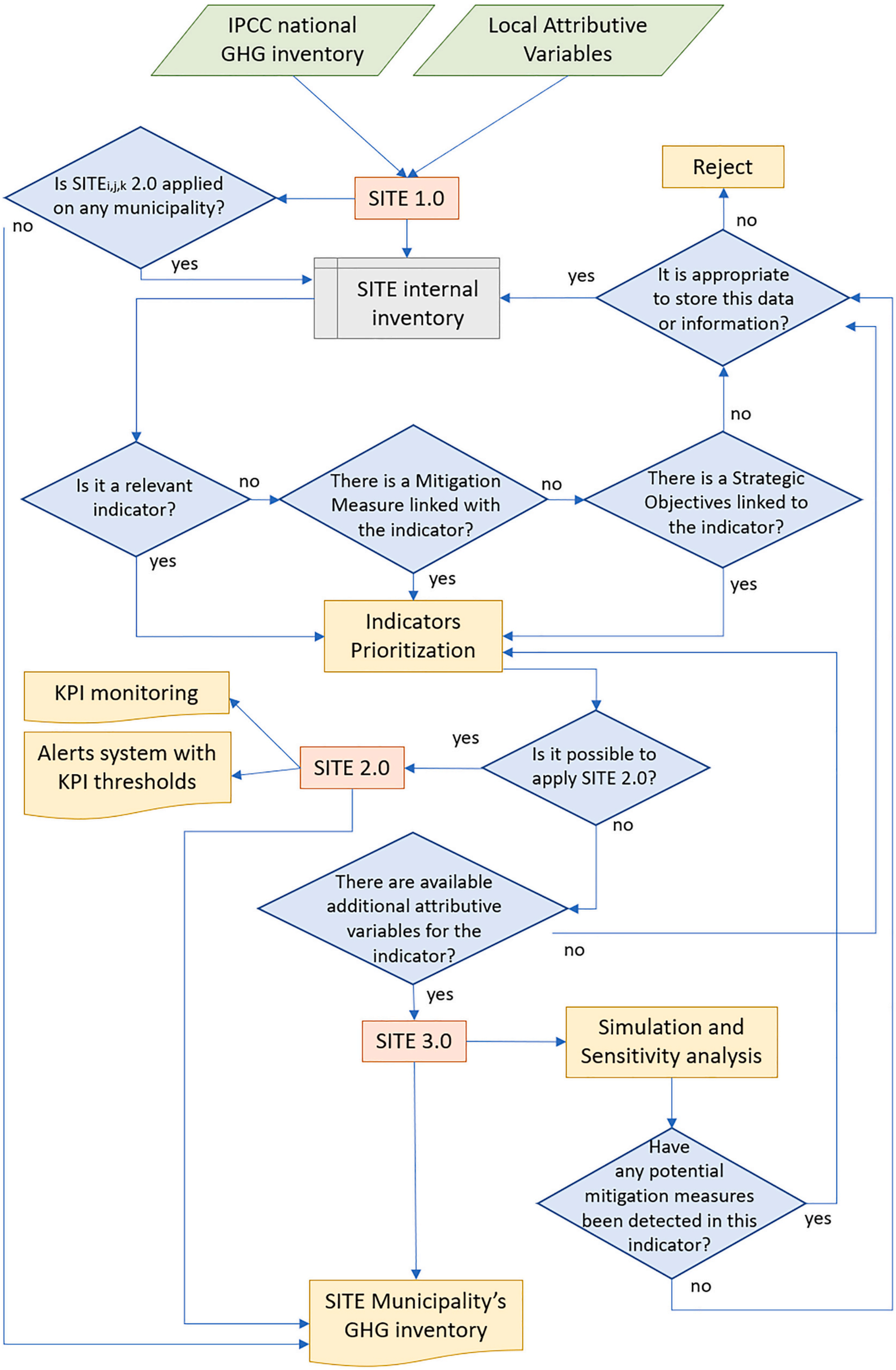

Fig. 2. Decision tree for an indicator in SITE as a climate governance tool.

1. if they are relevant,
2. if they are linked to any mitigation measure applied in the municipality
3. and if they are linked to any Strategic Objective of the municipality or region.

If the answer to any of these conditions is positive, the affected indicators are prioritized in that the municipality. Indicators prioritized have quantified through SITE 2.0-methodology if it is possible. SITE 2.0-methodology allows to monitor the evolution of these indicators as Key Performance Indicators (KPI) and to establish an alert system with thresholds based on strategic objectives linked.

Then, each SITE 2.0 indicator allows for applying SITE 3.0 hybrid approach to each municipality if additional local attributive variables are available for the indicator. Thus, SITE 3.0 allows to identify potential mitigation measures specific for this indicator through sensitivity analysis and simulations on variables used. Thus, if any potential mitigation measure in a municipality is identified, this indicator is prioritized for the municipality and SITE 2.0-methodology is applied. Finally, SITE 2.0 indicators are translated directly to Local GHG inventories due to is the approach that offers the highest quality results. In municipalities where SITE 2.0 indicators are not available, SITE 3.0 indicators are translated to GHG inventories at local level.

In summary, SITE GHG inventory in a municipality is composed, in priority order, by GHG emissions from:

a) Results from SITE 2.0 indicators available for that municipality;
b) Results from SITE 3.0 indicators available when SITE 2.0 is not available in that municipality and
c) Results from SITE 1.0 indicators when neither SITE 2.0 nor SITE 3.0 are available in that indicator in that municipality.

The combination of SITE methodological approaches and their systematization (Fig. 2) results in a GHG emissions quantification and monitoring scheme that allows maximizing the quality of results obtained using the allocated resources. Municipalities ensure that they have a complete scope since they have quantified all their emission sources (at least with SITE 1.0 accuracy). Moreover, only those relevant indicators linked to mitigation measures implemented or with strategic objectives directly related to them are entitled to implement the SITE 2.0-approach to allow their evaluation and monitoring and subsequently the degree of achievement of the objectives through KPIs. Globally, the effort made by a specific municipality to implement SITE 2.0 for a given indicator improves the quality of the information used by the rest of municipalities in connection with that indicator, thanks to the SITE 3.0-approach.

Finally, this step-by-step methodology allows to develop a cooperative effort strategy at the regional level where municipalities with greater resources can implement SITE 2.0 on priority indicators so that municipalities with fewer resources have better quantifications thanks to the hybrid approach of SITE 3.0.

The system allows to identify potential mitigation measures by generating simulated scenarios (sensitivity analysis) on the attributive variables used by SITE 3.0. In addition, as more municipalities implement SITE 2.0, the patterns generated by a bottom-up approach allow to apply SITE 3.0 quantification models. This SITE structure, built on the standardization of the IPCC, ensures interoperability and coherence with other systems and quantification methodologies used to establish the BEI and monitor any local, regional or national GHG emission commitment.

As a practical example, it is described how the decision tree in Fig. 2 is applied with the indicator 1.3.2 "Fuel burn in the residential sector" in two municipalities: a) 03009 "Alcoi/Alcoy" (with SITE 2.0 bottom-up method implemented), and b) 46005"Alaquàs" (without SITE 2.0 bottom-up methodology implemented).

a) Example of calculation of indicator 1.3.2 "Fuel burn in the residential sector" in 03009 "Alcoi" municipality.

Following the decision tree (Fig. 2), indicator 1.3.2 "Fuel burn in the residential sector" is calculated using SITE 1.0-methodology with eq. (1). Where: $IPCC_{1,\ 3,\ 2}$: 18,002,955 t CO_2 eq.; $C_{1,\ 3,\ 2}$: 1; $vL_{1,\ 3,\ 2}$: 2,296,198 m^2 of main dwellings.; $vN_{1,\ 3,\ 2}$: 1,645,021,965 m^2 of main dwellings.; $E_{1;\ 1,\ 3,\ 2}$: 25,129 t CO_2 eq.

The value obtained by SITE 1.0 methodology is stored internally and the next decision questions are asked: a) Is it a relevant indicator? b) There is a Mitigation Measure linked with the indicator? c) There is a Strategic Objectives linked to the indicator? In the example of Alcoi, as it has a SECAP with mitigation measures linked with this indicator, indicator 1.3.2 is considered as "Prioritized Indicator". Next, it is evaluated whether it is possible to apply SITE 2.0 in this indicator in this municipality. If the answer is yes, SITE 2.0 is calculated using eq. (4). Where: $AD_{1,3,2}$: Natural Gas: 47,595.77 MWh; Diesel Heating: 19,330.26 MWh and Liquefied petroleum gas (LPG): 22,801.95 MWh.; $EF_{1,3,2}$: Natural Gas: 0.202 t CO_2/MWh; Diesel Heating: 0.279 t CO_2/MWh: Liquefied petroleum gas (LPG): 0.227 t CO_2/MWh; $E_{2;\ 1,\ 3,\ 2}$: 20,183 t CO_2 eq. Finally, and since the SITE 2.0 result is the priority value, it is transferred to "SITE Municipality's GHG inventory".

b) Example of calculation of indicator 1.3.2 "Fuel burn in the residential sector" in 46005" Alaquàs".

Indicator 1.3.2 is calculated using SITE 1.0- methodology using the eq. (1). Where: $IPCC_{1,\ 3,\ 2}$: 18,002,955 t CO_2 eq.; $C_{1,\ 3,\ 2}$: 1; $vL_{1,\ 3,\ 2}$: 1,016,091 m^2 of main dwellings; $vN_{1,\ 3,\ 2}$: 1,645,021,965 m^2 of main dwellings; $E_{1;\ 1,\ 3,\ 2}$: 11,120 t CO_2 eq. Then it is evaluated if $SITE_{1,3,2}$ 2.0 is applied in any municipality, if not, the result of SITE 1.0 is transferred to "SITE Municipality's GHG inventory".

If $SITE_{1.3.2}$ 2.0 is applied in a municipality, the evaluation process of whether it is a priority is repeated. If the indicator is a priority, it is evaluated whether it is possible to apply $SITE_{1,3,2}$ 2.0. If this is not possible, and there are additional attributive variables, SITE 3.0 is applied by adapting eq. (5) to the available variables and the cvL_i calculated based on total amount of SITE 2.0 implementation as is explained on section 3.2.2.

3. Results and discussion

3.1. Implementation of SITE 1.0

3.1.1. Regional level analysis of GHG emissions: case study Region of Valencia

The implementation of SITE 1.0 in the case study (region of Valencia) has allowed quantifying GHG emissions for all 542 municipalities in year 2019. 163 indicators have been quantified, achieving full scope quantification in all municipalities. As a result, the total gross GHG emissions quantified for the analysed region were 29,986,561 t CO_2 eq. while annual fixation was 6,313,815 t CO_2 eq. from the forestry sector, wood products and agriculture. By provinces, Castellón had an emission of 5,054,984 t CO_2 eq. and a fixation of 2,152,925 t CO_2 eq. Alicante had an emission of 9,836,897 t CO_2 eq. and a fixation of 1,351,206 t CO_2 eq. and the province of Valencia had emissions of 15,094,680 t CO_2 eq. and a fixation of 2,809,684 t CO_2 eq. Therefore, the net GHG emissions of the Valencia region (discounting the fixation from gross emissions) were 23,672,746 t CO_2 eq.

The sectorial GHG emissions distribution shows that "Energy (without Transport)" is the most emitter sector (about 14 Mt. CO_2 eq.) followed by the "Transport" (over 9.5 M of t CO_2 eq.). Then the "Industrial Processes and Product Use" with "Agriculture, Livestock and Land Use (Without Forestry)" accounts for approximately 2.5 million t CO_2 eq. each one of them. Lastly, the "Waste" sector with 0.8 Mt. CO_2 eq. closes up the total emissions of Valencia (Fig. 3).

In addition, sectorial GHG emissions distribution has allowed prioritizing the most relevant indicators. In the study case, only 25 indicators (representing 20% of total indicators) are responsible for 85% of total GHG emissions (Fig. 4).

In consequence, any mitigation action, plan or strategy at regional scale should be focused on these indicators to achieve the maximum efficiency. Table 3 shows these most relevant indicators.

The territorial GHG emissions distribution shows that most emissions are produced in coastal cities (Fig. 8 Left). In addition, Table 4 shows the 10 most emitter cities that represent 34.45% of total emissions.

Regarding the territorial distribution of carbon fixation, it is distributed in a more uniform way along the whole territory, but generally, municipalities with the highest fixation are located in rural areas, where forests are mainly located (Fig. 8 Centre).

Table 5 shows the 10 most carbon fixation municipalities in Valencia that together achieve 21.45% of total carbon fixed. Indicators with relevant carbon fixation are "Land converted to pasture", "Harvested wood products", "Arable land remains as such", "Land converted to wetlands", "Land converted to forest land" and "Forest land remain as forest land". Forest-land indicators account for a fixation of 5.77 million t of CO_2 eq., which represents more than 90% of total CO_2 eq. fixation.

According to (Lorenzo-Sáez et al., 2021), annual forest-land fixation was 3.16 million t of CO_2 eq. fixation in the case study region calculated through a bottom-up approach (instead of the 5.77 million obtained here by means of the SITE top-down approach). This difference is mainly due to the inclusion of the quantification of litter and organic soils carbon within the SITE 1.0 result, as this indicator is actually included in the IPCC national inventory, yet not in (Lorenzo-Sáez et al., 2021).

Nevertheless, (Lorenzo-Sáez et al., 2021) and SITE 1.0 implementation results agree in 6 municipalities of 10 for being the top carbon fixation municipalities. The top 10 most fixation municipalities are responsible for 29% of total fixation, in contrast with 21.45% according to SITE 1.0 results (Table 5).

Emissions from ETS installations (174 in Valencia) are 8,725,623 t of CO_2 eq. in year 2019. The distribution among sectors identifies the ceramic sector as the largest emitter with 33% of direct emissions followed by the clinker sector (21%) and the electricity generation (18%). The regional distribution of ETS emissions affects 44 municipalities in Valencia (Fig. 5). However, 92% of the total

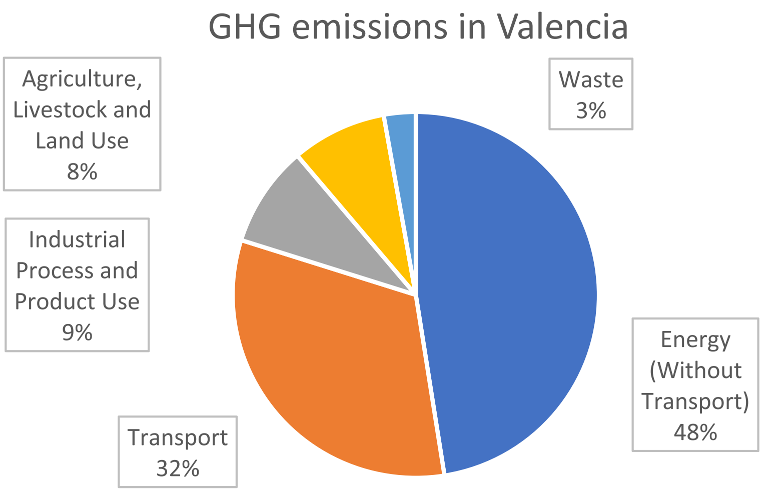

Fig. 3. Sectorial distribution of GHG emissions in Valencia.

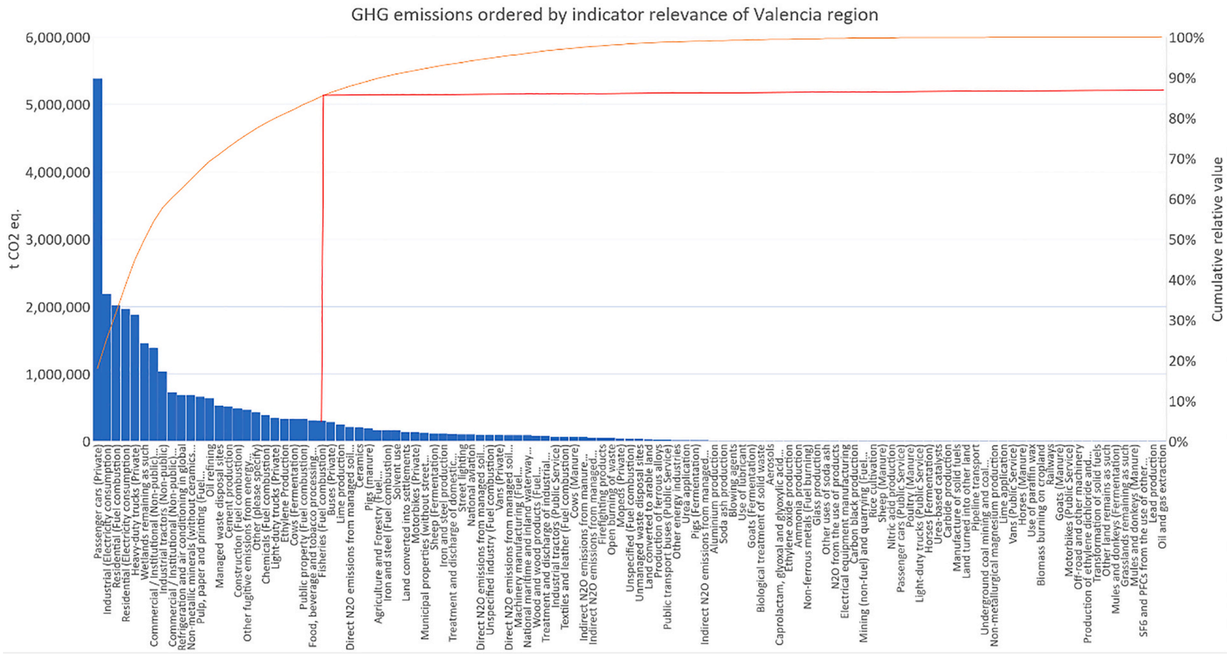

Fig. 4. GHG emissions ordered by indicator relevance in Valencia. GHG emissions of the 20% most relevant indicators are indicated by the red line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Most relevant indicators of Valencia region, GHG emissions of each indicator and relative value in % of total regional GHG emissions.

Code	Indicator name	t CO_2 eq. emissions	% of total GHG emissions
2.2.1	Passenger cars (Private)	5,387,380	17.97
1.7.2	Industrial (Electricity consumption)	2,194,085	7.32
1.3.2	Residential (Fuel combustion)	2,020,879	6.74
1.7.1	Residential (Electricity consumption)	1,968,522	6.56
2.2.3	Heavy-duty trucks (Private)	1,876,242	6.26
4.5.1	Wetlands remaining as such	1,452,465	4.84
1.7.3	Commercial / Institutional (Non-public) (Electricity consumption)	1,389,799	4.63
2.6.2	Industrial tractors (Non-public)	1,039,722	3.47
1.3.1	Commercial / Institutional (Non-public) (Fuel combustion)	734,830	2.45
3.6.1	Refrigeration and air conditioning in global	691,806	2.31
1.2.6	Non-metallic minerals (without ceramics) (Fuel combustion)	689,878	2.30
1.2.4	Pulp, paper and printing (Fuel combustion)	666,814	2.22
1.1.3	Oil refining	640,774	2.14
5.1.1	Managed waste disposal sites	528,163	1.76
3.1.1	Cement production	517,611	1.73
1.2.11	Construction (Fuel combustion)	493,496	1.65
1.6.1	Other fugitive emissions from energy production	469,487	1.57
1.2.3	Chemicals (Fuel combustion)	395,172	1.32
2.2.2	Light-duty trucks (Private)	348,988	1.16
3.2.9	Ethylene Production	341,915	1.14
4.1.1	Cows (Fermentation)	335,660	1.12
1.7.6	Other (please specify)	334,434	1.12
1.3.5	Public property (Fuel combustion)	333,818	1.11
1.2.5	Food, beverage and tobacco processing (Fuel combustion)	312,471	1.04
1.3.4	Fisheries (Fuel combustion)	307,671	1.03
Total GHG emissions of relevant indicators		25,472,083	85.00

emissions are concentrated in only 11 municipalities that contain more than 140 installations. These installations are mainly located in Castellón province, where an important ceramic industrial cluster is located (Fig. 5).

3.1.1.1. Local level analysis of GHG emissions: case study City of Valencia. Gross GHG emissions of each city are calculated by SITE. As example of local application, the GHG emissions were calculated for the City of Valencia. Valencia is the largest city in the region. For the year 2019 a total amount of 3.8 M of tCO_2 eq. have been calculated. Sectorial distribution of GHG emissions shows that "Energy

Table 4
Top 10 municipalities with more Net GHG emissions in Valencia.

Municipality code	Municipality name	Net GHG emissions (t CO_2 eq.)	% of total GHG emissions
46250	València	3,843,238	12.82
12040	Castelló de la Plana	1,734,695	5.78
03014	Alacant/Alicante	1,361,754	4.54
03065	Elx	1,281,369	4.27
46190	Paterna	568,544	1.90
46220	Sagunt	540,913	1.80
03133	Torrevieja	447,390	1.49
03099	Orihuela	443,986	1.48
46214	Riba-Roja	355,621	1.19
46244	Torrent	351,306	1.17
Total top 10 most emitter municipalities		10,928,817	36.45

Table 5
Top 10 cities with more CO_2 fixation in Valencia.

Municipality code	Municipality name	t CO_2 eq. fixation	% of total GHG fixation
46213	Requena	319,149	5.05
12080	Morella	194,682	3.08
46044	Ayora	189,500	3.00
46254	Venta del Moro	118,624	1.88
46106	Chelva	101,128	1.60
46099	Cortes de Pallás	95,121	1.51
46118	Enguera	90,111	1.43
3065	Elx/Elche	86,192	1.37
12139	Vistabella del Maestrat	80,482	1.27
12093	Pobla de Benifassà, la	79,282	1.26
Total top 10 most CO_2 fixation municipalities		1,354,271	21.45

(without transport)" is the largest emitter sector with 50% of total emissions, followed by the "Transport" with 35%. Then the "Industrial Processes and Product Use" accounts 8% and "Agriculture, Livestock and Land Use (without Forestry)" and "Waste" emit the 3% and the 5% of total gross emissions (Fig. 6).

In addition, the prioritization of most relevant indicators shows that only 25 of indicators (20% of total indicators) are responsible of 92% of total emissions in the Valencia city (Fig. 7). This prioritization adapted to local level and conditions can be used to develop highly efficient local action plans.

3.1.1.2. SITE as climate governance application at regional scale. There are many application possibilities of SITE as climate governance system. The combination of total emissions and total carbon fixation allows to calculate the net GHG emissions at local level (Fig. 8 Right). Thus, Fig. 8 Right allows the identification of 185 municipalities (34% of regional municipalities) that fix more GHGs than they emit and therefore act as net carbon sinks.

In addition, the analysis of the most relevant indicators obtained in the sectorial distribution of GHG emissions of the 542 municipalities of Valencia has allowed to identify the indicators that most times are in the top 10 relevant indicators at local level. So, the "Private passenger cars" indicator is the one most times considered as relevant (see Table 6) in the region. The indicator "Heavy-duty trucks (Private)" is also considered as relevant indicator in 540 municipalities being the second one that appears more times in the top 10 (Table 6) and the fifth most relevant indicator in the region (Table 3).

Another important example that shows the importance of analysing the relevance of indicators at both regional and local level are the indicators 4.8.4 "Direct N_2O emissions from managed soils (inorganic fertilisers (N))" and 4.8.6 "Direct N_2O emissions from managed soils (organic fertilisers (N))." These indicators are in the top 10 most relevant indicators in 313 and 234 municipalities, respectively, being the 4th and 10th (Table 6)), but at the total of the regional analysis they are the 28th and 42th most emitters, respectively (Table 3). The reason for this difference is that the small and rural municipalities have more emissions from agriculture than from industry or transport but industrial municipalities or big cities have very large number of GHG emissions in industry and transport. The consideration of these differences is crucial for planning effective strategies against climate change at different levels. Thus, local public authorities must define an action plan based on their GHG emissions but regional strategy has to be focused on most important emission sources making an equitable distribution of resources and territorial aid. Moreover, reaching a balance between the territorial and sectoral distribution of mitigation objectives is key to achieving a fair and sustainable climate change mitigation.

The methodology developed by SITE could also be used as a climate governance tool in combination with other approaches, such as that proposed by (Liu et al., 2016) based on the relative mitigation effort of countries. This approach can be used at regional scale by a regional administration thanks to the SITE quantification of territorial and sectoral emissions. In this way, the relative mitigation efforts in sectors and cities of the region could be identified to efficiently distribute the efforts and resources for mitigation.

Finally, one relevant indicator from Table 6 (1.3.2 "Fuel burn in the residential sector") has been chosen to be included into SITE

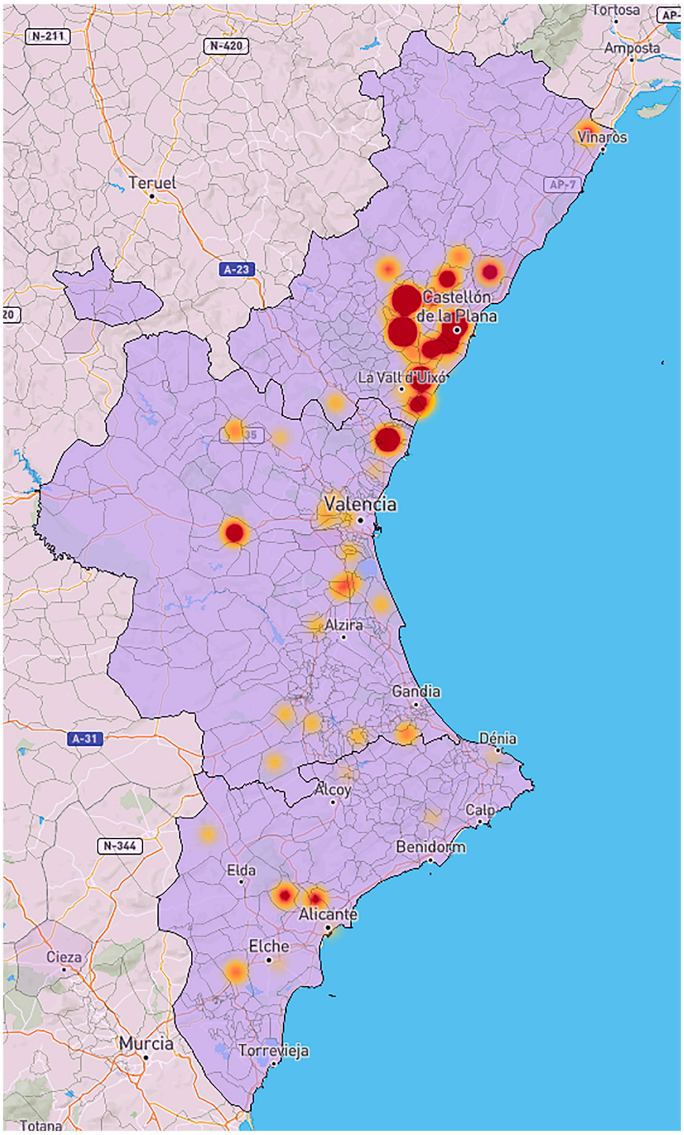

Fig. 5. Territorial distribution of GHG emissions from EU-ETS installations in Valencia.

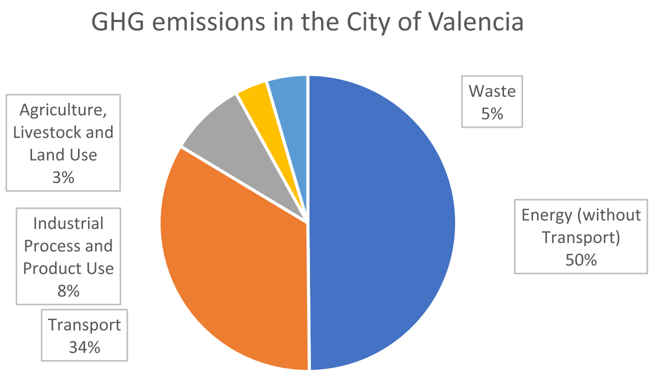

Fig. 6. Sectorial distribution of GHG emissions in the City of Valencia.

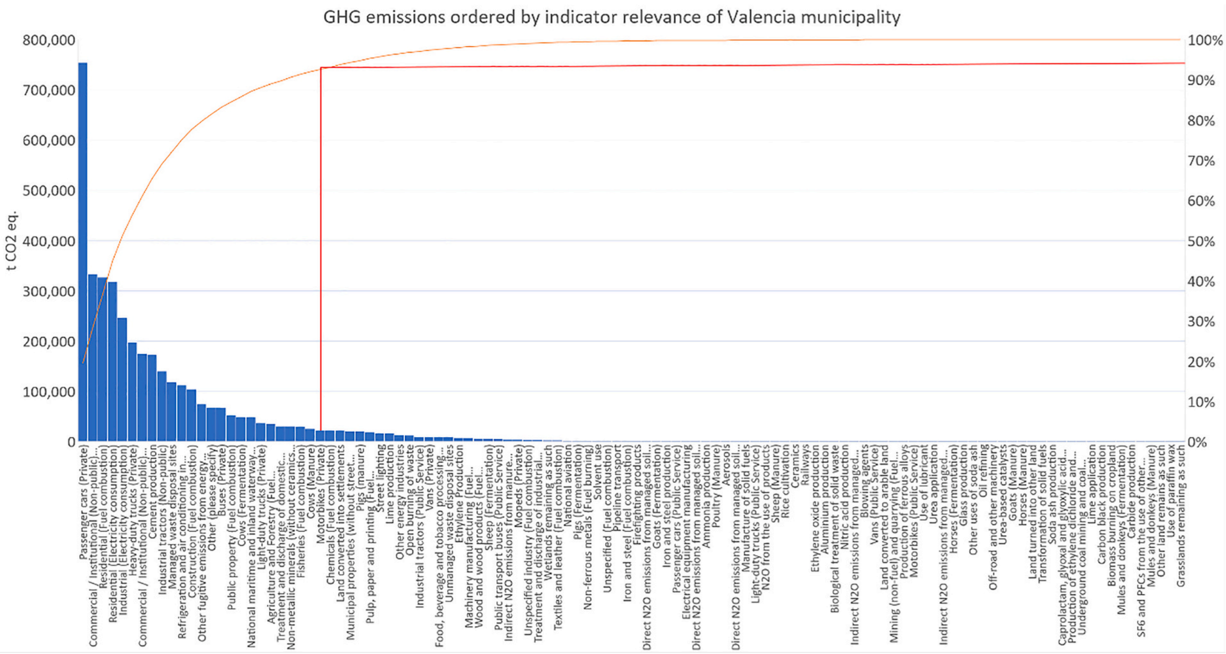

Fig. 7. GHG emissions ordered by indicator relevance in the City of Valencia (year 2019). GHG emissions of the 20% most relevant indicators are indicated by the red line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

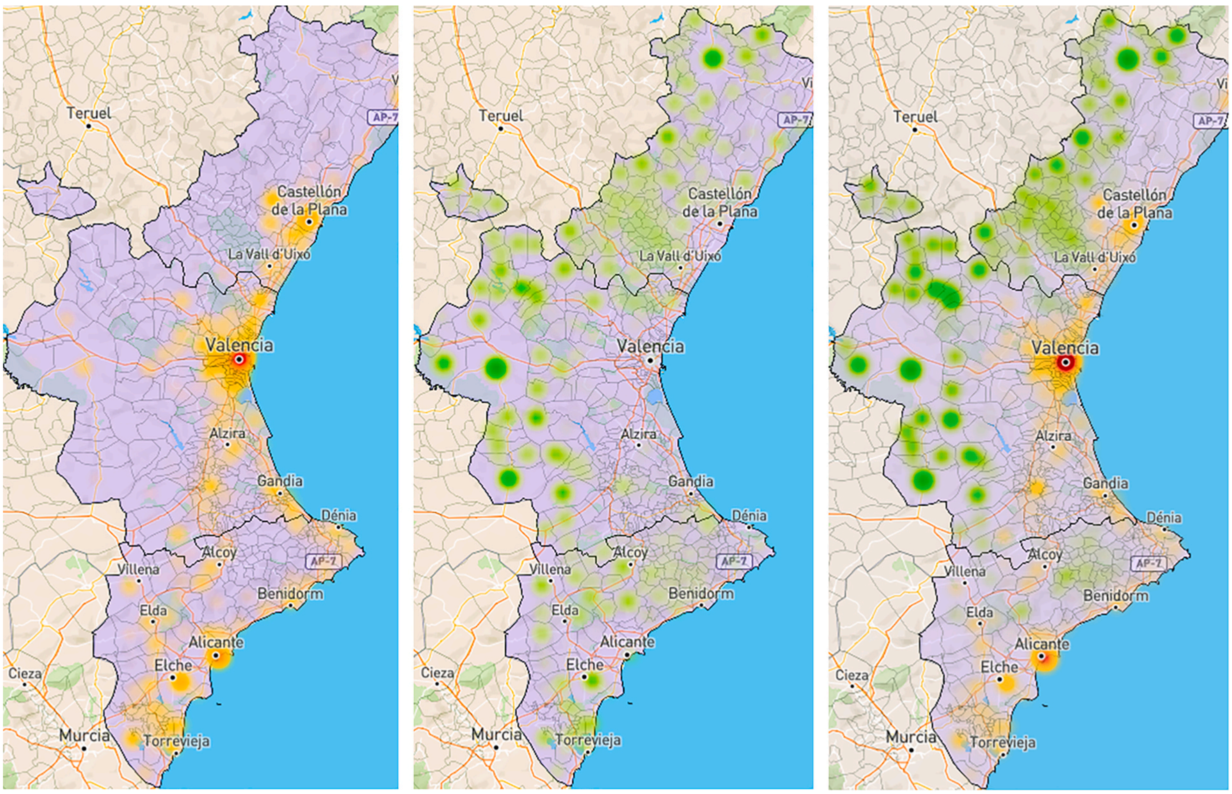

Fig. 8. Left: Territorial distribution of gross GHG emissions of Valencia region. Centre: Territorial distribution of GHG fixation in Valencia. Right: Territorial distribution of Net GHG emissions and fixation by municipality (Red: Net GHG emissions; Green: Net GHG fixation). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 6
Top 10 indicators that more times are in the top 10 of most relevant indicators at local level.

Indicator code	Indicator name	Number of times it is in the top 10 of a municipality
2.2.1	Passenger cars (Private)	542
2.2.3	Heavy-duty trucks (Private)	540
1.3.2	Residential (Fuel combustion)	314
4.8.4	Direct N_2O emissions from managed soils (inorganic fertilisers (N))	313
1.7.1	Residential (Electricity consumption)	311
2.2.2	Light-duty trucks (Private)	311
1.7.2	Industrial (Electricity consumption)	309
2.6.2	Industrial tractors (Non-public)	306
1.6.1	Other fugitive emissions from energy production	270
4.8.6	Direct N_2O emissions from managed soils (organic fertilisers (N))	234

2.0 to implement SITE 3.0 in municipalities with available data.

3.2. Implementation of SITE 3.0

3.2.1. Selected representative cities

According to the accomplishment of sampling criteria described in section 2.3.2 "Criteria for sampling representative municipalities", five cities have been selected. Thus, municipalities selected are Alcoi, Novelda, Pobla de Vallbona, Ibi and Muro de Alcoi to apply SITE 3.0 hybrid approach.

Criterion 1 has discarded 15 cities for presenting non-comparable quantification methodologies and/or presenting other scopes. The consumption of liquid petroleum gas (LPG) and diesel for heating is obtained by extrapolating consumption at a regional level based on the relationship of population and hence cannot be considered a bottom-up approach. Other examples are Canals, Ontinyent, Alcúdia de Crespins, Paterna and Simat de Valldigna where electrical and thermal consumption is aggregated without the possibility to disaggregate.

Criterion 2 has identified Alcalalí as possible outlier by analysing the Box-Whiskers plots generated from the CO_2 eq./inhabitant ratio. It was possible to identify the possible reason for such misalignment as surveys, instead of direct consumption records, were used to collect data to energy consumption in the residential sector. Therefore, Alcalalí was discarded from the analysis to avoid possible biases.

The analysis of criterion 3 has discarded València, Elx, Castelló de la Plana, Torrent, Vila Joiosa, Villena, Almassora, Petrer, Nules, Carlet, Pego, Callosa d'en Sarrià and Cabanes due to these municipalities do not quantify every source of fossil fuel consumed. Most times if a municipality quantify natural gas, do not quantify diesel and vice versa.

Finally, criterion 4 has discarded Elda, Benissa, Xàbia, and Concentaina due to their quantification are based on a survey sampling with too low number of surveys (for example Concentaina has more than 11,000 inhabitants and quantify the residential sector emissions based on 20 surveys).

3.2.2. Implementation of SITE 3.0 hybrid approach

As highlighted in section 4.2.2.3 there are different possible approaches to use the SITE 3.0 strategy, depending on which variables are locally available. In this subsection we test the possible scope and limitations of such an approach, implementing it for the indicator 1.3.2 "Fuel burn in the Residential sector". Due to the extensive availability of Energy Performance of Buildings Certificates (EPBCs) (compulsory in case a dwelling is sold or rented) in the case of the Valencia region we have found information about several key variables such a) total living area (main dwellings, secondary dwellings and empty dwellings); b) area per category of energy efficiency and c) energy rating in each of the categories obtained from the Energy Performance of Buildings certificates available. In many municipalities, over 10% of the registered dwelling surface is covered by EPBCs, being representative of the overall energy performance of the building sector.

Based on these data, the total heating and cooling demand covered by fossil fuel in a given municipality is given by:

$$D_t = \mathrm{c}\; S_t \sum_{i=1}^{7} \left(p_{i1}\overline{d_{i1}} + p_{i2}\overline{d_{i2}} + p_{i3}\overline{d_{i3}}\right)$$

In this context, index i refers to the 7 different Energy Performance labels (A,..,G) and the second sub index 1,2,3 refers to the occupancy category (main, secondary and empty).

$\overline{d_{ij}}$: real thermal demand intensity per unit of dwelling area for label class i and occupancy class j.

p_{ij}: total area of dwelling with label class i and occupancy class j with respect to the total area of dwellings in the municipality.

c: non-dimensional coefficient that relates the thermal demand of an average dwelling in terms of primary energy consumption (as given by its EPBC) with the average fuel fossil consumption of that dwelling (which aggregates HW, gas/fossil based kitchen and gas/fossil based HVAC consumptions). According to IDAE statistics (IDAE 2011), this coefficient is expected to be around 0.4 for an average dwelling in the Mediterranean climate. In our model it will be treated as an unknown.

Eq. (10) can be rewritten as:

$$D_t = \mathrm{c}\ S^*{}_t \sum_{i=1}^{7} (\beta_{i1}\ p^*{}_{i1}\overline{d_{i1}} + \beta_{i2}\ p^*{}_{i2}\overline{d_{i2}} + \beta_{i3}\ p^*{}_{i3}\overline{d_{i3}})$$

where $S^*{}_t$ is the total area of dwellings with an EPBC and $p^*{}_{i1} = S^*{}_{i1}/_{S^*{}_t}$ is the observed ratio of area within each label class and occupancy category. Therefore:

$$\sum_{i=1}^{7} p^*{}_{i1} + p^*{}_{i2} + p^*{}_{i3} = 1$$

A new parameter is defined as:

$$\beta_{i1} = S_{i1}/_{S^*{}_i}$$

which represents the ratio of dwellings of a given label/use in a certain municipality with respect to those which have been given an EPBC. For a certain municipality a given large β_{ij}would mean that from all dwellings belonging to a certain ij group, only a small fraction is certified.

Some assumptions are needed to make the model computable and reduce the number of parameters:

Assumption 1. The unknown population distribution $\overline{d_{ij}}$ can be approximated by the sample mean of each category of energy certificates $\overline{d_{ij}} = \overline{d_{ij}}^*$. This requires a sufficient coverage of the existing building stock with EPDCs. A coefficient of use according to the type of dwelling (main, secondary or empty dwelling) can be introduced to relate $\overline{d_{i1}}$, $\overline{d_{i2}}$ and $\overline{d_{i3}}$ with the average use factor for each category. In summary:

$\overline{d_{i1}} = f_1\ \overline{d_i}^*$; $\overline{d_{i2}} = f_2\ \overline{d_i}^*$ $\overline{d_{i3}} = 0$

$\overline{d_i}^*$: is the actual energy rating of the available EPBCs, averaged over the dwelling population of each EPBC class, i.

$f_{1/2}$: are nondimensional coefficients of use which relate the rated EPBC demand with the actual average HVAC energy consumption depending of the many factors of influence (occupation time, climatic variables, user profiles, etc..)We are assuming simplistically that empty homes do not substantially contribute to the thermal demand.

Assumption 2. There is no correlation between the energy category and the type of use of the dwelling. For example, if in a municipality 10% of the dwellings sampled were in category A, we would assume that 10% of the secondary and empty dwellings will be in category A.

Hence: $\beta_{i1} = \beta_{i2} = \beta_{i3} \equiv \beta_i$

Assumption 3. Municipalities with a sufficient number of EPBC-certified dwellings and similar $p^*{}_i$ distribution, possess similar β_i distribution. This assumption implies that the β_i could serve as a system of 7 local variable coefficients to be used within a SITE 3.0 predictor for emissions.

The model finally can be expressed as

$$E_{3;1,3,2} = \mathrm{ef\ c}\ S^*{}_t \sum_{i=1}^{7} \beta_i\ p^*{}_i (f_1\ s_1 + f_2\ s_2)\ \overline{d^*{}_i}$$

$E_{3;\,1,\,3,\,2}$: GHG emissions (in t CO_2 eq.) corresponding to indicator 1.3.2" Fuel burn in the Residential sector" belonging to criterion 3 "Fuel burn in other sectors" of sector 1 "Energy (without Transport)".

ef: Emission factor used to convert thermal primary energy consumption into GHG emissions.

$S^*{}_t$: total area of dwellings of the municipality in m^2 rated with EPBC.

s1: ratio of main use dwelling area with respect to total dwelling area in the municipality.

s2: ratio of secondary use dwelling area with respect to total dwelling area in the municipality.

If we note that $S^*{}_t p^*{}_i \overline{d^*{}_i}\ (f_1\ s_1 + f_2\ s_2) = D_i^*(f_1, f_2)$ is the overall aggregated demand of all dwellings with EPBC of a certain category i, we can easily write the above equation adapted to the form of eq. (5):

$E_{3;1,3,2} = \mathrm{ef\ c}\ \sum_{i=1}^{7} \beta_i\ D_i^* = \mathrm{ef\ c}\ \sum_{i=1}^{7} \mathrm{cvL}_i\ \nu L_i$ where:

$\nu L_i = D_i{}^*\ (f_1, f_2)$: is the local attribution variable vector, which is a function of coefficients f1 and f2.

$cvL_i = \beta_i$ is the vector of coefficients allowing to relate the local vector to the emission data.

The task can be expressed now as a linear regression or Minimum Least Square problem allowing to find the set of coefficients that allow a best correlation with SITE 2.0 data. Note that in this particular implementation of the method the fit coefficients will depend on the assumptions made for c, f1, f2. Hence an iterative procedure is required to find an optimal set of parameters that minimize the overall MSE.

SITE 3.0 implementation in indicator 1.3.2 "Fuel burn in the Residential sector"

SITE 3.0 has been implemented in municipalities without implementation of SITE 2.0 thanks to the SITE 2.0 of selected municipalities Alcoi, Novelda, Pobla de Vallbona, Ibi and Muro de Alcoi. Thus, SITE 3.0 has been applied in indicator 1.3.2 "Fuel burn in the Residential sector" of 197 municipalities of the case study region with available attributive variables and with at least 10% of total dwelling area sampled (Fig. 9).

Thus, SITE has shown that it is possible to make collaborative efforts at the regional level so that all municipalities can carry out rigorous and quality emissions inventories to define their own action plans against climate change at local level. Thus, the developed system offers tools to quantify GHG emissions, to prioritize the most relevant indicators, to make sensitivity analysis on specific actions to mitigate emissions and to monitor KPI to evaluate and to control the achievement of local and regional mitigation objectives. These tools allow public decision makers to rigorously manage climate change and to invest efforts and available resources in a highly efficient way.

Finally, the major limitations of this work are discussed following.

The estimation accuracy of SITE 3.0-hybrid and SITE 1.0 approaches depend on the adequacy of the attributive variables used. Therefore, a good availability of specific variables for each indicator is required. In this work, the example of only one of them (indicator 1.3.2 “Fuel burn in the residential sector”) has been exposed. The other 162 indicators require the development of a specific model adapted to the available local attributive variables. In addition, the implementation of SITE 3.0-hybrid methodology requires an adequate number of implementations of bottom-up methodologies for each indicator.

Regarding SITE 1.0, $IPCC_{i,j,k}$ data are obtained from national emission inventory. National emissions inventory has a delay of 2 years. Thus, the major limitation of SITE 1.0 is that GHG emissions estimation only can be estimated for the year *n*-2 (been *n* the year of SITE implementation).

The implementation of SITE 1.0 or SITE 3.0 approach only shows the impact of the mitigation measures implemented in a specific municipality when this impact affects the attributive variable used (for example, a mitigation measure that consists of replacing diesel vehicles by electric vehicles will only be reflected in the local emissions inventory if the attributive variable used contemplates the type of fuel or the fuel sold/consumed), otherwise, only the bottom-up approach (SITE 2.0) would show the real impact of this mitigation measure.

4. Conclusions

A territorial and sectorial information system to monitor GHG emissions (SITE) as a local and regional climate governance tool has been developed and applied. SITE climate governance system integrates top-down and bottom-up approaches with an innovative hybrid approach that allows to quantify the GHG emissions of all the indicators of the municipality efficiently, with a complete scope and ensuring standardization with the Intergovernmental Panel on Climate Change metrics. In addition, SITE indicators prioritization functionality allows to optimize and to adapt the regional and local strategies and action plans against climate change to the local context, identifying the most relevant indicators to invest available resources efficiently.

The application and evaluation of SITE has been implemented in the case study of Valencia, both at regional and local level. This case study has allowed quantifying GHG emissions of a total of 163 indicators in the entire region (approx. 5 million inhabitants distributed in 542 municipalities). The gross GHG emissions in the region in 2019 were 29,986,561 t CO_2 eq., while the fixation was 6,313,815 t CO_2 eq.

The analysis of territorial distribution of GHG emissions showed that most are produced in coastal municipalities with high

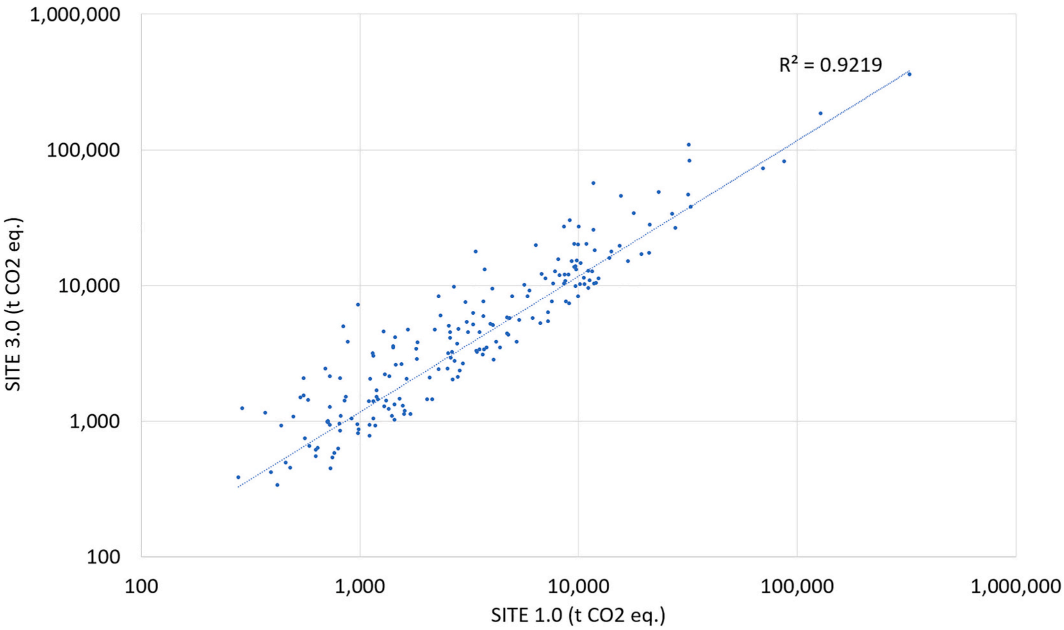

Fig. 9. SITE 3.0 implementation results of the 197 municipalities with available data. Logarithmic scale.

socioeconomic activity (industrial and services). It has to be taken into account, that in this region most than 75% of the population lives close to the coast. So, only 10 municipalities (1.8%) emit 34.45% of total gross emissions. Net GHG emissions showed that 34% of the municipalities in the region (185 municipalities) are net carbon sinks by fixing more GHG than they emit, and these are mainly located in the interior of Valencia. This unbalanced territorial distribution of emissions and carbon sinks is very representative to several regions in Europe, especially in the Mediterranean countries, where the socioeconomic activity is mainly concentrated at the coast or in large urban areas.

On the other side, the analysis of the sectoral distribution of GHG emissions in the case study region shows that only few indicators account for almost all emissions (in the case study region 20% of the indicators are responsible for 85% of the total emissions). SITE also made it possible to identify those indicators that are most often in the top 10 of relevant indicators in the all municipalities analysed in the region. This information is valuable for regional climate governance since it allows planning a collaborative regional strategy against climate change, but meeting the needs of each city or municipality in particular.

Finally, the implementation of the hybrid SITE 3.0 methodological approach has improved the accuracy of the quantification of GHG emissions of one relevant and very important indicator ("Fuel burn in the Residential sector") of municipalities in the case study region with available attributive variables (197 municipalities). This shows that SITE allows developing a collaborative GHG emissions quantification strategy at the regional level to optimize the available resources to the maximum.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Edgar Lorenzo-Sáez: Conceptualization, Formal analysis, Methodology, Investigation, Writing – original draft. **Jose-Vicente Oliver-Villanueva:** Conceptualization, Supervision, Writing – review & editing. **Lenin-Guillermo Lemus-Zúñiga:** Supervision, Data curation, Writing – review & editing. **Javier F. Urchueguía:** Supervision, Validation, Writing – review & editing. **Victoria Lerma-Arce:** Data curation, Writing – review & editing, Validation.

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.

Appendix A. SITE Inventory structure

Indicator code	Name description
1.	ENERGY (WITHOUT TRANSPORT)
1.1	Fuel combustion in Energy Industries
1.1.1	Electricity generation as main activity
1.1.2	Power generation plants as main activity
1.1.3	Oil refining
1.1.4	Manufacture of solid fuels
1.1.5	Oil and gas extraction
1.1.6	Other energy industries
1.1.7	Other (please specify)
1.1.8	Remaining fuel combustion in energy industries
1.2	Fuel combustion in manufacturing and construction industries
1.2.1	Iron and steel (Fuel combustion)
1.2.2	Non-ferrous metals (Fuel burning)
1.2.3	Chemicals (Fuel combustion)
1.2.4	Pulp, paper and printing (Fuel combustion)
1.2.5	Food, beverage and tobacco processing (Fuel combustion)
1.2.6	Non-metallic minerals (without ceramics) (Fuel combustion)
1.2.7	Transport equipment (Fuel combustion)
1.2.8	Machinery manufacturing (Fuel combustion)
1.2.9	Mining (non-fuel) and quarrying (Fuel combustion)
1.2.10	Wood and wood products (Fuel combustion)
1.2.11	Construction (Fuel combustion)
1.2.12	Textiles and leather (Fuel combustion)
1.2.13	Unspecified industry (Fuel combustion)
1.2.14	Ceramics industry (Fuel combustion)
1.2.15	Remaining fuel combustion in manufacturing and construction industries
1.3	Fuel combustion in other sectors
1.3.1	Commercial / Institutional (Non-public) (Fuel combustion)

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Indicator code	Name description
1.3.2	Residential (Fuel combustion)
1.3.3	Agriculture and Forestry (Fuel combustion)
1.3.4	Fisheries (Fuel combustion)
1.3.5	Public property (Fuel combustion)
1.3.6	Remaining fuel combustion in other sectors
1.4	Fuel combustion in Unspecified
1.4.1	Unspecified (Fuel combustion)
1.5	Fugitive emissions from the manufacture of solid fuels
1.5.1	Underground coal mining and coal management
1.5.2	Coal mining and surface coal management
1.5.3	Transformation of solid fuels
1.5.4	Remaining fugitive emissions from solid fuel manufacture
1.6	Other fugitive emissions from energy production
1.6.1	Other fugitive emissions from energy production
1.7	Emissions from electricity consumption
1.7.1	Residential (Electricity consumption)
1.7.2	Industrial (Electricity consumption)
1.7.3	Commercial / Institutional (Non-public) (Electricity consumption)
1.7.4	Municipal properties (without street lighting) (Electricity consumption)
1.7.5	Street lighting
1.7.6	Other (please specify)
1.7.7	Remaining emissions from electricity consumption
2.	TRANSPORT
2.1	Civil aviation
2.1.1	National aviation
2.2	Private land transport
2.2.1	Passenger cars (Private)
2.2.2	Light-duty trucks (Private)
2.2.3	Heavy-duty trucks (Private)
2.2.4	Motorbikes (Private)
2.2.5	Mopeds (Private)
2.2.6	Buses (Private)
2.2.7	Vans (Private)
2.2.8	Other vehicles (Private)
2.2.9	Remaining private land transport
2.3	Railways
2.3.1	Railways
2.4	Maritime and inland waterway navigation
2.4.1	National maritime and inland waterway navigation
2.5	Public service land transport
2.5.1	Passenger cars (Public Service)
2.5.2	Light-duty trucks (Public Service)
2.5.3	Motorbikes (Public Service)
2.5.4	Vans (Public Service)
2.5.5	Industrial tractors (Public Service)
2.5.6	Public transport buses (Public Service)
2.5.7	Other public service vehicles
2.5.8	Remaining public service land transport
2.6	Other transport
2.6.1	Pipeline transport
2.6.2	Industrial tractors (Non-public)
2.6.3	Off-road and other machinery
2.6.4	Remaining of other type of transport
3.	INDUSTRIAL PROCESSES AND PRODUCT USE
3.1	Minerals industry
3.1.1	Cement production
3.1.2	Lime production
3.1.3	Glass production
3.1.4	Ceramics
3.1.5	Other uses of soda ash
3.1.6	Non-metallurgical magnesium production
3.1.7	Other (please specify)
3.1.8	Remaining mineral industry
3.2	Chemical industry
3.2.1	Ammonia production
3.2.2	Nitric acid production
3.2.3	Adipic acid production
3.2.4	Caprolactam, glyoxal and glyoxylic acid production
3.2.5	Carbide production
3.2.6	Titanium dioxide production

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Indicator code	Name description
3.2.7	Soda ash production
3.2.8	Methanol Production
3.2.9	Ethylene Production
3.2.10	Production of ethylene dichloride and vinyl chloride monomer
3.2.11	Ethylene oxide production
3.2.12	Acrylonitrile production
3.2.13	Carbon black production
3.2.14	Fluorochemical production and derivatives
3.2.15	Other (please specify)
3.2.16	Remaining chemical industry
3.3	Metals industry
3.3.1	Iron and steel production
3.3.2	Production of ferrous alloys
3.3.3	Aluminium production
3.3.4	Magnesium production
3.3.5	Lead production
3.3.6	Zinc production
3.3.7	Other (please specify)
3.3.8	Remaining metal industry
3.4	Use of non-energy fuel and solvent products
3.4.1	Use of lubricant
3.4.2	Use of paraffin wax
3.4.3	Solvent use
3.4.4	Urea-based catalysts
3.4.5	Remaining non-energy use of fuels and solvents products
3.5	Electronics industry
3.5.1	Integrated circuit or semiconductor
3.5.2	TFT type flat screen
3.5.3	Photovoltaic products
3.5.4	Heat transfer and transport fluid
3.5.5	Other (please specify)
3.5.6	Remaining of electronics industry
3.6	Uses of products as substitutes for ozone-depleting substances
3.6.1	Refrigeration and air conditioning in global
3.6.2	Blowing agents
3.6.3	Firefighting products
3.6.4	Aerosols
3.6.5	Solvents (as an ozone-depleting substance)
3.6.6	Other applications (please specify)
3.6.7	Remaining use of products as substitutes for ozone-depleting substances
3.7	Manufacture and use of other products
3.7.1	Electrical equipment manufacturing
3.7.2	SF6 and PFCs from the use of other products
3.7.3	N_2O from the use of products
3.7.4	Other (please specify)
3.7.5	Remaining manufacture and use of other products
3.8	Other
3.8.1	Pulp and Paper Industry (Production process)
3.8.2	Food and beverage industry (Production process)
3.8.3	Other (please specify)
4.	AGRICULTURE, LIVESTOCK AND OTHER LAND USES (WITHOUT FORESTRY)
4.1	Livestock, Enteric fermentation
4.1.1	Cows (Fermentation)
4.1.2	Sheep (Fermentation)
4.1.3	Goats (Fermentation)
4.1.4	Horses (Fermentation)
4.1.5	Mules and donkeys (Fermentation)
4.1.6	Pigs (Fermentation)
4.1.7	Other (please specify)
4.1.8	Remaining livestock, enteric fermentation
4.2	Livestock, Manure management
4.2.1	Cows (Manure)
4.2.2	Sheep (Manure)
4.2.3	Goats (Manure)
4.2.4	Horses (Manure)
4.2.5	Mules and donkeys (Manure)
4.2.6	Pigs (manure)
4.2.7	Poultry (Manure)
4.2.8	Dogs (Manure)
4.2.9	Chickens (Manure)

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Indicator code	Name description
4.2.10	Chickens (Manure)
4.2.11	Partridges (Manure)
4.2.12	Other (please specify)
4.2.13	Indirect N_2O emissions from manure management
4.2.14	Direct N_2O emissions from manure management
4.2.15	Remaining livestock, manure management
4.3	Agriculture, arable land
4.3.1	Arable land remains as such
4.3.2	Land converted to arable land
4.4	Grasslands
4.4.1	Grasslands remaining as such
4.4.2	Land converted to pasture
4.5	Wetlands
4.5.1	Wetlands remaining as such
4.5.2	Land converted to wetlands
4.6	Land use, Settlements
4.6.1	Settlements remaining as such
4.6.2	Land converted into settlements
4.7	Other land
4.7.1	Other land remains as such
4.7.2	Land turned into other land
4.8	Aggregate sources and non-CO_2 emission sources on land
4.8.1	Biomass burning on cropland
4.8.2	Lime application
4.8.3	Urea application
4.8.4	Direct N_2O emissions from managed soils (inorganic fertilisers (N))
4.8.5	Direct N_2O emissions from managed soils (Crop residues, Urine and manure from grazing animals)
4.8.6	Direct N_2O emissions from managed soils (organic fertilisers (N))
4.8.7	Indirect N_2O emissions from managed soils (Atmospheric deposition)
4.8.8	Indirect N_2O emissions from managed soils (nitrogen leaching and run-off)
4.8.9	Rice cultivation
4.8.10	Remaining aggregate sources and non-CO_2 land-based emission sources
4.9	Other
4.9.1	Harvested wood products
4.9.2	Other (please specify)
5.	WASTE
5.1	Solid waste disposal
5.1.1	Managed waste disposal sites
5.1.2	Unmanaged waste disposal sites
5.1.3	Non-categorised waste disposal sites
5.1.4	Remaining solid waste disposal
5.2	Biological treatment of solid waste
5.2.1	Biological treatment of solid waste
5.3	Incineration and open burning of waste
5.3.1	Waste incineration
5.3.2	Open burning of waste
5.4	Wastewater treatment and discharge
5.4.1	Treatment and discharge of domestic waste water
5.4.2	Treatment and discharge of industrial waste water
5.5	Other (please specify)
5.5.1	Other (please specify)
6.	FORESTRY
6.1	Forest land
6.1.1	Forest land remain as forest land
6.1.2	Land converted to forest land

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