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DESARROLLO DE UNA HERRAMIENTA INTEGRAL DE GESTIÓN DE GASES DE EFECTO INVERNADERO PARA LA TOMA DE DECISIÓN CONTRA EL CAMBIO CLIMÁTICO A NIVEL REGIONAL Y LOCAL EN LA COMUNITAT VALENCIANA

TESIS DOCTORAL

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A mi padre y a mi madre por convertirse, sin quererlo, en mi ejemplo a seguir en la vida, apoyándome y motivándome a hacer siempre lo que me haga feliz. Y a mi hermana por su cariño y apoyo incondicional.

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II. RESUMEN

Actualmente, los responsables de tomar decisiones contra el cambio climático carecen de herramientas para desarrollar inventarios de emisiones de gases de efecto invernadero (GEI) con suficiente rigor científico-técnico y precisión para priorizar e invertir los recursos disponibles de manera eficiente en las medidas necesarias para luchar contra el cambio climático. Por ello, en esta tesis se expone el desarrollo de un sistema de información territorial y sectorial (SITE) para monitorear las emisiones de GEI que sirva como herramienta de gobernanza climática local y regional. SITE combina las ventajas de los enfoques metodológicos descendente o *top-down* (de arriba hacia abajo) y ascendente o *bottom-up* (de abajo hacia arriba), para lograr un enfoque híbrido innovador para contabilizar y gestionar de manera eficiente las emisiones de GEI. Por tanto, en esta tesis se definen los diferentes desarrollos metodológicos, tanto generales como específicos de sectores clave del Panel Intergubernamental de Cambio Climático (IPPC) (edificación, transporte, sector forestal, etc.), un desarrollo informático para la parte de SITE que se ejecuta del lado del servidor, que de ahora en adelante denominaremos *back-end* del sistema, y siete implementaciones como casos de estudio representativos, a diferentes escalas y aplicados sobre diferentes sectores. Esto queda descrito en seis capítulos.

En el primer capítulo se expone el desarrollo metodológico general de los tres enfoques del sistema (descendente, ascendente y enfoque híbrido). Además, se describe la implementación del enfoque descendente sobre todos los sectores de la Comunitat Valenciana (España) y la implementación local de este mismo enfoque sobre todos los sectores emisivos del municipio de València. Así, los 162 indicadores cuantificados en los 542 municipios de la región emitieron un total de 30Mt CO_2 eq. y fijaron un total de 6Mt CO_2 eq. durante el año 2019. Además, el enfoque territorial del sistema individual ha permitido identificar que tan solo 10 municipios (el 1,8% del total) emiten el 34% del total mientras que 185 municipios (34% del total) fijaron más emisiones de las que emitieron. Por último, el enfoque

sectorial del sistema permitió identificar el 20% de indicadores de las actividades sectoriales que son responsables del 85% del total de emisiones.

En el segundo capítulo se expone una propuesta informática para el *back-end* del sistema basado en agentes para la cuantificación de emisiones y una aplicación local simplificada sobre todos los sectores mediante un enfoque ascendente en un municipio representativo de tamaño medio de aproximadamente 25.000 habitantes (Llíria, España). El sistema basado en agentes propuesto ha permitido la gestión automática de grandes volúmenes de datos e información necesaria para el cálculo de emisiones.

En el tercer capítulo se expone el desarrollo metodológico de un enfoque híbrido basado en un sistema de información geográfica (SIG) para mapear el consumo de energía primaria y las emisiones de GEI en el sector de la edificación a nivel local en base a los certificados energéticos disponibles. Además, la aplicación de la metodología desarrollada a nivel local en un municipio representativo de tamaño medio de aproximadamente 25.000 habitantes (Quart de Poblet, España) ha permitido calcular un total de 32.000 t CO_2 eq. emitidas derivadas de un consumo de energía primaria de 140 GWh en edificios residenciales con alta resolución espacial (a nivel de edificio).

En el cuarto capítulo se describe el desarrollo de una metodología ascendente (*bottom-up)* para cuantificar las emisiones de GEI del tráfico urbano con alta resolución espacial y temporal a nivel local. La metodología desarrollada utiliza datos de los sistemas de control y monitoreo del tráfico urbano (espiras electromagnéticas) para calcular las emisiones de GEI. Además, su implementación en el municipio de València (España) ha permitido obtener resultados con gran resolución de las emisiones de GEI en los más de 1.400 tramos sensorizados de la ciudad con una resolución temporal horaria y una resolución espacial a nivel de calle. Los patrones de emisión obtenidos de la aplicación de la metodología desarrollada en los años 2016-2019 permiten analizar las emisiones GEI de un agente emisor clave, como es el tráfico, así como de la dinámica de la ciudad y su movilidad ciudadana.

En el quinto capítulo se describe la implementación del sistema en el sector forestal de la Comunitat Valenciana para el cálculo de fijación anual y del stock de carbono acumulado mediante un enfoque metodológico híbrido. Los resultados obtenidos de esta implementación se utilizan para alimentar una metodología propia para valorizar el carbono fijado por el sector forestal en esta Comunidad Autónoma, como región representativa de la Europa mediterránea. La metodología propia desarrollada permite calcular bonos de compensación de emisiones por gestión forestal sostenible teniendo en cuenta el riesgo de emisión por incendios forestales para que se ajuste a la realidad forestal mediterránea. Los resultados obtenidos muestran un potencial de compensación voluntaria de emisiones en la región de entre el 1,2 y el 5,6% del total de las emisiones no consideradas en el Sistema de Comercio de Emisiones de la Unión Europea (EU ETS).

En el sexto capítulo se utiliza un método simplificado con enfoque ascendente para calcular las emisiones fijadas por las áreas verdes urbanas a escala local en el municipio de València. El resultado permite evaluar la contribución de las áreas verdes urbanas a la consecución del Objetivo de Desarrollo Sostenible (ODS) 13 "Acción Climática" con alta resolución espacial. Los 901 parques y jardines urbanos del caso piloto de València fijan 812 t CO_2 eq. equivalente al 0,04% del total de emisiones GEI del municipio.

Estas implementaciones a diferentes escalas y sectores demuestran el potencial del sistema como herramienta de apoyo en la toma de decisión contra el cambio climático a nivel regional y local. Las diferentes implementaciones en casos piloto representativos, tanto a nivel regional en la Comunitat Valenciana como a nivel local en municipios grandes (València) y medianos (Quart de Poblet y Llíria) muestran el potencial de adaptación territorial y sectorial que tiene la herramienta. Las metodologías desarrolladas para los sectores específicos de tráfico rodado, edificación o sector forestal, ofrecen cuantificaciones con una resolución espacial con gran capacidad de optimizar las políticas locales y regionales. Por tanto, la herramienta cuenta con un gran potencial de escalabilidad y gran capacidad de mejora continua mediante la inclusión de nuevos enfoques metodológicos, adaptación de las metodologías a la disponibilidad de datos, metodologías concretas para sectores clave y actualización a las mejores metodologías disponibles derivadas de actividades de investigación de la comunidad científica.

III. ABSTRACT

Currently, regional and local decision-makers lack of tools to achieve greenhouse gases (GHG) emissions inventories with enough rigor, accuracy and completeness in order to prioritize available resources efficiently against climate change. Thus, in this thesis the development of a territorial and sectoral information system (SITE) to monitor GHG emissions as a local and regional climate governance tool is exposed. 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. Furthermore, this thesis defines the methodologies developed, a computer proposal for the back-end of the system and seven implementations as representative case studies at different scales (local and regional level), with the different methodological approaches and applied to different sectors. This is described in six chapters.

The first chapter presents the general methodological development of the three approaches of the system (top-down, bottom-up and hybrid approach). In addition, the implementation of the top-down approach on all sectors of the Valencia region (Comunitat Valenciana, Spain) and the local implementation on all sectors of the municipality of Valencia are described. Thus, the 162 indicators quantified in the 542 municipalities of the region emitted a total of 30Mt CO_2 eq. and fix a total of 6Mt CO_2 eq. in 2019. In addition, the territorial approach of the system has made it possible to identify that only 10 municipalities (1.8% of the total) emit 34% of the total, while 185 municipalities (34% of the total) fixed more emissions than they emit. Finally, the sectoral approach of the system made it possible to identify the 20% most emitter indicators of sectorial activities that are responsible for 85% of the total emissions.

The second chapter presents a computer proposal for the back-end of the system based on cooperative agents for the quantification of emissions and a simplified local application on all sectors through a bottom-up approach in a representative medium-sized municipality of approximately 25,000 inhabitants (Llíria, Spain). The proposed system

based on cooperative agents has allowed the automatic management of large volumes of data and information necessary for calculating emissions.

The third chapter presents the methodological development of a hybrid approach based on a geographic information system (GIS) to map primary energy consumption and GHG emissions in the building sector at the local level based on available energy certificates. In addition, the application of the methodology developed at the local level in a representative medium-sized municipality of approximately 25,000 inhabitants (Quart de Poblet, Spain) has allowed calculating a total of 32,000 t CO_2 eq. emitted derived from a primary energy consumption of 140 GWh in residential buildings with high spatial resolution at the individual building level.

The fourth chapter describes the development of a bottom-up methodology to quantify GHG emissions from urban traffic with high spatial and temporal resolution at the local level. The methodology developed uses data from urban traffic monitoring and control systems (induction loops) to calculate GHG emissions. In addition, its implementation in the municipality of Valencia (Spain) has made it possible to obtain a high resolution results of GHG emissions in 1,000 sensorized road segments of the city with hourly time resolution and spatial resolution at street level. The emission patterns obtained from the application of the methodology developed in the years 2016-2019 allow the analysis of GHG emissions from a key emitting agent, such as traffic, as well as from the dynamics of the city and its citizen mobility.

The fifth chapter describes the implementation of the system in the forestry sector of the Valencia region (Comunitat Valenciana) for calculating the annual fixation and the carbon stocked using a hybrid methodological approach. The results obtained from this implementation are used in an own methodology developed to valorise carbon fixed by the forestry sector in this region, as representative Mediterranean region. The methodology developed allows to calculate emission compensation carbon credits for sustainable forest management taking into account the risk of emission from forest fires to take into account Mediterranean forest reality conditions. The results obtained show a potential to offset emissions in Valencia pilot region of between 1.2 and 5.6% of the total emissions not considered in the European Union Emission Trading System (EU ETS).

In the sixth chapter, a simplified method with a bottom-up approach is used to calculate the emissions fixed by green urban areas at local level in the municipality of Valencia. The result allows evaluating the contribution of green urban areas to the achievement of Sustainable Development Goal (SDG) 13 "Climate Action" with high spatial resolution. The 901 urban parks and gardens of the Valencia pilot case set 812 t CO_2 eq. equivalent to 0.04% of the total GHG emissions of the municipality.

Thus, these implementations demonstrate the potential of the system as decision-making tool against climate change at the regional and local level as climate governance tool. The different implementations in representative pilot cases, both at the regional level in the Valencian Community and at the local level in large (Valencia) and medium-sized municipalities (Quart de Poblet and Llíria) demonstrate the potential for territorial and sectoral adaptation of the system developed. The methodologies developed for the specific sectors of road transport, building and forestry, offer quantifications with a spatial resolution with a great capacity to optimize local and regional policies. Therefore, the tool has a great potential for scalability and a great capacity for continuous improvement through the inclusion of new methodological approaches, adapting the methodologies to the availability of data, specific methodologies for key sectors, and updating to the best methodologies available in the scientific community.

IV. RESUM

Actualment, els responsables de prendre decisions contra el canvi climàtic no tenen eines per aconseguir inventaris d'emissions de gasos d'efecte hivernacle (GEH) amb prou cientificotècnic rigor, precisió i integritat per invertir els recursos disponibles de manera eficient en les mesures necessàries contra el canvi climàtic. Per això, en aquesta tesis se exposa el desenvolupa un sistema d'informació territorial i sectorial (SITE) per monitoritzar les emissions de GEH com a eina de governança climàtica local i regional. Aquest sistema combina els avantatges dels enfocaments metodològics descendent o *top-down* (de dalt a baix) i ascendent o *bottom-up* (de baix a dalt), per aconseguir un enfocament híbrid innovador per comptabilitzar i gestionar de manera eficient les emissions de GEH. Per tant, en aquesta tesi doctoral es descriuen els diferents desenvolupaments metodològics, tant generals com específics de sectors clau del Panel Intergovernamental contra el Canvi Climàtic (edificació, transport, forestal, etc.), un desenvolupament informàtic per al *back-end* del sistema i set implementacions com a casos d'estudi representatius, a diferents escales, amb els diferents enfocaments metodològics i aplicats sobre diferents sectors. Això queda descrit en sis capítols.

En el primer capítol s'exposa el desenvolupament metodològic general dels tres enfocaments del sistema (descendent, ascendent i enfocament híbrid). A més, es descriu la implementació de l'enfocament descendent sobre tots els sectors de la Comunitat Valenciana (Espanya) i la implementació local d'aquest mateix enfocament sobre tots els sectors del municipi de València. Així, els 162 indicadors quantificats en els 542 municipis de la regió van emetre un total de 30Mt CO_2 eq. i van fixar un total de 6Mt CO_2 eq. durant l'any 2019. A més, l'enfocament territorial del sistema individual ha permès identificar que tan sols 10 municipis (el 1,8% del total) emeten el 34% del total mentre que 185 municipis (34% del total) van fixar més emissions de les que van emetre. Finalment, l'enfocament sectorial del sistema va permetre identificar el 20% d'indicadors que són responsables del 85% del total d'emissions.

En el segon capítol s'exposa una proposta informàtica per al *back-end* del sistema basat en agents cooperatius per a la quantificació d'emissions i una aplicació local simplificada sobre tots els sectors mitjançant un enfocament ascendent en un municipi representatiu de mida mitjana de aproximadament 25.000 habitants (Llíria, Espanya). El sistema proposat basat en agents cooperatius ha permès la gestió automàtica de grans volums de dades i informació necessària per al càlcul d'emissions.

En el tercer capítol s'exposa el desenvolupament metodològic d'un enfocament híbrid basat en un sistema d'informació geogràfica (SIG) per mapejar el consum d'energia primària i les emissions de GEH en el sector de l'edificació a nivell local en base als certificats energètics disponibles. A més, l'aplicació de la metodologia desenvolupada a nivell local en un municipi representatiu de mida mitjana de aproximadament 25.000 habitants (Quart de Poblet, Espanya) ha permès calcular un total de 32.000 t CO_2 eq. emeses derivades d'un consum d'energia primària de 140 GWh en edificis residencials amb alta resolució espacial a nivell d'edifici individualment.

En el quart capítol es descriu el desenvolupament d'una metodologia ascendent (*bottom-up)* per quantificar les emissions de GEH del trànsit urbà amb alta resolució espacial i temporal a nivell local. La metodologia desenvolupada utilitza dades dels sistemes de control i monitorització del trànsit urbà (espires electromagnètiques) per calcular les emissions de GEH. A més, la seva implementació en el municipi de València (Espanya) ha permès obtenir resultats en gran resolució de les emissions de GEH en els més de 1.000 trams sensoritzats de la ciutat amb una resolució temporal horària i una resolució espacial a nivell de carrer. Els patrons d'emissió obtinguts de l'aplicació de la metodologia desenvolupada en els anys 2016-2019 permeten analitzar les emissions de GEH de un agent clau, com es el tràfic, així com de la dinàmica de la ciutat i la seva mobilitat ciutadana.

En el cinquè capítol es descriu la implementació del sistema en el sector forestal de la Comunitat Valenciana per al càlcul de fixació anual i de l'estoc de carboni acumulat mitjançant un enfocament metodològic híbrid. Els resultats obtinguts d'aquesta implementació s'utilitzen per alimentar una metodologia pròpia desenvolupada per valoritzar el carboni fixat pel sector forestal en esta Comunitat Autònoma, com regió representativa de la Europa mediterrània. La metodologia desenvolupada permet calcular bons de carboni per a la compensació d'emissions per gestió forestal sostenible tenint en compte el risc d'emissió per incendis forestals perquè s'ajusti a la realitat forestal mediterrània. Els resultats obtinguts mostren un potencial de compensació d'emissions a la regió pilot d'entre el 1,2 i el 5,6% del total de les emissions no considerades en el Sistema de Comerç d'Emissions de la Unió Europea (EU ETS).

En el sisè capítol s'utilitza un mètode simplificat amb enfocament ascendent per calcular les emissions fixades per les àrees verdes urbanes a escala local al municipi de València. El resultat permet avaluar la contribució de les àrees verdes urbanes a la consecució de l'Objectiu de Desenvolupament Sostenible (ODS) 13 "Acció Climàtica" amb alta resolució espacial. Els 901 parcs i jardins urbans del cas pilot de València fixen 812 t CO_2 eq. equivalent a 0,04% del total d'emissions GEH del municipi.

Aquestes implementacions a diferents escales i sectors demostren el potencial del sistema com a eina de suport en la presa de decisió contra el canvi climàtic a nivell regional i local. Les diferents implementacions en casos pilot representatius, tant a nivell regional a la Comunitat Valenciana com a nivell local en municipis grans (València) i mitjans (Quart de Poblet i Llíria,) mostren el potencial d'adaptació territorial i sectorial que té l'eina. Les metodologies desenvolupades per als sectors específics de trànsit rodat, edificació i forestal, ofereixen quantificacions amb una resolució espacial amb gran capacitat d'optimitzar les polítiques locals i regionals. Per tant, l'eina compta amb un gran potencial d'escalabilitat i gran capacitat de millora contínua mitjançant la inclusió de nous enfocaments metodològics, adaptació de les metodologies a la disponibilitat de dades, metodologies concretes per a sectors clau, i actualització a les millors metodologies disponibles derivades de activitats de investigació de la comunitat científica.

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1. INTRODUCCIÓN

1.1. Cambio climático y gobernanza climática

1.1.1 Cambio climático

La concentración actual de CO_2 atmosférico es la más alta de los últimos tres millones de años, alcanzando un promedio mundial de 421 ppm en abril de 2021 (NOAA 2021). Este gas junto a las altas concentraciones de otros gases de efecto invernadero (GEI) como el CH_4 o el N_2O, provocan el calentamiento global observado desde mediados del siglo XX. Estas y otras variaciones del estado del clima, identificables en variaciones del valor medio y/o en la variabilidad de sus propiedades, persistentes durante largos períodos de tiempo, es lo que la comunidad científica a nivel mundial ha definido como cambio climático (IPCC 2013) que afecta tanto a los sistemas naturales como a los humanos (Hoegh-Guldberg et al. 2019).

La Convención Marco de las Naciones Unidas sobre el Cambio Climático (CMNUCC), en su artículo 1, define el cambio climático como "cambio de clima atribuido directa o indirectamente a la actividad humana que altera la composición de la atmósfera global y que se suma a la variabilidad natural del clima observada durante períodos de tiempo comparables".

El cambio climático afecta a todas las regiones del mundo (Allen et al. 2018). Los casquetes polares se están derritiendo y el nivel del mar está subiendo (Hoegh-Guldberg et al. 2019). En algunas regiones, los fenómenos meteorológicos extremos y las inundaciones son cada vez más frecuentes, y en otras hay olas de calor y sequías que provocan, entre otras catástrofes naturales, incendios forestales que además retroalimentan el ciclo con la emisión de grandes cantidades de dióxido de carbono (CO_2) que anteriormente habían fijado mediante a la acción fotosintética (Binkley et al. 2002). Además, entre la comunidad científica existe un consenso a nivel mundial sobre la previsible intensificación de las consecuencias en las próximas décadas (Hoegh-Guldberg et al. 2019). Concretamente, la zona mediterránea se está convirtiendo en una región más seca que la hace todavía más vulnerable a la sequía y a los incendios (European Commission 2021a).

1.1.2 Objetivos de mitigación del Cambio Climático

Para minimizar el impacto del cambio climático, 195 países firmaron el Acuerdo de París (Paris Agreement 2016). Los firmantes acordaron "mantener el aumento de la temperatura media global en la superficie muy por debajo de los 2° C, y limitar el aumento a 1,5° C, ya que esto reduciría significativamente la riesgos e impactos del cambio climático". Para lograr este objetivo, las emisiones globales deberían alcanzar su punto máximo lo antes posible y la neutralidad de carbono debería lograrse en la segunda mitad del siglo (EEA 2020).

La Unión Europea (UE) se alinea con estos objetivos y se ha comprometido a reducir sus emisiones de gases de efecto invernadero en un 80-95% para 2050 en comparación con los niveles de 1990. Para ello se establece un objetivo a medio plazo de reducción en un 40% de emisión gases efecto invernadero (EEA 2020). Este objetivo se aplica legislativamente en tres Reglamentos:

a) Régimen de comercio de derechos de emisión de la UE (Emissions Trading System o ETS): EU ETS es una de las piedras angulares de la política de lucha contra el cambio climático de la UE y un instrumento esencial para reducir de forma económicamente eficaz las emisiones de gases de efecto invernadero. Es el principal mercado de carbono del mundo y el de mayor tamaño. El régimen de comercio de derechos de emisión de la UE se aplica en todos los países de la Unión, además de Islandia, Liechtenstein y Noruega (Estados AELC del EEE). Actualmente limita las emisiones de más de 10.000 instalaciones del sector energético, de la industria manufacturera y de las compañías aéreas que operan entre esos países. En total, las instalaciones y compañías aéreas afectadas, suponen en torno al 40% de las emisiones de gases de efecto invernadero de la UE (European Commission 2021b).

b) Reglamento de reparto del esfuerzo y los objetivos de reducción de emisiones de los Estados miembros. Establece objetivos nacionales de reducción de emisiones para 2030 para todos los Estados miembros, que oscilan entre el 0% y el -40% con respecto a los niveles de 2005. España: Reducciones de las emisiones de gases de efecto invernadero de los Estados miembros en 2030 en relación con sus niveles de 2005 determinados de conformidad con el artículo 4, apartado 3: España -26% (European Union 2018).

c) Reglamento sobre el uso de la tierra, el cambio de uso de la tierra y la silvicultura. El 14 de mayo de 2018, el Consejo adoptó el Reglamento sobre la inclusión de las emisiones y absorciones de gases de efecto invernadero resultantes del uso de la tierra, el cambio de uso de la tierra y la silvicultura (Land Use, Land-Use Change and Forestry o LULUCF) en el marco de actuación en materia de clima y energía hasta 2030, que previamente había votado el Parlamento Europeo el 17 de abril. El Reglamento establece un compromiso vinculante por el que cada Estado miembro debe asegurarse de que el cómputo de las emisiones generadas por el uso de la tierra se compense en su totalidad por una absorción equivalente de CO_2 de la atmósfera mediante la adopción de medidas en este sector. Esto es lo que se conoce como la "norma de deuda cero". Aunque los Estados miembros ya asumieron parcialmente ese compromiso de forma individual hasta 2020 dentro del Protocolo de Kioto, ahora el Reglamento lo traslada por primera vez a la legislación de la UE durante el periodo 2021-2030 (European Commission 2021c).

De este modo, todos los sectores contribuirán a la consecución del objetivo del 40% mediante la reducción de las emisiones, así como mediante el aumento de las absorciones (European Commission 2021d).

Sin embargo, la Comisión Europea publicó en 2019 la Comunicación del Pacto Verde Europeo (o European Green Deal) en cuyo objetivo de reducción de emisiones de GEI para 2030 se ha incrementado al 50-55% en comparación con los niveles de 1990 (European Commission 2019). Para monitorear el cumplimiento de este objetivo, los firmantes de la Convención Marco de las Naciones Unidas sobre el Cambio Climático (CMNUCC) deben informar anualmente sus emisiones de GEI a través de inventarios de GEI (European Commission 2021e). Esto pone de manifiesto la importancia que tienen los inventarios de emisiones a la hora de evaluar y de actuar en la mitigación de las emisiones y por tanto la necesidad de realizar inventarios de emisiones rigurosos.

1.1.3 Gobernanza climática

El término gobernanza, hace referencia a instituciones o conjunto de normas, procedimientos y prácticas implementadas colectivamente para resolver un problema compartido u otras cuestiones que deben gestionarse de manera eficaz (European Commission 2020a). En este sentido, Groff (2020) define la gobernanza climática como la gestión eficaz del sistema climático global con el objetivo de mantener a la humanidad y toda su gama de ecosistemas existentes, diversidad de especies y recursos naturales, dentro de un “espacio operativo seguro”.

La responsabilidad histórica de la Unión Europea en materia de emisiones GEI, los escenarios pronosticados por el Panel Intergubernamental contra el Cambio Climático (IPCC 2014a), y la voluntad de la Unión Europea de convertirse en el líder global en materia climática, propicia el escenario ideal para que la Unión Europea se atribuya un papel fundamental en la Gobernanza Climática global (Lázaro Touza 2011, European Commission 2019a).

a) Elementos clave de la gobernanza climática

Los elementos necesarios de un sistema de gobernanza climática eficaz son:

- **Responsabilidad climática**: Identificación de la responsabilidad climática (Lázaro Touza and Gómez de Agreda 2016) mediante cuantificación de las emisiones GEI de todos los focos de emisión.
- **Dominio del sujeto (cambio climático):** tener en consideración todo el alcance. Tener cuantificado el escenario base para saber el punto de partida en cuanto a emisiones GEI para saber dónde tenemos las opciones de mejora. Poder contemplar diferentes escenarios para tomar decisiones eficientes argumentadas en resultados cuantitativos (WEF 2019).
- **Estructura de acción:** un sistema de gobernanza climática debe tener la capacidad de integrar de forma eficiente las responsabilidades climáticas en la estructura general de administración pública o del agente emisor (Harris et al. 2016).
- **Evaluación de riesgos y oportunidades:** tener en cuenta los riesgos (por ejemplo, riesgo de incendios forestales por la no gestión forestal) y oportunidades dentro del sistema (por ejemplo, simulación de medidas de mitigación de emisiones que generen empleo y reducción de costes) (WEF 2019).
- **Integración estratégica y operativa:** un sistema de gobernanza climática debe permitir la planificación táctica (a medio y largo plazo) sobre los objetivos estratégicos, así como la planificación operativa (a corto plazo) para evaluar medidas y proyectos de mitigación concretos implementados.
- **Incentivación:** Debe dar la oportunidad de incentivar el reporte y la mitigación de las emisiones (por ejemplo, beneficios fiscales, posibilidad de solicitar ayudas públicas, etc.). (WEF 2019)
- **Presentación de Informes y divulgación:** El sistema debe poder generar informes estandarizados para asegurar la interoperabilidad con los diferentes acuerdos y compromisos nacionales e internacionales establecidos,

así como generar infografías que permitan la divulgación y la educación climática.

- **Mejora continua y actualización:** debe ser compatible con las mejores metodologías y mejores técnicas disponibles para poder actuar siempre de manera eficiente y rigurosa, sobre todo en base de herramientas digitales adaptadas a las necesidades de escala territorial o sectorial.

b) Pacto de los Alcaldes

Los compromisos internacionales de Naciones Unidas y de la Unión Europea focalizan los esfuerzos a nivel nacional donde todavía hay espacio para aumentar la eficiencia de las políticas nacionales en términos de reducción de emisiones de GEI (Niedertscheider et al. 2018). Para dar cumplimiento a las contribuciones determinadas a nivel nacional se requiere la contribución de las autoridades locales y regionales (CMNUCC 2016). En este sentido, a nivel local, las ciudades firmantes del Pacto de los Alcaldes por el Clima y la Energía (*Covenant of Mayors*) están comprometidas a apoyar la implementación del objetivo de reducción de emisiones de GEI del 40% de la UE para 2030 y la adopción de un enfoque conjunto para abordar la mitigación y la adaptación al cambio climático (Covenant of Mayors 2021). Con este Pacto, además, los firmantes se comprometen a presentar un Plan de Acción Climática y de Energía Sostenible (PACES) que describa las acciones clave que planean emprender (Kona et al. 2016) para reducir sus emisiones de GEI.

1.2. Estado del arte

La planificación y ejecución de los ***Planes de Acción Climática y de Energía Sostenible*** (PACES) deben basarse en los Inventarios de Emisiones de Referencia (IER o BEI, *Baseline Emission Inventory*) (JRC 2018). Esto significa que cualquier estrategia de compromiso de recursos destinados a la mitigación del cambio climático a nivel local se ve afectada por la calidad de los inventarios de emisiones de GEI. A pesar de esta estricta necesidad, los gestores públicos carecen de herramientas para cuantificar las emisiones de GEI con suficiente rigor, precisión y con un alcance que incluya todas las fuentes de emisión existentes en el municipio. Por ello, a menudo se utilizan inventarios simplificados con un alcance incompleto para definir estos Inventarios de Emisiones de Referencia (IER).

Esta deficiencia se debe a la falta de adaptación al contexto local/regional de los dos enfoques principales existentes para la cuantificación de emisiones de GEI, el enfoque descendente, de arriba hacia abajo (*top-down*), y el enfoque ascendente, de abajo hacia arriba (*bottom-up*).

El enfoque descendente o *top-down* consiste en desagregar un valor global utilizando variables específicas (definidas en este trabajo como variables atributivas al ser las variables utilizadas para atribuir a cada municipio su parte del total de las emisiones) disponibles en una escala menor para obtener los valores desagregados (Fiorillo et al. 2020). Tomando como ejemplo la industria del cemento, las emisiones nacionales totales asignadas a este sector podrían desagregarse para un municipio utilizando una variable atributiva como el número de fábricas de cemento en este municipio. La ventaja clave de este enfoque es que requiere menos datos y, por lo tanto, consume menos recursos. Sin embargo, la precisión del enfoque descendente (*top-down)* depende tanto de la precisión del valor global utilizado como de la calidad de la variable atributiva utilizada. En el ejemplo descrito, se puede suponer que el número de fábricas de cemento es importante, pero lo que determina sus emisiones es el combustible consumido y el flujo del material introducido en el proceso en cada una de ellas. Por lo tanto, la calidad o precisión del enfoque descendente es menor en comparación con el enfoque ascendente (Jing et al. 2016; Mateo-Pla et al. 2021). Además, este enfoque no permite monitorizar las medidas de mitigación implementadas en el municipio, como por ejemplo las medidas planificadas en los PACES locales, ya que las medidas de mitigación implementadas por los emisores locales normalmente tendrán un pequeño impacto en el agregado nacional de emisiones GEI y por tanto en el valor global utilizado para obtener el desagregado local. Tan solo si las variables específicas utilizadas recogieran el cambio producido por las medidas implementadas, este enfoque reflejaría el impacto logrado por la medida de mitigación en el municipio (por ejemplo, si la variable específica fuera proporción de coches de combustión interna respecto al total y la medida de mitigación fuera sustituir un número determinado de vehículos por vehículos eléctricos). En consecuencia, en la mayoría de los casos no será posible realizar un seguimiento de la implementación de las medidas de los PACES con el enfoque *top-down*.

Por otro lado, el enfoque ascendente o *bottom-up* consiste en agregar los resultados calculados para obtener el resultado global de una escala mayor (Fiorillo et al. 2020). Siguiendo nuestro ejemplo anterior, este enfoque consiste en la agregación de emisiones de cada una de las fábricas de cemento del municipio calculadas individualmente para obtener las emisiones totales de la actividad industrial cementera de este municipio. La ventaja clave es la mayor precisión que permite monitorizar las medidas de mitigación realizadas por cada agente de manera individual, requiriendo, por otro lado, de mucha mayor cantidad de datos, esfuerzo de cómputo y recursos (Mateo Pla et al. 2021). Hay experiencias en las que se ha aplicado un enfoque *bottom-up* a nivel subnacional, como en la provincia de Siena en Italia (Bastianoni et al. 2014). Sin embargo, en las experiencias mencionadas, el enfoque *bottom-up* ha conllevado dos grandes desventajas: 1) no permiten obtener valores desagregados a nivel local para desarrollar PACES locales, tan solo los resultados globales de la región, y 2) requieren un gran consumo de recursos para recolectar y tratar los datos específicos de la región.

Las debilidades mencionadas de cada uno de los dos enfoques descritos, propician que los inventarios de emisiones de referencia en los que se basan los PACES de los municipios suelan tener las siguientes limitaciones:

1. Se trata de inventarios basados en enfoques *top-down* con pocas variables atributivas (población, número de automóviles, etc.) que dan como resultado inventarios de baja calidad que no permiten un seguimiento adecuado de las medidas de mitigación implementadas en sus PACES. Este enfoque es el más utilizado para desarrollar inventarios de emisiones de referencia (Dai et al. 2016).

2. Inventarios basados en enfoques *bottom-up* limitados a unos pocos agentes de los cuales los municipios tienen datos fácilmente disponibles, lo que deja la mayoría de los indicadores sin cuantificar debido a la dificultad de acceso a los datos necesarios. Este enfoque conlleva el riesgo de realizar un diagnóstico erróneo de las emisiones reales. Así, los PACES planificados con base en estos inventarios son muy poco rigurosos y conducen a una inversión de los recursos disponibles en medidas de bajo impacto como se puede observar al comparar la eficiencia de sus medidas de mitigación planificadas. Por ejemplo, en el PACES de la ciudad de Palermo, una medida adoptada sobre coches y bicicletas compartidas tuvo un coste de implementación por tonelada de CO_2 reducido de 2,587 € (Covenant of Mayors Palermo 2015), mientras que una medida similar del PACES de la ciudad de València (servicio de bicicletas compartidas) tiene un coste de implementación de 34 € por tonelada de CO_2 reducida (Covenant of Mayors Valencia 2019).

Finalmente, a parte de estos enfoques aplicables a diferentes metodologías, existe una metodología ampliamente utilizada y aceptada internacionalmente (IPCC 2006), desarrollada por el Panel Intergubernamental sobre el Cambio Climático (o IPCC por sus siglas en inglés Intergovernmental Panel on Climate Change). El IPCC fue creado por el Programa de las Naciones Unidas para el Medio

Ambiente (ONU Medio Ambiente) y la Organización Meteorológica Mundial (OMM) en 1988. El IPCC es un panel compuesto por expertos internacionales que se encarga de determinar el estado de los conocimientos sobre el cambio climático. Por tanto, la metodología propuesta por el IPCC (IPCC 2006) es la que utilizan los diferentes países para realizar sus inventarios de emisiones anuales y la que cuenta con el mayor reconocimiento internacional. Sin embargo, esta metodología está pensada para aplicación a nivel nacional, por lo que tanto la estructura de implementación como los datos necesarios para su aplicación no siempre están disponibles a escala local o requiere de diferentes adaptaciones (Bastianoni et al. 2014).

1.3. Justificación de la investigación

La consecución o no de los objetivos de mitigación de emisiones descritos dependen de invertir de manera eficiente los recursos disponibles en materia de cambio climático. Para ello, los tomadores de decisión deben disponer de herramientas adecuadas con capacidad de realizar diagnósticos de emisiones de GEI a nivel local y regional rigurosos, precisos y con un alcance total de los focos de emisión. Además, es necesario contar con herramientas que permitan realizar un seguimiento del impacto de las medidas implementadas por cada municipio o de poder evaluar el impacto de programas estratégicos llevados a cabo a nivel regional.

Debido a que los recursos disponibles son limitados, estas herramientas deben permitir optimizar el enfoque utilizado en función de las necesidades específicas del municipio, para lograr también la máxima eficiencia en la monitorización y gestión de las emisiones. Así, podríamos sensorizar cada metro cuadrado del municipio para cuantificar sus emisiones, pero no sería eficiente. Las Tecnologías de la Información y las Comunicaciones (TIC), como tecnologías *Big Data y GIS* permiten mejorar significativamente la gestión de emisiones, ya que permiten sistematizar y digitalizar metodologías para poder abordar la recopilación y el tratamiento de los datos de manera más eficiente. Esto nos permite trabajar y analizar patrones a partir de grandes cantidades de datos (*Big Data*) que permiten una definición de los BEI mucho más precisa y permiten al mismo tiempo monitorear estas emisiones de un modo constante pudiendo ofrecer al tomador de decisiones la información más precisa de la que se dispone, así como de información sobre qué medidas de mitigación tienen más potencial para contribuir a la reducción de emisiones de GEI.

Por tanto, esta tesis muestra el desarrollo de una herramienta de gestión de emisiones que da respuesta a estas necesidades, a fin de ser una herramienta que proporcione a los decisores públicos de información rigurosa y precisa para poder definir e implementar las medidas más adecuadas y eficaces contra el cambio climático a nivel local y regional.

Los capítulos de la investigación incluidos en esta tesis describen el desarrollo metodológico de la herramienta, su estructura informática y la aplicación de la herramienta desarrollada en sectores clave en la mitigación del cambio climático como son la edificación, el transporte y la fijación de carbono en el sector forestal y en las zonas verdes urbanas.

2. OBJETIVOS

2.1 Objetivo general

El objetivo general de la investigación es desarrollar una herramienta integral de gestión de gases de efecto invernadero para la toma de decisión contra el cambio climático a nivel regional y local con implementación en la Comunitat Valenciana.

2.2 Objetivos específicos

Para alcanzar el objetivo general, la investigación cuenta con los siguientes objetivos específicos (OE), correspondiendo a cada uno a los capítulos de la tesis.

OE1. Desarrollar un sistema de información territorial de emisiones de GEI como herramienta de gobernanza climática a nivel local y regional (SITE). Caso de estudio en la Comunitat Valenciana (España).

OE2. Desarrollar una herramienta informática de gestión basada en agentes para la cuantificación de emisiones a nivel local.

OE3. Desarrollar una metodología innovadora basada en SIG para mapear el consumo de energía primaria y las emisiones de GEI en los edificios de acuerdo con los certificados de eficiencia energética con el fin de apoyar los procesos de toma de decisiones públicas contra el cambio climático en las ciudades.

OE4. Desarrollar una metodología *bottom-up* para cuantificar las emisiones del tráfico urbano con alta resolución espacial y temporal a nivel local.

OE5. Analizar el potencial forestal mediterráneo para compensar emisiones GEI a nivel regional con resolución a nivel local. Evidencia de Valencia, España.

OE6. Analizar la contribución de las áreas verdes urbanas para la consecución de los Objetivos de Desarrollo Sostenible (ODS). Caso de estudio: Valencia (España).

2.3 Objetivos operativos

Los seis objetivos específicos descritos se alcanzan por los objetivos operativos (OO) de la investigación, que se estructuran en los seis capítulos de la tesis.

a) Los objetivos operativos del Capítulo I (Desarrollo de un sistema de información territorial de emisiones de GEI como herramienta de gobernanza climática a nivel local y regional (SITE). Caso de estudio en la Comunitat Valenciana son:

   OOI1. Adecuar la estructura del inventario del Panel Intergubernamental sobre Cambio Climático (IPCC) a nivel local.

   OOI2. Desarrollar una metodología innovadora de cuantificación de GEI basada en un enfoque híbrido ascendente y descendente.

   OOI3. Implementar el sistema SITE de gobernanza climática en la Comunidad Valenciana.

b) Los objetivos operativos del Capítulo II (Desarrollo una herramienta informática de gestión basada en agentes para la cuantificación de emisiones a nivel local.) son:

OOII1. Diseñar la arquitectura informática de un sistema multiagente como herramienta de gestión de emisiones a nivel local.

OOII2. Definir los tipos de agentes necesarios para recopilar, almacenar y tratar los datos a fin de poder cuantificar las emisiones GEI del municipio.

c) Los objetivos operativos del Capítulo III (Desarrollo de una metodología innovadora basada en SIG para mapear el consumo de energía primaria y las emisiones de GEI en los edificios de acuerdo con los certificados de eficiencia energética con el fin de apoyar los procesos de toma de decisiones públicas contra el cambio climático en las ciudades.) son:

OOIII1. Calcular y caracterizar la eficiencia energética y las emisiones de GEI de las tipologías de edificios residenciales, públicos y terciarios en función de la ocupación.

OOIII2. Desarrollar modelos de integración de datos geoespaciales y alfanuméricos basados en la directiva EU INSPIRE.

OOIII3. Desarrollar un modelo innovador para obtener la distribución espacial de la energía primaria y las emisiones de GEI de los edificios a nivel de distrito y ciudad mediante el análisis y la estructuración de la base de datos geográfica y alfanumérica y la carga de datos.

OOIII4. Probar y validar el modelo desarrollado en una acción piloto en una ciudad representativa de tamaño medio para apoyar la toma de decisiones sobre medidas de transición energética y mitigación del cambio climático.

d) Los objetivos operativos del Capítulo IV (Desarrollo de una metodología *bottom-up* para cuantificar las emisiones del tráfico urbano con alta resolución espacial y temporal a nivel local) son:

OOIV1. Desarrollar una metodología *bottom-up* para cuantificar las emisiones del tráfico urbano con alta resolución espacial y temporal a nivel local.

OOIV2. Aplicar la metodología desarrollada a la ciudad de Valencia (España) para obtener una imagen detallada de la distribución espacial y temporal de las emisiones reales en la ciudad.

e) Los objetivos operativos del Capítulo V (Análisis del potencial forestal mediterráneo para compensar emisiones GEI a nivel regional con resolución a nivel local (Valéncia) son:

OOV1. Cuantificar la fijación de CO_2 en la biomasa total de los bosques de la zona de estudio en condiciones mediterráneas.

OOV2. Desarrollar y aplicar una metodología para monetizar el CO_2 eq. fijado por los bosques en condiciones mediterráneas.

OOV3. Comparar la fijación total de CO_2 forestal con las emisiones totales de GEI a nivel regional en la región analizada.

OOV4. Evaluar el potencial de la forestal mediterráneo para compensar las emisiones de GEI.

f) Los objetivos operativos del Capítulo VI (Analizar la contribución de las áreas verdes urbanas para la consecución de los Objetivos de Desarrollo Sostenible (ODS). Caso de estudio: València son:

OOVI1. Analizar la contribución directa y específica de las Zonas Verdes Urbanas a la consecución de los ODS a escala de sección censal.

OOVI2. Evaluar la contribución de las Zonas Verdes Urbanas a la consecución del ODS 13 “Acción Climática” en el caso práctico de la ciudad de València (España) mediante la cuantificación de fijación de carbono anual como sumidero.

3. ESTRUCTURA DE LA TESIS

El presente documento está formado por 12 secciones con el siguiente contenido:

- La primera sección comprende la introducción general de la tesis donde se describe la motivación de la investigación realizada, el estado del arte de la temática tratada y la justificación de la investigación.

- La segunda sección describe los objetivos de la investigación. En ella se definen el objetivo general, los objetivos específicos que se han establecido para lograr alcanzar el objetivo general, así como los objetivos operativos que se han seguido a fin de lograr el objetivo general de la investigación.

- La tercera sección describe la estructura de la tesis y el contenido de cada una de las secciones que la componen.

- Las secciones de la cuatro a la nueve conforman los seis capítulos que abordan los seis objetivos específicos de la investigación. Cada una de estas secciones cuenta con su propia estructura siguiendo el método científico: introducción, objetivos, material y métodos, resultados y discusión y conclusiones.

- La décima sección recoge las conclusiones generales de la investigación realizada en base al conocimiento científico adquirido durante toda la fase de desarrollo de la tesis.

- La undécima sección enumera los diferentes elementos de transferencia de los resultados de la investigación logrados y se citan cada uno de los elementos científicos publicados que envuelven la investigación clasificados en: publicaciones en revistas científicas, comunicaciones en congresos científicos tanto nacionales como internacionales, jornadas y seminarios de transferencia, proyectos y contratos de investigación y transferencia de los resultados a empresas y administraciones públicas.

- La duodécima sección recoge todas las referencias bibliográficas citadas en todo el documento de la tesis.

4. CAPÍTULO 1 Desarrollo de un sistema de información territorial de emisiones de GEI como herramienta de gobernanza climática a nivel local y regional (SITE). Caso de estudio en la Comunitat Valenciana (España).

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

CAPÍTULO I

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4. CAPÍTULO 1 Desarrollo de un sistema de información territorial de emisiones de GEI como herramienta de gobernanza climática a nivel local y regional (SITE). Caso de estudio en la Comunitat Valenciana (España).

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

4.1 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 2014a). 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 2020b). 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 2019a).

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 2019a). To monitor the 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 2021e).

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. 2021). 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. 2021). 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 analyzing 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 CO2 reduced of 2,587 € (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 CO2 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).

4.2 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 systematize.

4.2.1 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 (IDAE 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 (Figure 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

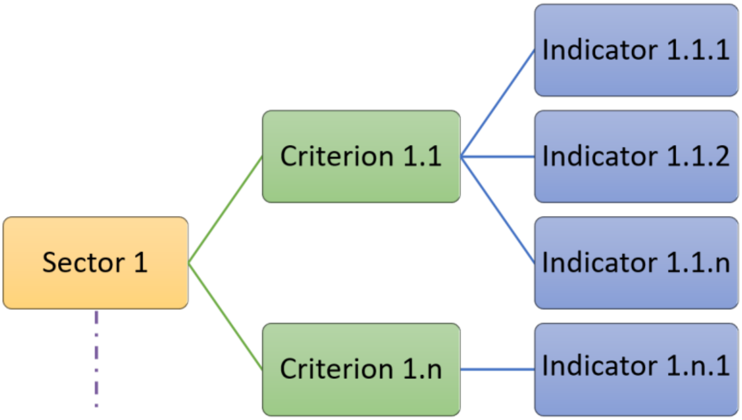

Figure 1. SITE inventory structure scheme.

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

4.2.2 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 between accuracy and cost.

In the following subsections, SITE 1.0, 2.0, and 3.0 quantification methodologies will be explained in detail.

4.2.2.1 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:

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

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:

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

Where:

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

4.2.2.2 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:

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

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.

Equation (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 equation (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.

4.2.2.3 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:

$$\begin{aligned} E_{3;i,j,k} &= cvL_{i,j,k,1} \times vL_{i,j,k,1} + \cdots + cvL_{i,j,k,n_{i,j,k}} \times vL_{i,j,k,n_{i,j,k}} \\ &= \sum_{s=1}^{n_{i,j,k}} cvL_{i,j,k,s}\, vL_{i,j,k,s} \end{aligned} \tag{5}$$

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 (equation (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:

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

The local attributive variable vector is given by:

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

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

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

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:

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

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 ($n_{i,j,k} \leq M_{i,j,k}$). 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:

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

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 2012a) 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.

4.2.2.4 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.

4.2.3 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 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.

4.2.3.1 Data gathering

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

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	

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[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

Urban planning area classified as "Endowment"	Generic	Statistics portal of Valencia region[3]
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

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[3] http://pegv.gva.es/va/bdt

[4] https://sedeapl.dgt.gob.es/WEB_IEST_CONSULTA/subcategoria.faces

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.

4.2.3.2 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.

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	

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).

4.2.4 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.

Figure 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:

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 (Figure 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.

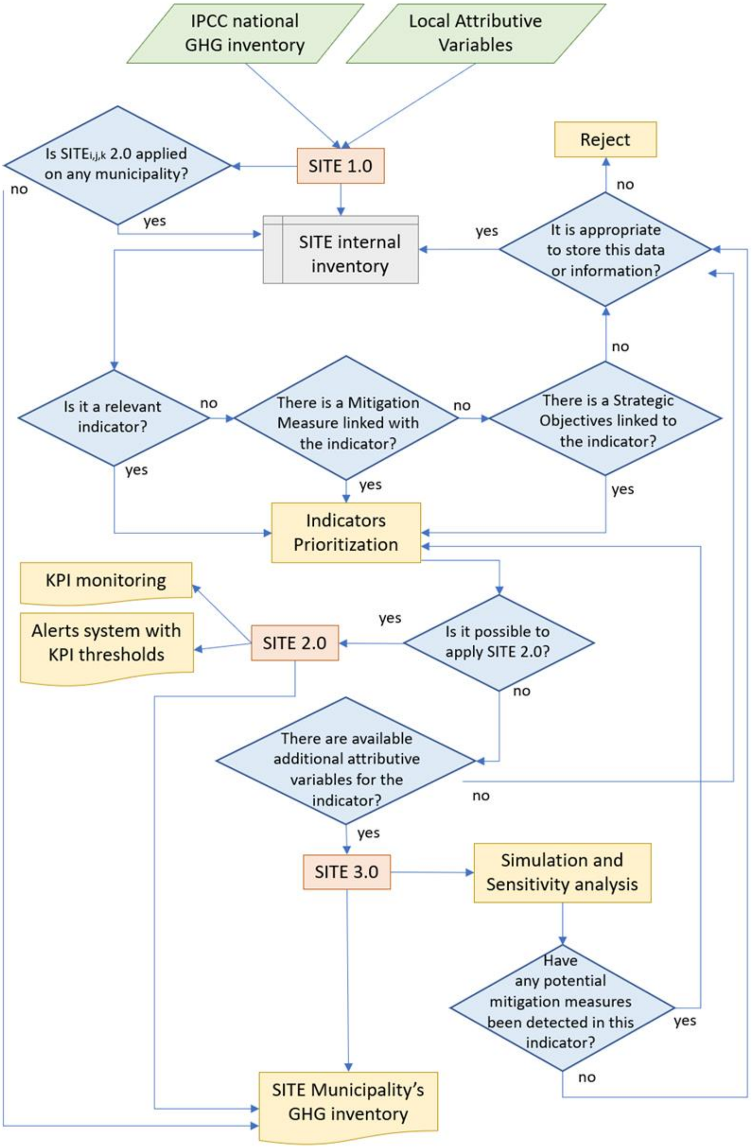

Figure 2. Decision tree for an indicator in SITE as a climate governance tool.

4.3 Results and Discussion

4.3.1 Implementation of SITE 1.0

a. 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 (Figure 3).

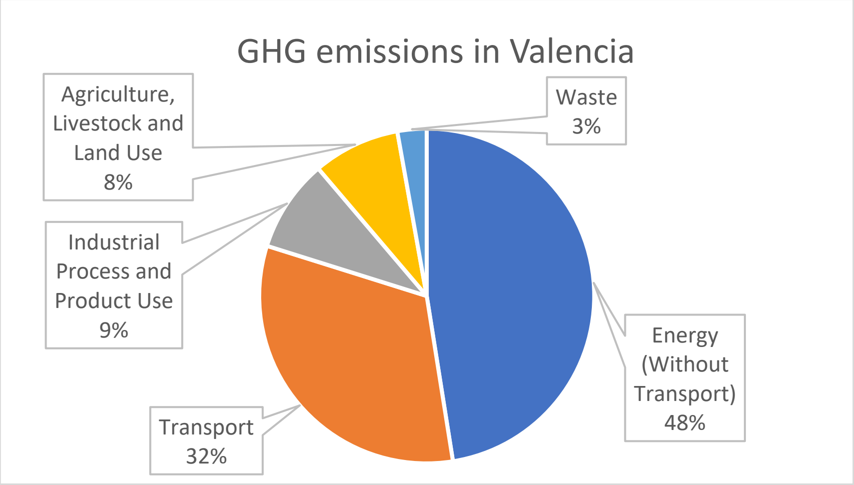

Figure 3. Sectorial distribution of GHG emissions in Valencia.

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 (Figure 4).

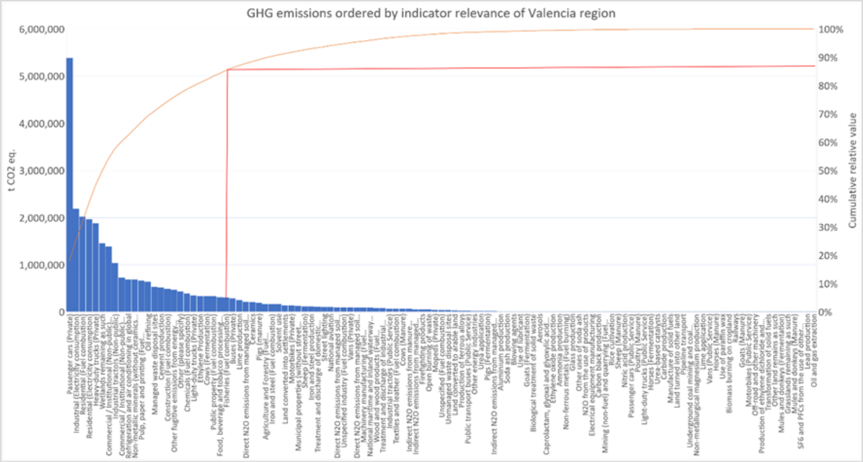

Figure 4. GHG emissions ordered by indicator relevance in Valencia. GHG emissions of the 20% most relevant indicators are indicated by the red line.

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.

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**

The territorial GHG emissions distribution shows that most emissions are produced in coastal cities (Figure 8**¡Error! No se encuentra el origen de la referencia.** Left). In addition, Table 4 shows the 10 most emitter cities that represent 34.45% of total emissions.

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 cities		**10,928,817**	**36.45**

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 (Figure 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.

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**

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 (Figure 5). However, 92% of the total 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 (Figure 5).

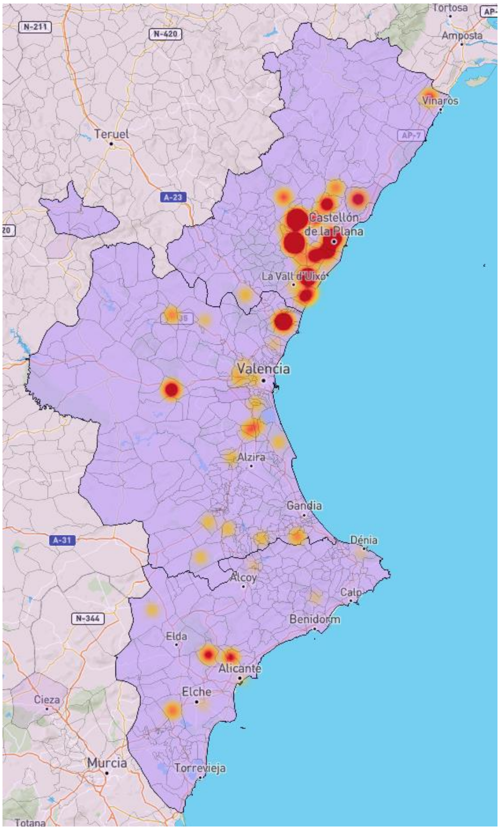

Figure 5. Territorial distribution of GHG emissions from EU-ETS installations in Valencia.

b. 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 (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 (Figure 6).

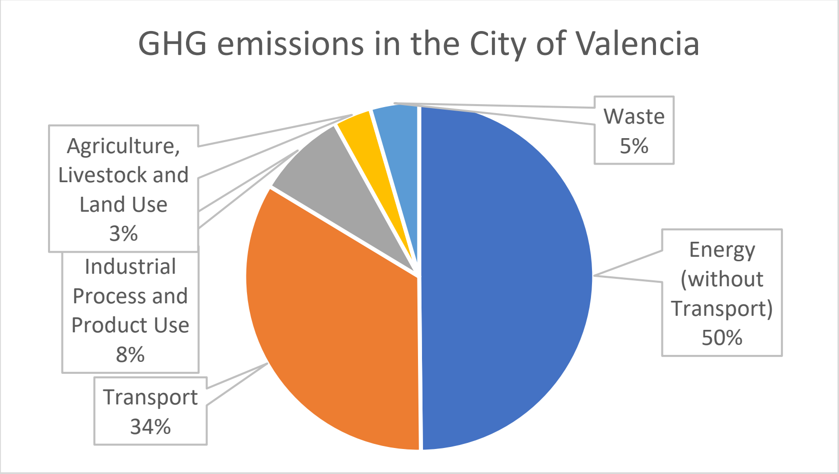

Figure 6. Sectorial distribution of GHG emissions in the City of Valencia.

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 (Figure 7). This prioritization adapted to local level and conditions can be used to develop highly efficient local action plans.

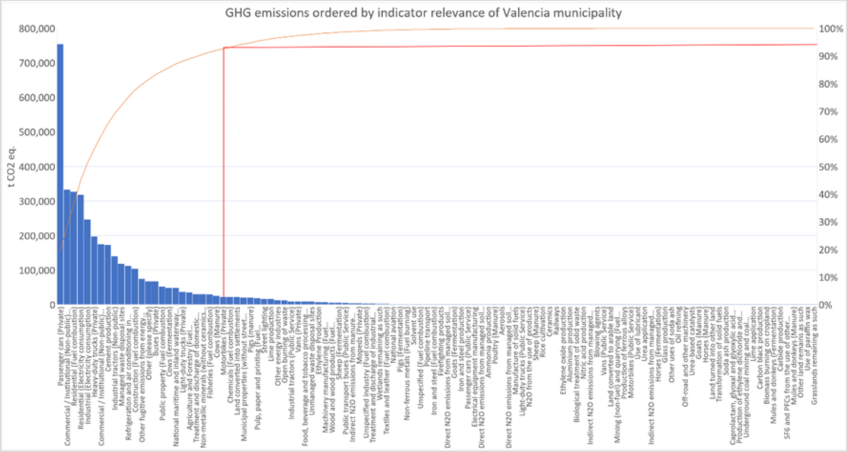

Figure 7. GHG emissions ordered by indicator relevance in the City of Valencia (year 2019). GHG emissions of the 20% most relevant indicators are indicated by the red line.

c. 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 (Figure 8 Right). Thus, figure 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.

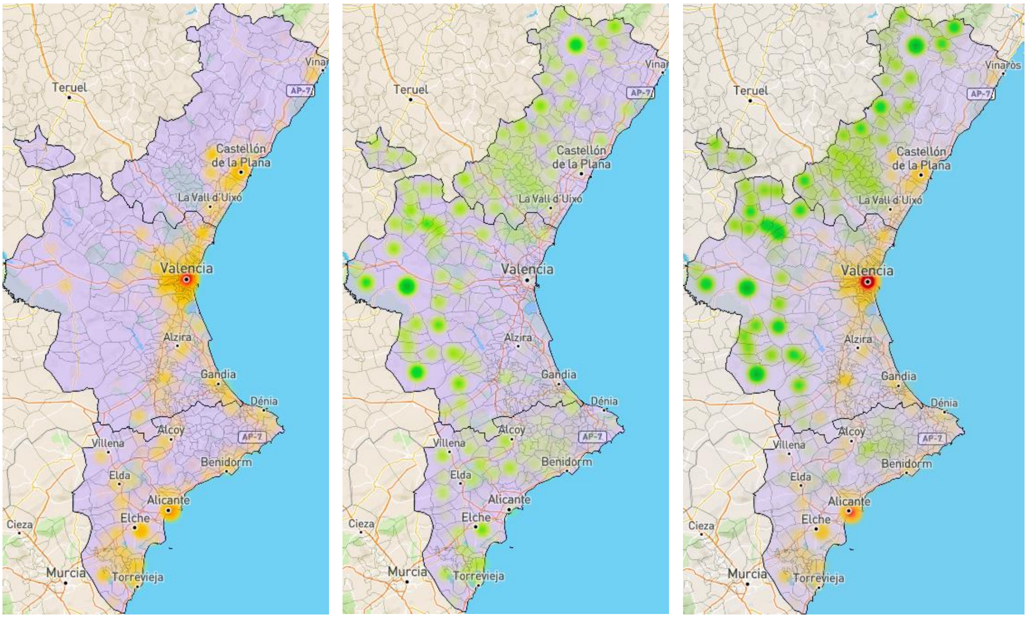

Figure 8. Left: Territorial distribution of gross GHG emissions of Valencia region. Centre: Territorial distribution of GHG fixation in Valencia. Right: Territorial distribution of Net GHG emissions and fixation by municipality (Red: Net GHG emissions; Green: Net GHG fixation).

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).

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

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 2.0 to implement SITE 3.0 in municipalities with available data.

4.3.2 Implementation of SITE 3.0

4.3.2.1 Selected representative cities

According to the accomplishment of sampling criteria described in section 4.2.3.2 “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 CO2 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).

4.3.2.2 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:

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

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).

$\overline{d_{\mathrm{ij}}}$: 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 (IDEA 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.

Equation (10) can be rewritten as:

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

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

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

A new parameter is defined as:

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

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:

<u>Assumption 1:</u> The unknown population distribution $\overline{d_{\mathrm{ij}}}$ can be approximated by the sample mean of each category of energy certificates $\overline{d_{\mathrm{ij}}} = \overline{d_{\mathrm{ij}} *}$. 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 $\overline{d_{\mathrm{i1}}}, \overline{d_{\mathrm{i2}}}\ and\ \overline{d_{\mathrm{i3}}}$ with the average use factor for each category. In summary:

$$\overline{d_{\mathrm{i1}}} = f_1 \overline{d_{\mathrm{i}} *}; \quad \overline{d_{\mathrm{i2}}} = f_2 \overline{d_{\mathrm{i}} *} \quad \overline{d_{\mathrm{i3}}} = 0$$

$\overline{d_{\mathrm{i}} *}$: 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

<u>Assumption 2:</u> 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: $\beta_{i1} = \beta_{i2} = \beta_{i3} \equiv \beta_i$

<u>Assumption 3:</u> Municipalities with a sufficient number of EPBC-certified dwellings and similar $p *_{\mathrm{i}}$ distribution, possess similar $\beta_i\ distribution$. 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

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

$E_{3;1,3,2}$: 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 $S *_t\, p *_\mathrm{i}\, \overline{d *_\mathrm{i}}\; (f_1\, s_1 + f_2\, s_2) = D_i * (f_1, f_2)$ 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 equation (5):

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

Where:

$vL_i = D_i * (f_1, f_2)$: 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 (Figure 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.

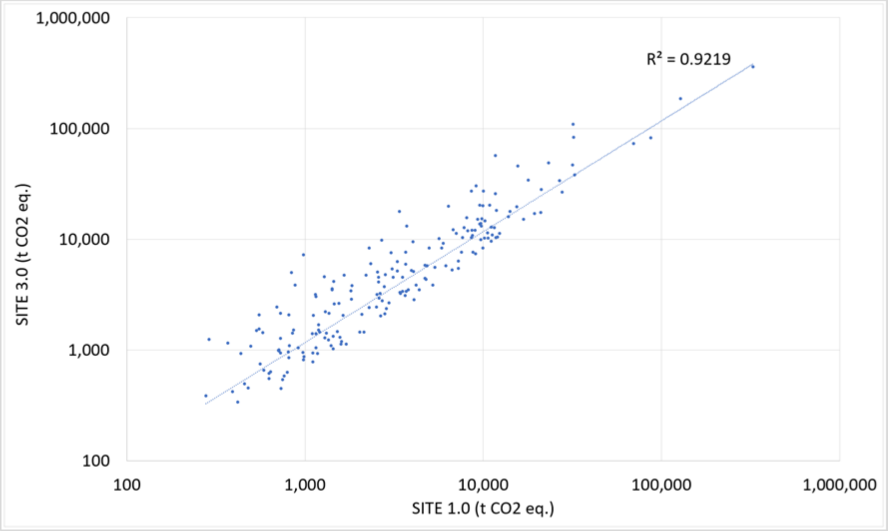

Figure 9. SITE 3.0 implementation results of the 197 municipalities with available data. Logarithmic scale.

4.4 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 optimise 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 162 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 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.

4.5 Appendix. SITE Inventory structure.

Ind. 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)
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
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)

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

5 CAPÍTULO 2 Desarrollo de una herramienta informática de gestión basada en agentes para la cuantificación de emisiones a nivel local.

A cooperative agent-based management tool proposal to quantify GHG emissions locally.

CAPÍTULO II

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5. CAPÍTULO 2 Desarrollo de una herramienta informática de gestión basada en agentes para la cuantificación de emisiones a nivel local.

A cooperative agent-based management tool proposal to quantify GHG emissions locally.

5.1 Introduction

Global warming is undeniable. Problems like droughts, forest fires, floods, soil erosions and desertification, among others, are affecting our planet, specifically the Mediterranean region human influence is determined by the significant increase of the anthropogenic Greenhouse Gases emissions (GHG).

The transition to a low-carbon economy in cities is increasingly seen as a crucial contribution to limiting global warming (IPCC 2014b). As a basis for acting on climate change, cities need to quantify and report their GHG emissions (Ibrahim et al. 2012, Dodman 2011, Kennedy et al. 2012, Lin et al. 2013, Rauland and Newman 2015, Ramaswami et al. 2012). Thus, after adopting the European Union's climate and energy package of measures in 2008, the European Commission presented the Covenant of Mayors for Climate and Energy initiative (European Commission 2016a). The commitments for Covenant Signatories have been proposed to exceed the European Union's goal of reducing CO_2 emissions by 20% by 2020 and by 40% by 2030 (European Commission 2016a). Based on these quantifications and reports, cities must define specific policies and strategies to achieve their emissions reduction objectives. Therefore, public decision-makers at local administrations need appropriate tools that help them to evaluate objectively and transparently the activities and decisions carried out to reduce GHG emissions in quantitative terms. However, there are no such tools today.

Thus, from a multidisciplinary research group on Information and Communication Technologies against Climate Change (ICTvsCC) have developed an advanced management tool based on the quantification of GHG emissions within the integral SimBioTIC project. It facilitates decision-making optimizing the available resources to raise climate metrics and evidence-based objectives in real time according to environmental criterion.

The smart city concept integrates information and communication technologies (ICT), with different types of electronic data collection devices connected to a network, in order to supply information to optimize city operations and services, to manage assets and resources efficiently, as well as to empower their citizens (Hamblen 2015). SimBioTIC helps to add and improve services to a smart city as part of the strategy to face the climate change from a local scale. The first pilot action is being deployed successfully in the city of Llíria.

The developed tool was designed as an integral Balanced Scorecard (Kaplan and Norton 2007) to be used by both public decision-makers and citizens, promoting transparency in decision-making processes. It also encourages participation and promotes massive engagement through creating a community of contribution, increasing the awareness and interest of the citizens to stay updated with the evolution of GHG emissions and the results of the decisions taken. The tool is in constant improvement, based on the results of experiences and the feedback from users. It is also envisaged to add new modules for the GHG emissions' management to the actual tool's version.

The rest of the paper is organized as follows. Section 5.2 is dedicated to present our current management tool system that process, organize and classify data from several number of sources with the aim of highlight the valuable data and transforms the way in which final users interact with the data. Section 5.3 focuses on materials used to adapt and construct our architecture and the methods used to structure the categorization of the modules. Next, Section 5.4 presents the proposed multiagent architecture to improve the performance of our current management tool system. Section 5.5 shows the preliminary results of the first successful pilot action in Llíria and Section 5.6 concludes the paper with the achievements and potentialities of our advanced management tool.

5.2 System description

In this section, we describe the design of the platform architecture as a base for the development and subsequently deployed in Llíria as Smart City. The core mission of this platform is to address key topics of climate change problems with ICT infrastructure (technologies, frameworks, models) and services in communities, cities and regions. ICT become the structural enabler of change for addressing the problems mentioned in Section 5.1. In fact, we develop this platform in order to:

(a) make the information transparent as possible to the end users,

(b) take specific measures to reduce cost and consumptions,

(c) monitor the consumptions information,

(d) provide context from historical data,

(e) allow a better understanding of cost and consumptions, i.e., when it is compared against same periods of past years or other neighbour communities and

(f) adjust the terms and parameters to address efficiency to engage more effectively and actively with citizens.

The general architectural schema of the platform can be seen in Figure 10. Where to meet previously defined functional requirements, it is separated through different logical layers: broker, data handling, and external services.

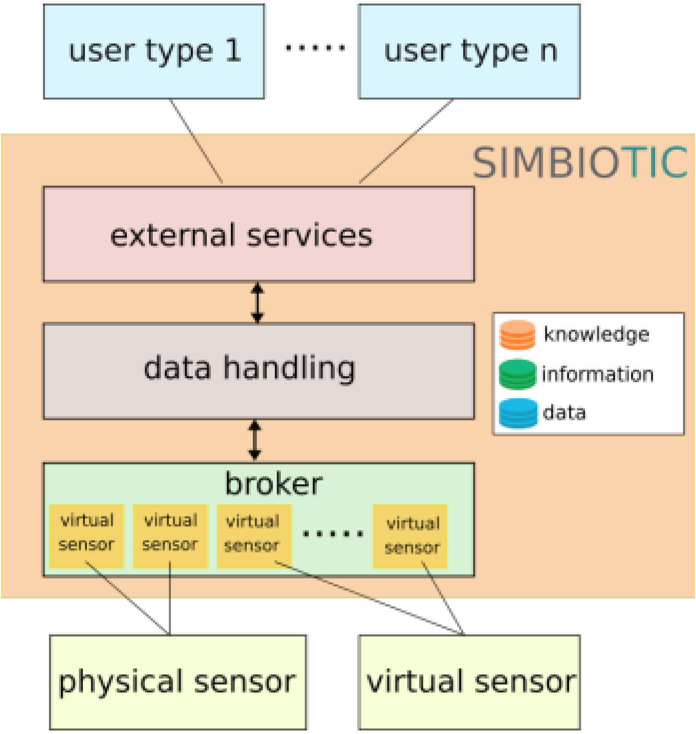

Figure 10. SimBioTIC's General Architecture.

The platform receives and gathers information from sensors. Two different kinds of sensors were defined and characterized depending on the source that provide data. On the one side, a physical sensor is considered as a simple Internet of Things (IoT) board with networking capabilities using either an Ethernet module or a wireless module. On the oter side, a virtual sensor is an abstraction to heterogeneous data sources that produce measurements as if it would be a physical sensor (e.g. complex data calculated by the report (IPCC 2014b) related to the GHG footprint measured and converted to its CO_2 equivalent in terms of global warming potential).

The broker layer is an intermediary between the external data sources and the system. It is in charge of getting data from registered sensors, regardless of their type: real or virtual. To take care of pre- and postprocessing of data, this layer also includes a semantic adapter, which is used to add certain semantics to the received data.

Data handling layer manages the store of all the data that has passed through the broker layer. It will create a large non-relational database or data lake. It should be considered that the data volumes are very large since the granularity of the information is very fine. Thus, depending on the requirements from these data, it can be structured in tables and/or stored in relational databases. In the analysis, a variety of methods and approaches were used to generate information and certain knowledge, depending on location and different circumstances adapted to each case. Finally, the layer of external services is able to allow operations of visualization and management to different users or even other applications.

5.3 Material and methods

This section is composed by two parts: the characteristics of the pilot city and the description of two modules of the advanced management tool.

5.3.1 City for the pilot study

The selection of the pilot city is important to test the tools and methodologies developed and to ensure results with high representativeness. To achieve this, a representative medium-sized city it is needed, with presence of all economic sectors.

For these reasons, the first pilot action was deployed in the city of Llíria, located 25 km NW of Valencia, as can be seen in Figure 11. Llíria has approximately 25,000 inhabitants, placing itself in an average position between large cities and small towns. The city of Llíria has activity representation of the main economic sectors: in primary sectors (e.g. agriculture, forestry, livestock), in industrial sectors (e.g. ceramic, plastic, metal, electronic components, agro-food products) and in services (e.g. energy, transport, tourism, commerce), as well as a waste treatment plant. Llíria's characteristics are ideal and representative to test the methodologies and tools developed.

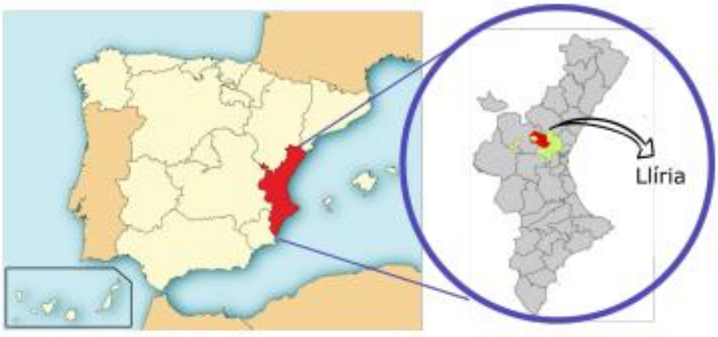

Figure 11. Location of the pilot city Llíria (Spain).

5.3.2 Inventory of GHG emissions

The first platform module is the basis of the tool. The inventory of GHG emission is structured in three levels of categorization (sectors, criteria and indicators) and their corresponding Key Performance Indicators (KPIs) to quantity the GHG emissions of each emitting source located in the city. The quantitative results are expressed in terms of CO_2-equivalent (CO_2-eq), calculated according to the global warming potentials of the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2006).

Different methodologies have been consulted and evaluated in order to elaborate this module. The more relevant are GHG PROTOCOL 2014 (Bhatia et al.2012) as well as the IPCC guidelines (IPCC 2006). The structure of the categorization of the inventory of GHG emission module facilitates the standardization of status reports generated by the second module.

5.3.3 Status report generator

The Status Report generator platform module can produce several report models, among them the normalized mandatory reports that each country must present at European level to comply with agreements and/or objectives at national and international level. This module helps in decision-making as well as the rectification of incidents or the modifications of inefficient measures detected, guaranteeing real-time monitoring of GHG emissions.

The modular structure of the tool allows to generate a specific report that complains with the Covenant of Mayors (European Commission 2016a). In order to achieve this, the standardization of the categorization of the IPCC guide (IPCC 2006) has been ensured, respecting the alphanumeric nomenclature between the structure of the categories in order to guarantee also the comparability between inventories.

5.4 Proposed architecture

The decentralized approach of the SimBioTIC project (Figure 10) allows to gain in flexibility, fault tolerance and scalability. These properties allow to model and implement a cooperative multi-agent system.

Following agents are considered in the multi-agent system: the sensors, actuators, smart objects (the IoT Things), the information adapters, the entity who stores the collected data in databases and the recipients of information (citizens, politics, institutions, among others). The objective is to develop a middleware based solution to allow that the agents could interact to each other and with the environment in a cooperative way, by the definition of communication protocols to the interaction, communication and interoperability made between them.

As shown in Figure 12, the middleware architecture is composed by five main layers, at the bottom as our previous architecture, physical and virtual elements have identities, physical attributes, and virtual personalities in the sense that they are seamlessly integrated into the information network (Rogers 2011). At the top is the user interface layer, which presents by different dashboards an abstraction of the information in conjunction of fields and controls to provide the interaction with the final users. The layer called Composition and Management is where all the data are transformed to a common and manageable standard for all middleware architecture. Indeed, it is where most of the agents are introduced (Padgham and Winikoff 2005). Following different agents' types are defined:

a) PublisherAgents embedded in IoT boards and in the addition of emission information of the IPCC reports.
b) BrokerAgents are responsible for routing information obtained by agents, coordinating and insuring the data delivery to rest of the agents.
c) SubcriberAgents embedded in all the agents that receives data, this type of agent is in charge of extracting and collecting

all the information and leave it available for the data preprocessing techniques.

d) PersistenceAgents provide persistence to the information also perform backup tasks, as well as to ensure the correct consistency and storage of information.
e) DisplayAgents show real-time information about GHG emissions.
f) ReportGeneratorAgents this agent's type facilitate the retrieval of useful information from the database and provides custom reports.

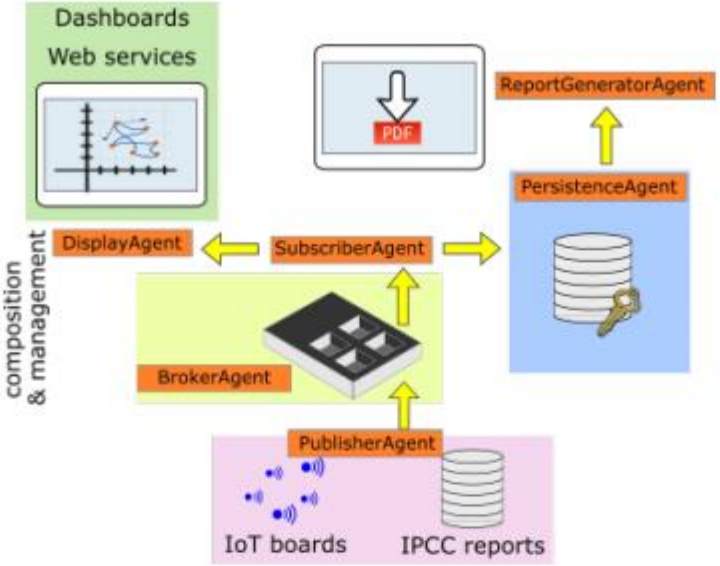

Figure 12. SimBioTIC's General Architecture based in cooperative agents.

5.5 Preliminary results

5.5.1 Inventory of GHG emissions

The GHG emissions inventory module applied to 2016 in the city of Llíria reflects a total of GHG emissions of 175,427 tonnes CO_2-eq. As it can be seen in Figure 13 the total level of GHG emissions is considerably reduced by the “Forestry” sector. Due to its carbon sink effect, forestry is responsible for the absorption of a large amount of GHG. Thus, the total net value of emissions is reduced to 156,133 tonnes CO_2-eq.

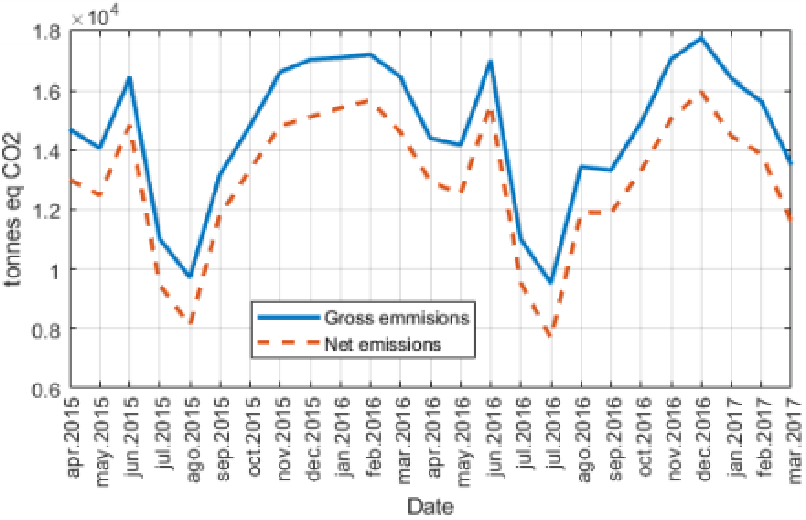

Figure 13. Influence of forestry on net GHG emissions in Llíria in year 2016.

Disaggregating the GHG emissions by sectors (Figure 14), close to 60% of total emissions were recorded in the “Energy (without Transport)” sector. Within this sector, the criterion with the highest emission levels is “Burning of fuel in manufacturing and construction industries” that represents 24% of the total, with the “Ceramic Industry” indicator as the main responsible with 18% of the total amount.

The next sector with the largest amount of GHG emissions is the “Transport” sector, with 25% of the total. The criterion “Private ground transport” dominates clearly with 24% of emissions, being the indicator “Automobiles” the most significant with 16% of the total GHG emissions.

The third highest GHG emissions sector is “Agriculture, Livestock and Other Land Uses”, with 9% of total emissions, very far from the previous two. The sectors “Industrial Processes and Product Use” and “Waste” represent each of them, only the 3% of the emissions.

Concerning to the carbon sink effect, the forests of the municipality of Llíria calculated in the “Forestry” sector are responsible for an 11% reduction in gross GHG emissions.

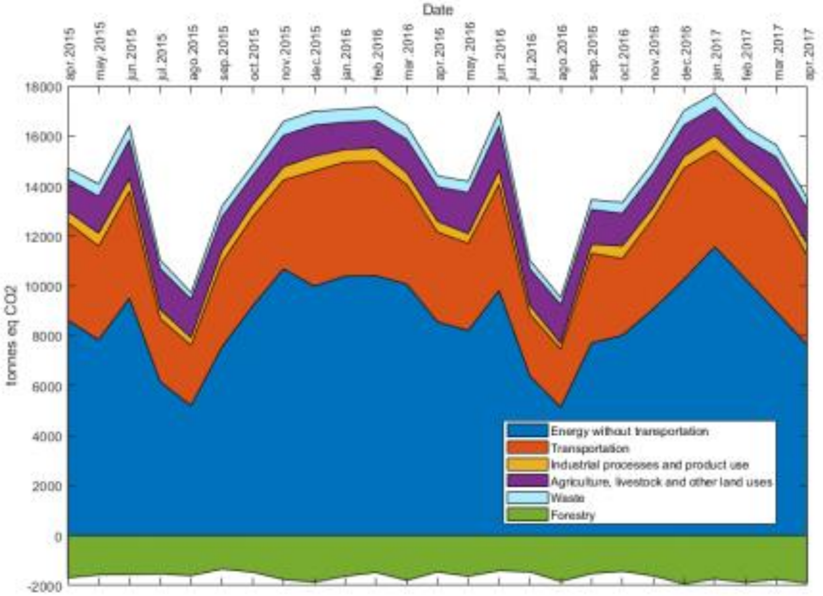

Figure 14. Dynamic GHG emissions separated by sectors in Llíria in year 2016.

Figure 14 also represents the results obtained in its monthly distribution by sectors. A clear seasonal variability in the sectors “Energy (without transport)”, “Industrial Processes and Use of products”, “Transport” and “Waste” can be observed, due to the industrial activity that reflects a decrease in summer and two peaks of GHG emissions in June, before the break of August holidays and the months of December-January for industrial activity during the Christmas season. The sum of the seasonal variability observed mainly in the sectors “Energy (without Transport)” and “Transportation”, determines the seasonality of the total GHG emissions in Llíria.

5.5.2 Status report generator

The results of the status report generator module consist in two standardized reports: a complete report of the 2016 emissions of all the emitting sources and with sink effect of the city of Llíria and a second report adapted to the requirements of the Covenant of Mayors for Climate and Energy that presents a comparative analysis with the reference year 2010.

5.6 Conclusions

An agent-based management tool has been developed and presented. This advanced tool allows to know accurately in real time the status and the evolution of GHG emissions from each source at local level. Thus, the tool helps local administrations to transit to Smart Cities using the potential of ICTs.

The emission sources could be showed in a quantitative way by sectors and by a disaggregated manner in criteria and indicators. With this systematic analysis and evaluation, the tool enables the decision-making processes on the most efficient actions against climate change. Moreover, the tool generates automatically the mandatory reports to comply with the international agreements. The tool is in constant improvement, based on the results of experiences derived from the first pilot action carried out in a representative medium-sized city, being able to be transferred and extrapolated to other cities and regions with different socio-economic conditions.

Therefore, the standardization of reports and structure for categorization allow setting secondary objectives such as the development of carbon compensation mechanisms between sinks and emitting sources at local level, among others. This should be researched in near future.

Finally, based on the obtained results, the research group is developing new tool modules related to the integral management of GHG emissions at local and regional scale, e.g. carbon stocks management, risk management of large volumes of GHG emissions and simulation module of alternative scenarios to evaluate the impacts of mitigation measures using sustainable criteria.

6 CAPÍTULO 3 Desarrollo de una metodología innovadora basada en SIG para mapear el consumo de energía primaria y las emisiones de GEI en los edificios de acuerdo con los certificados de eficiencia energética con el fin de apoyar los procesos de toma de decisiones públicas contra el cambio climático en las ciudades.

Energy efficiency and GHG emissions mapping of buildings for decision-making processes against climate change at local level.

CAPÍTULO III

Referencia de la publicación:

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6. CAPÍTULO 3 Desarrollo de una metodología innovadora basada en SIG para mapear el consumo de energía primaria y las emisiones de GEI en los edificios de acuerdo con los certificados de eficiencia energética con el fin de apoyar los procesos de toma de decisiones públicas contra el cambio climático en las ciudades.

Energy efficiency and GHG emissions mapping of buildings for decision-making processes against climate change at local level.

6.1 Introduction

Climate change adaptation and mitigation have become a central concern of many cities in Europe. Following European Commission (2016b) around 65% of European cities with more than 5,000 inhabitants have a mitigation plan in place. There is, however, a wide variation among countries. The mayors of 300 EU cities signed the Covenant of Mayors for Climate and Energy (European Commission 2019b), pledging to reduce their greenhouse gas (GHG) emissions by at least 40% by 2030 (European Commission 2018b). Many other cities have also signed the covenant, including some from outside the EU. European cities are seeking to reduce both energy consumption and GHG emissions by supporting better thermal insulation of buildings, using more efficient lighting technologies and promoting new low-energy buildings. But more will be needed to meet the ambitious EU goal of cutting GHG emissions by 80% by 2050 (European Commission 2018c). Many cities are testing new nature-based solutions to adapt to climate change. Such solutions often also support additional goals, such as reducing GHG emissions, pollution or flood risks (Yang et al.

2005). For example, green roofs can help reduce the impact of heat waves and they can catch run-off water and reduce the need for cooling (Escobedo et al. 2011). Trees can reduce the heat island effect and reduce air pollution (Min et al. 2010; McPherson et al. 1998; Nowak and Crane 2002; Nowak et al. 2006).

Buildings in urban areas are responsible for approximately 40% of energy consumption and 36% of CO_2 emissions in the European Commission (2011). This is because 35% of the EU's buildings are over 50 years old and 75% of the building stock is energy inefficient, while only 1% of the building stock is renovated each year (European Commission 2016b). Therefore, the building sector has high potential to implement measures to reduce energy consumption (Gouldson et al. 2016). Accordingly, EU policies are oriented to improve energy efficiency in buildings, e.g. Energy Performance of Buildings Directive 2010/31/EU (European Commission 2010) and Energy Efficiency Directive 2012/27/EU (European Commission 2012b).

Local governments have to act against climate change with energy transition measures, monitoring their impacts. Therefore, local authorities have to define strategically planning in multi-level governance to mitigate and adapt to climate change, especially in their urban development and rehabilitation programmes of the housing stock (Gouldson et al. 2015; Matsumoto et al. 2014). So, we are facing a scenario that makes that policies and directives at supra-municipal level should be supported with the commitment of local councils to achieve the targets (Wilson 2006). Therefore, local authorities must take on the challenge posed by the problem of climate change and turn it into an opportunity. As evidence of it, the Covenant of Mayors for Climate and Energy has the purpose to support and foster the efforts of local authorities in the implementation of sustainable energy policies (European Commission 2016b). This agreement has become the main European movement in which local authorities participate, assuming a voluntary commitment to improve energy transition in their territories to significantly reduce CO_2 emissions.

Public decision makers have a lack of tools to support strategic planning in a quantitative, objective and transparent manner. In addition, an accurate and monitorised energy characterization as well as a quantification of GHG emissions of buildings are necessary:

a) to estimate the baseline energy consumption of the building sector, disaggregated by residential, tertiary and public typologies (Kavgic et al. 2010),
b) to analyse geospatial distribution of the different levels of energy efficiency and related GHG emissions (Mastrucci et al. 2014) and
c) to combine urban energy geospatial characterization to simulate scenarios to determine integrated planning-energy strategies and to support, evaluate and control sustainable transition measures in cities (Evola et al. 2016).

For this purpose, various modelling techniques, based on top-down and bottom-up approaches, allow energy consumptions calculation at city level (Nouvel et al. 2015). Top-down approaches relate the energy consumption of buildings to macroeconomic variables such as population growth and tax revenues that treat the built environment as a black box and rarely describe in detail the demand characteristics or the performance of building components (Bentzen and Engsted 2001). On the other hand, bottom-up approaches base their estimations on single buildings analysis (Kavgic et al. 2010). These approaches aim to take into account both statistical data and building physics, which generally achieve a comprehensive characterization of energy services at any spatial or temporal scale (Fonseca and Schlueter 2015).

Moreover, Geographical Information Systems (GIS) offer the opportunity to characterize geospatial energy consumption intensities using geo-referenced information (Mastrucci et al. 2014). So, several GIS-based models have been already developed at city scale (Caputo et al. 2013; Theodoridou et al. 2012; Howard et al. 2012; Heiple and Sailor 2008). Nevertheless, in order to ensure interoperability at EU level it is necessary to develop the data model adapted to standard normative. For this purpose, the European INSPIRE Directive (European Commission 2007) defines specifications and metadata in buildings topic. Thus, data models adapted to the INSPIRE directive should be developed to achieve higher spatial resolution for public decision-making processes on sustainable urban planning towards energy transition and mitigation of climate change (Nouvel et al. 2015).

The general objective of this multidisciplinary research is to develop an innovative methodology based on GIS for mapping primary energy consumption and GHG emissions in buildings according to energy efficiency certificates in order to support public decision-making processes against climate change in cities. To achieve this overall objective, following specific objectives have been defined:

1. to calculate and characterize energy efficiency and GHG emissions from residential, public and tertiary buildings typologies based on occupancy,
2. to develop geospatial and alphanumerical data integration models based on the EU INSPIRE directive,
3. to develop an innovative model to obtain spatial distribution of primary energy and GHG emissions of buildings at district and city levels by analysing and structuring geographic and alphanumeric data base and data loading and
4. to test and validate the developed model in a pilot action in a representative medium-sized city to support decision-making about energy transition measures and mitigation of climate change.

6.2 Materials and Methods

The research methodology is based on a bottom-up approach including data gathering, calculation and characterization of energy efficiency and GHG emissions of buildings, data model development adapted to the EU INSPIRE Directive integrating alphanumeric and geographic data, analysis and structure of geographic and alphanumeric databases and data loading to obtain spatial distribution of primary energy and GHG emissions of buildings and, finally, testing and evaluating of the methodology in a representative medium-sized city.

6.2.1 Selection of representative city: pilot action

According to the United Nations (United Nations 2014), approximately two thirds of the world's population will be living in urban areas by 2050. This rapid pace of change is projected to be driven primarily by changes in Africa and Asia, as the focus of global urbanisation patterns continues to shift towards developing and emerging economies. In Europe, around 75% of the population is nowadays living in cities, towns and suburbs (EUROSTAT 2016). So, the pace of urbanisation change in Europe is likely slower, with the share of the population living in urban areas projected to rise over 80 % by 2050. In fact, Europeans tend to live in mid-sized cities. Following European Commission (2016b), European cities are on average located closer to each other than cities in other parts of the world. This is the outcome of Europe's dense network of mid-size cities, generally in a range between 25,000 and 100,000 inhabitants.

In this research, the selection of the pilot urban area is important to test the methodology developed and to ensure results with high representativeness. To achieve this, a representative mid-sized city is needed, with all activity sectors (several land uses including agriculture, industry and services as well as public administration facilities), but also with available data on residential, tertiary and public buildings. For these reasons, Quart de Poblet was selected as pilot city. It is located 6 km W of Valencia (Spain). Quart de Poblet has approximately 25,000 inhabitants and meets with all selection requirements.

Quart de Poblet city has specially interest on GHG emissions reduction. In 2016, the city adopted the goals of the Covenant of Mayors for

Climate and Energy initiative and has been proposed to exceed the EU goals of reducing CO_2 emissions by 20 % for 2020 and by 40% for 2030, adopting a joint approach to tackling mitigation and adaptation to climate change (European Commission 2018b). In fact, energy consumption reduction in buildings tackle both two objectives: on the one hand, mitigation due to reduction of fossil energy consumption and therefore GHG emissions and, on the other hand, adaptation due to improvement of energy efficiency.

6.2.2 Data gathering, calculation and characterization of energy efficiency and GHG emissions of buildings

The bottom-up methodology is based on building physics and a statistical hybrid approach, which calculates energy demand per living area (m^2). For this purpose, three different types of buildings based on occupancy are differentiated: residential, tertiary (non public) and public buildings.

Energy consumption has been calculated based on the building energy certificates rating following EU Directive 2010/31 (European Commission 2010). The rating is the result of the energy consumption necessary to satisfy the building energy demand calculation under normal operating and occupancy conditions. Buildings are classified by letters from A to G, where G corresponds to the least efficient building and A to the most efficient, according to primary energy consumption and CO_2 emissions compared to a base building with same geometry and location and following EU legislation (European Commission 2010).

Energy rating scales depend on whether the building is recently constructed or not, as well as according to its use, either residential or tertiary. The methodology for tertiary building certification consists in the comparison with a building archetype, based on geometrical building characteristics (European Commission 2010).

Energy certificates of residential and tertiary (non public) buildings are obtained from available databases of the Energy Agency in the region (IVACE). This database includes a total of 1,218 registers in the pilot city which allow characterize the primary energy consumption and CO_2 emissions of residential, commercial and other tertiary buildings.

Furthermore, 37 public buildings with several uses (administration buildings, schools, library, sports facilities, social centres, care centres for elderly people etc.) were audited and certificated carrying out inventory visits to characterize the energy consumption equipment and to verify the state of the thermal insulation, following EU Directive (European Commission 2010). These input data are entered into the energy certification tools to obtain the expected energy consumption in each audited building according to their characteristics. Finally, results were contrasted with the actual energy consumption of the building, obtained from the energy bills from the last two years (2016 and 2017) provided by the local public administration.

6.2.3 Development of a data model adapted to INSPIRE integrating alphanumeric and geographic data

The developed model contains every data needed to identify and locate the buildings and every data used to obtain the primary energy consumption and the GHG emissions Thus, in order to comply with the EU INSPIRE Directive (2007/2/EC) (European Commission 2007), the data model is composed by the fields showed in Table 7.

Table 7. Fields of data model developed to comply with EU INSPIRE Directive (European Commission 2007).

Fields	Metadata
Code	Code id of the building
Type	Type of building
Description	Description of aim of the building (f.e. hospital, office, restaurant …)
Address	Address of the building
Municipality	Name of the municipality
Postal code	Code id of the municipality
Region	Name of the region
Primary energy consumption (kWh/m^2*year)	Primary energy consumption of the building per square meter and year
Primary energy consumption level	Primary energy consumption level of classification
GHG emissions (kg CO$_2$ eq./m^2*year)	GHG emissions of the building per square meter and year

GHG emissions level	GHG emissions level of classification
Normative	Regulations followed for the construction of the building
Cadastral reference	Cadastral reference
Area (m^2)	Total square meters of the building
Total primary energy consumption (MWh)	Total primary energy consumption of the building
Total GHG emission (t CO_2 eq.)	Total GHG emissions of the building
Year of construction	Year of construction
Classified housing units	Number of dwellings classified of the building
Total housing units	Number of total dwellings of the building

6.2.4 Analysis and structuring of geographic and alphanumeric databases and data loading to obtain spatial distribution of primary energy and GHG emissions of buildings

Geographical layers and field data compose necessary data. Filed data were obtained from local administration, cadastre, databases of the Energy Agency and additional energy audits carried out by the researchers.

Data to characterize the General Information (explained in Section 5.2.3) are available in national cadastre. For the example of Spain, is available in the catalogue file “46_104_U_2019-02-06” of Spanish Cadastre website [https://www.sedecatastro.gob.es]. From the cadastre information file, Land register is extracted for each cadastral parcel involved. The constructive unit register exists for each construction of each constructive unit in each cadastral parcel. Finally, there is one construction register for each constructive unit for each parcel involved. Geographical data of buildings, parcels and streets are obtained from the Electronic Headquarters of the Cadastre (cadastre website) that also provides access to the INSPIRE services (the atom file of buildings).

Furthermore, data of energy certificates not available in the Energy Agency database are obtained through bottom-up methodology based on building physics and statistical hybrid approach estimated by energy audits in public buildings.

Once the available data has been collected and analysed, the following domains are defined (Table 8 and Table 9):

Table 8. Buildings type domains definition of the data model.

Building type	Description
Residential	Individual dwelling, apartment, residential building block
Tertiary	Commercial building, restaurant, hospital, office, others
Public	Public buildings

Table 9. Primary energy and GHG emissions certification levels.

Primary Energy/GHG emissions certification level	Description
G	Red colour Building without any type of energy efficiency and high GHG emissions
F	Totally orange colour Building with almost zero energy efficiency and high level of GHG emissions
E	Light orange colour Very little energy efficiency and significant GHG emissions
D	Yellow colour Normal energy efficiency and moderate GHG emissions
C	Yellowish green colour Acceptable energy efficiency and low GHG emissions
B	Light green colour Good energy efficiency and very low GHG emissions
A	Dark green colour Highest energy efficiency and lowest GHG emissions

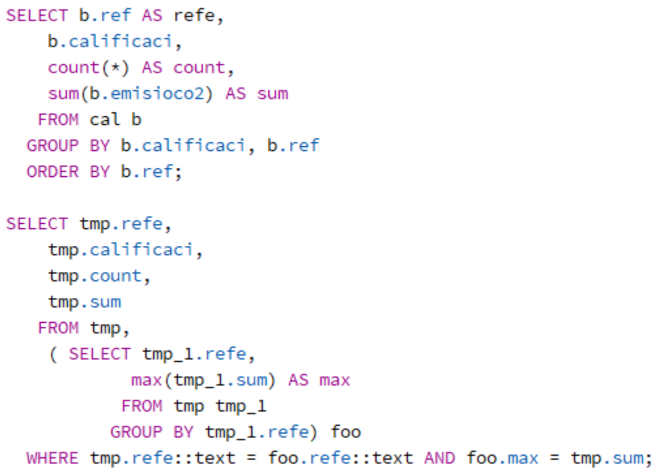
Then, this information is loaded from databases to the developed model to analyse. Information from the Energy Agency and own performed energy certification estimations is classified by building type categories as shown in Table 10.

Table 10. Energy certificates classification by building type.

Energy certificates	Quantity	Building type
Commercial building	11	Tertiary
Residential building block	69	Residential
Commercial premises	84	Tertiary
Office	37	Tertiary
Other	22	Tertiary
Restaurant	6	Tertiary
Individual dwelling	946	Residential
Single-family dwelling	43	Residential
Public buildings	37	Public

The analysis of geographical data shows some cadastral reference with more than one energy efficiency certificate by parcel. This is because a building could be composed by different dwellings with different energy supply or different energy efficiency level.

Thus, it has established a methodology to calculate the level of energy certificates of a parcel with more than one certificate, for the case that it has more than one dwelling with different energy efficiency certificate levels. For this purpose, a SQL query is developed and applied (see Figure 15) to calculate the quantity of dwellings per parcel with energy efficiency certificate available. Then, total amount of building area (m^2) of each efficiency energy level is summed up. Finally, it is assigned to the parcel the energy efficiency level calculated.



```
SELECT b.ref AS refe,
    b.calificaci,
    count(*) AS count,
    sum(b.emisioco2) AS sum
   FROM cal b
  GROUP BY b.calificaci, b.ref
  ORDER BY b.ref;

SELECT tmp.refe,
    tmp.calificaci,
    tmp.count,
    tmp.sum
   FROM tmp,
    ( SELECT tmp_1.refe,
            max(tmp_1.sum) AS max
           FROM tmp tmp_1
          GROUP BY tmp_1.refe) foo
  WHERE tmp.refe::text = foo.refe::text AND foo.max = tmp.sum;
```

Figure 15. SQL query to calculate the quantity of dwelling per parcel with energy efficiency certificate available.

6.2.5 Representativeness level of data concerning the total of the city

The representativeness level of city data is calculated as amount of parcel calculated based on efficiency energy certificates concerning total parcels in the city. Then, a representativeness map is generated in order to improve data gathering of the districts with low level of representativeness.

6.2.6 Integration of the model for decision making at the local level

The integration of the model developed generates maps of primary energy consumption and GHG emissions to identify the potential districts for improving energy efficiency and reducing GHG emissions. This will help the public decision-maker to define local strategies towards a low-carbon economy and energy transition policies against climate change in a more efficient and transparent manner, based on metrics of high spatial resolution.

Furthermore, an example for the application of the developed model for decision-making at the local/district level has been carried out. For this purpose, primary energy consumption and GHG emissions of buildings without available data nowadays have been calculated based on statistical correlation with results of buildings, which have been determined following the described methodology. Thus, the energy efficiency level based on the year of construction and orientation of building has been calculated based on energy classification by national law (Ministry of Spain 2013).

Therefore, an intersection of the parcel layer with the buildings layer is done to obtain the year and the number of dwellings in each parcel. On the other hand, the CAT format with alphanumeric information is provided by the cadastre, obtaining the properties of each plot, with the m^2 and year of construction or rehabilitation. Then, energy efficiency classification average is obtained per year. Finally, an algorithm is developed and applied in order to calculate GHG emissions and primary energy consumption of buildings without available data.

6.3 Results and discussion

6.3.1 Representativeness level of data concerning the total of the city

The representativeness level of available data concerning the total of the city is 17% (Table 11). Each parcel has calculated the representative level as the relation between dwellings with available energy efficiency certification and total dwellings of the parcel (Figure 16).

Table 11. Representativeness level of the city data concerning the total of the city.

Type of Parcels	Amount with data	Total city	Representativeness
Tertiary	99	732	14%
Residential	333	1,891	18%
Public	27	56	48%
Total Parcels with data	459	2,679	17%

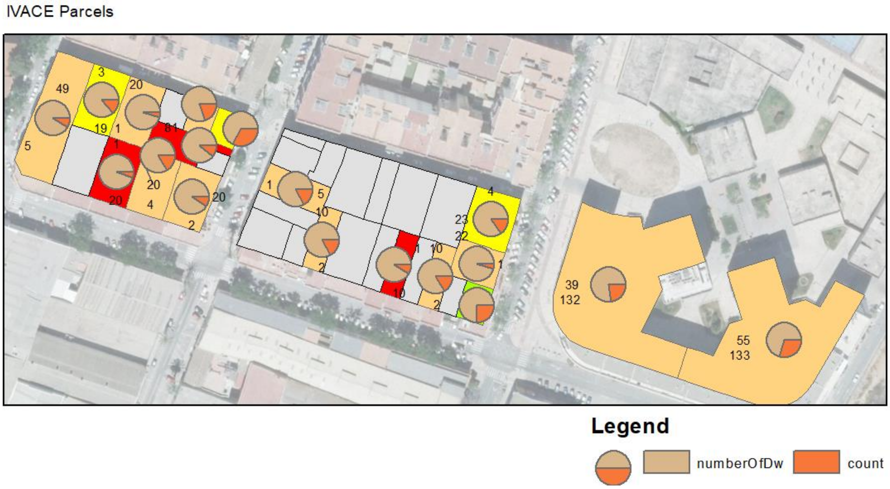


Figure 16. Representativeness level of an example of parcels of a district of the pilot city Quart de Poblet. In brown number of energy

efficiency certification in parcel, in orange, number of total buildings/locals in the parcel.

6.3.2 Energy efficiency and GHG emissions level of buildings

a) Residential and tertiary (non public) buildings

Most of the 1,218 available energy certificates of the municipality are individual dwellings located in housing blocks (77%), followed by commercial premises (7%) and complete housing blocks (5%). The classification of energy certificates by use type obtained from the Energy Agency database can be observed in Figure 17.

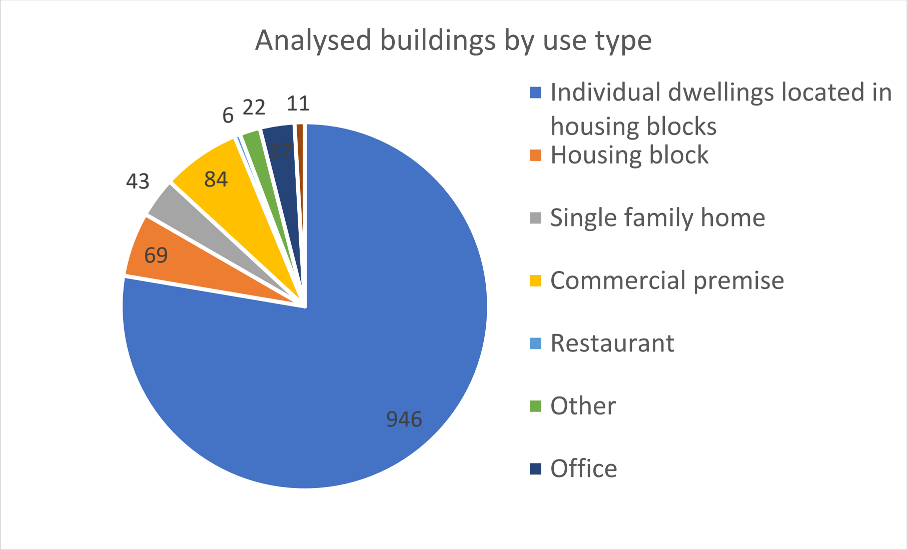


Figure 17. Analysed buildings by use type.

The results of energy certificates obtained from these buildings are shown in Figure 18. Energy certification levels E, G, D and F are the most common in the analysed buildings. This low rating is due to the age structure of the residential buildings in the city, most of them constructed in the decades from 1960 to 1990, many of them without an integral rehabilitation since construction. In terms of GHG emissions this implies an annual average GHG emissions of 45 kg CO_2/m^2.

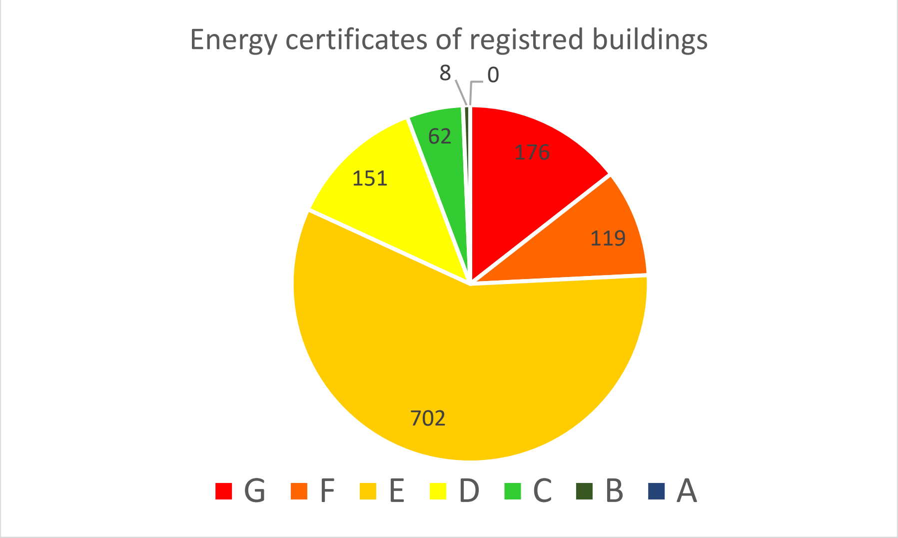


Figure 18. Energy certificated of registered buildings.

Furthermore, the obtained results show that tertiary buildings have a significant higher energy efficiency, obtaining approximately the 30% of them a level of energy efficiency of C or more. On the other side, more than 90% of residential buildings have obtained a certification of D or less. It is also important that no one building has obtained level A.

These results were compared with the data from (IDAE 2017) that collects energy certificates of every building audited in Spain by regions. This comparative shows that the results obtained Quart de Poblet are very similar to the region (Valencia) and the country (Spain), as shown in Figure 19. In all local, regional and national scales predominates E energy certification level with more than 50% of total amount of audited buildings followed by G level. Nevertheless, the results in terms of energy certification of Quart de Poblet buildings are slightly better than the region of Valencia (8% of the buildings have C or more energy efficiency level while in the region of Valencia only 4% have C or more).

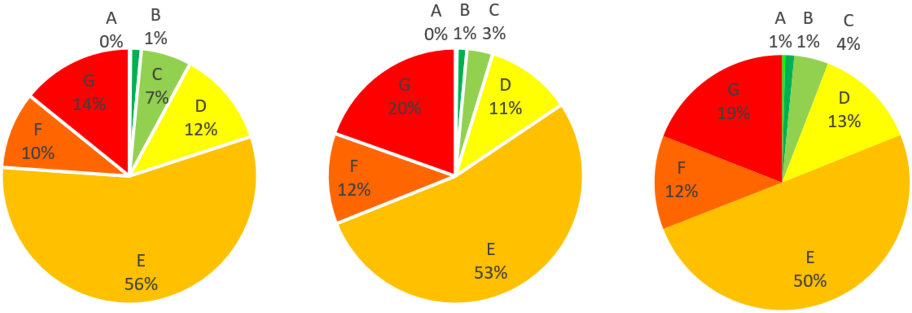


Figure 19. Comparative results at local, regional and national level. (a) Local level (pilot city of Quart de Poblet); (b) Regional level (Valencian Community) and (c) National level (Spain).

b) Public buildings

Energy certification results and its analysis in terms of GHG emissions and primary energy consumption are shown in the Figure 20.

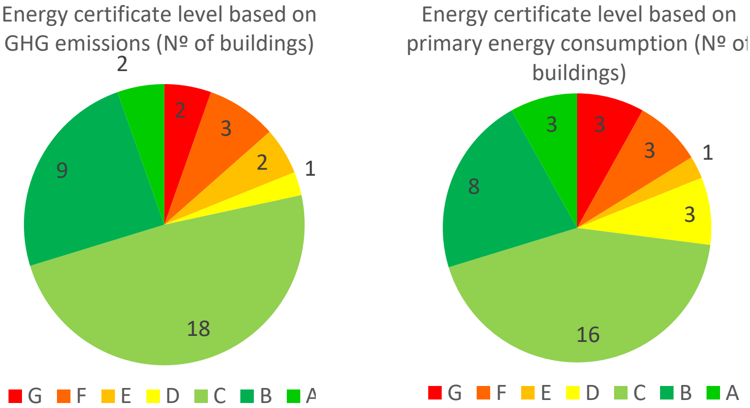


Figure 20. Energy certificate level based on GHG emissions and Primary energy consumption.

The obtained results show a good level of energy efficiency and GHG emissions, in comparison with the total sample. Concretely, 78% of buildings audited have C or even higher energy certificate level. This can be explained as follows:

a) most of these buildings audited have non intensive use of energy due to its main activity closing at night (schools, social centres, office buildings).
b) most of these buildings use heat pumps (with high coefficient of performance) and natural gas boilers (with moderate emission factor of CO_2) as source energy for heating, which reduce total emissions significantly in comparison with electricity.

6.3.3 Data model adapted to INSPIRE directive integrating alphanumeric and geographic data

The data model developed consists in one data table (Table 12) and three geographical layers (Public, Tertiary and Residential).

Table 12. Data table of the developed data model.

Fields Name	Data type
Code	Text
Type	Text
Description	Text
Address	Text
Municipality	Text
Postal_code	Text
Region	Text
PEC	Double
PEC_level	Text
GHG	Double
GHG_level	Text
Normative	Text
Cadastral_reference	Text
area	Double
Tota_PEC	Text
Total_GHG	Text
Building_Year	Text

The geographic data table of the data model developed is shown in Table 13:

Table 13. Geographical data table of data model.

Fields Name	Data type
Shape	Geometry
Name	Text
Description	Text
Address	Text
Municipality	Text
Postal_code	Text
Region	Text
Cadastral_reference	Text
Area	Double
Total_PEC	Text
Total_GHG	Text
Building_year	Text
Housing_classified	Integer
Housing_total	Integer

The application of the developed model to the parcels with available energy certificates data shows total emissions in amount of 12,015 t CO_2 due to the primary energy consumption of 144 GWh of tertiary, residential and public buildings based on the developed model (Table 14).

Table 14. GHG emissions and Primary energy consumption of Tertiary, Residential and public buildings.

Type	Number of Parcels	Emissions (t CO_2)	Primary energy consumption (MWh)
Tertiary	99	6,125	30,714
Residential	333	3,697	16,742
Public	27	623	3,038
Total	459	12,015	144,415

The GIS tool developed and applied allows a geographical representation of a GHG emissions map, which enable a good diagnosis of the state of energy efficiency of the buildings in the city. Figure 21, Figure 22 and Figure 23 show the spatial distribution of GHG emissions in public, residential and tertiary buildings.

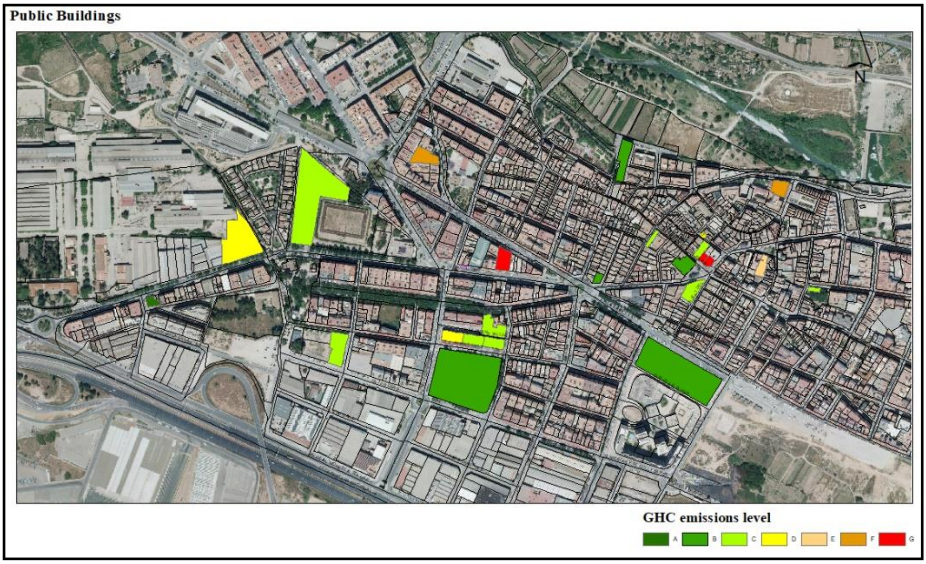


Figure 21. Results of the GHG emissions of the 37 public buildings distributed in 27 parcels.

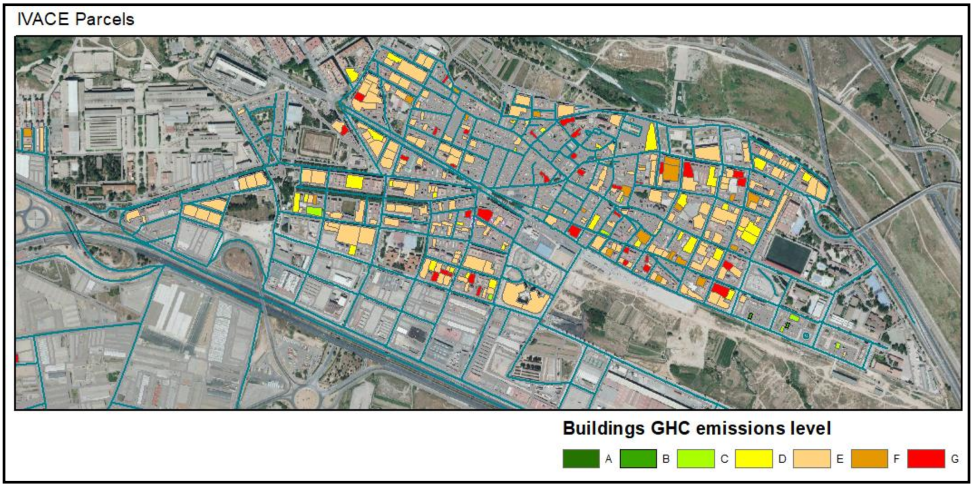


Figure 22. Results of the GHG emissions of the 1,058 residential buildings distributed in 333 parcels.

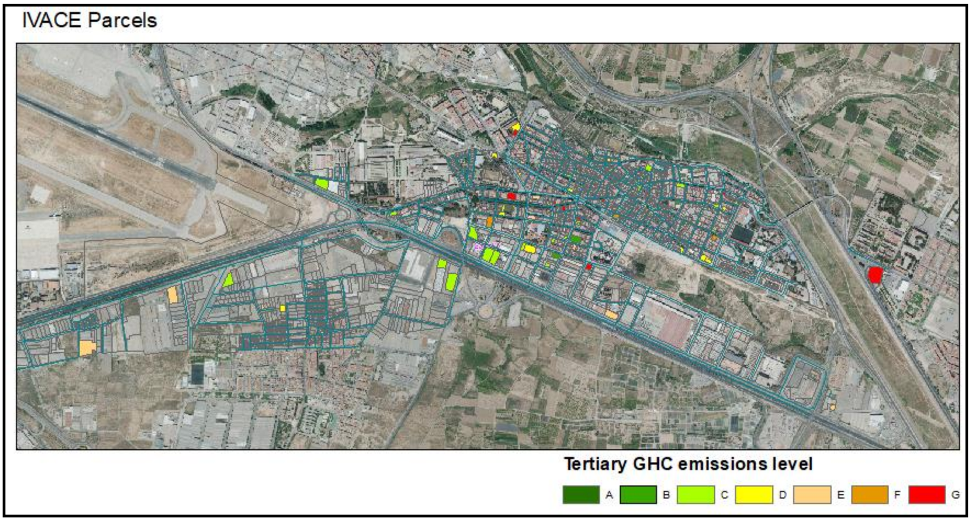


Figure 23. Results of the GHG emissions of the 160 tertiary buildings distributed in 99 parcels.

6.3.4 Application of results and methodology for local decision-making

Following the developed model, a total amount of 31,984 t CO_2 of GHG emissions and a primary energy consumption of 140,750 MWh can be estimated for the entire city. The spatial distribution of the obtained results is shown in Figure 24 and Figure 25.

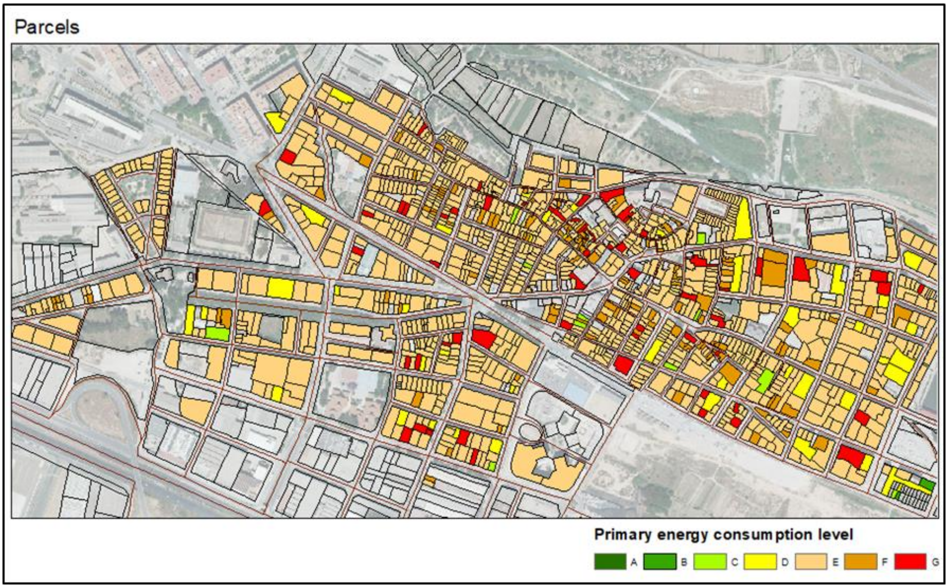


Figure 24. Spatial distribution of primary energy consumption.

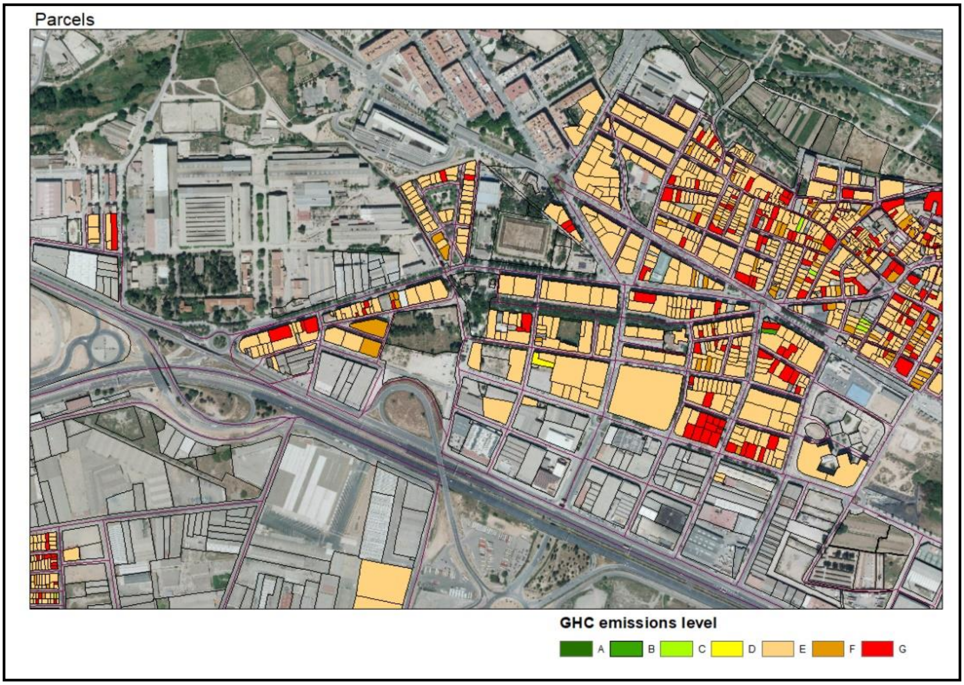


Figure 25. Spatial distribution of GHG emissions.

The results obtained and its spatial representation allow the public authorities to prioritize the available resources on the priority measures on buildings or districts towards an efficient reduction of GHG emissions, following the required objectives determined at EU level.

6.4 Conclusions

An innovative methodology based on a geographic information system (GIS) for mapping primary energy consumption and GHG emissions in buildings has been developed. This tool aims to support decision-making processes against climate change at local or district level. The developed methodology and its implementation with a simple tool allow to know the diagnosis of buildings contribution to climate change in an accurate manner with high spatial resolution. Thus, local authorities as public decision-makers can identify the most relevant GHG emitters buildings or districts and consequently focus their efforts and resources to reduce it with high level of efficiency.

The developed model has been tested in a representative medium-sized pilot city obtaining a quantification of GHG emissions and primary energy consumption of its buildings. The developed model has allowed integrating heterogeneous available data (local databases, national cadastre, external databases and own performed energy audits) to achieve a good level of representativeness of the city. The result of its application to the pilot city shows an acceptable level of energy efficiency in public buildings and a lower level in tertiary and residential buildings. Furthermore, a methodology to extrapolate primary energy consumption and GHG emissions to buildings without previous energy certification has been developed and validated.

Finally, data model has been adapted to INSPIRE directive integrating alphanumerical and geographical data ensuring interoperability and therefore the possible application to other EU cities.

7 CAPÍTULO 4 Desarrollo de una metodología *bottom-up* para cuantificar las emisiones del tráfico urbano con alta resolución espacial y temporal a nivel local.

From traffic data to GHG emissions: A novel bottom-up methodology and its application to Valencia city.

CAPÍTULO IV

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7. CAPÍTULO 4 Desarrollo de una metodología *bottom-up* para cuantificar las emisiones del tráfico urbano con alta resolución espacial y temporal a nivel local.

From traffic data to GHG emissions: A novel bottom-up methodology and its application to Valencia city.

7.1 Introduction

Climate change is one of the most pressing global challenges the international community is facing today. This challenge leads decision-makers to adopt actions and policies to reduce climate change causes and mitigate its effects. In this context, greenhouse gases (GHG) emissions reduction policies are key in any long-term plan tackling climate change. For example, the European Union (EU) has recently set out a clear vision in the European Green Deal on how to achieve climate neutrality by 2050. The EU aims to increase its reduction targets of GHG emissions in 2030 by at least 50% (around 55% as compared to 1990 levels) (European Commission 2019a).

In order to meet these EU and national policy framework goals, mitigation actions must be efficiently converted into the immediate local level (Wilson 2006). Consequently, more than 300 cities inside and outside of the EU, signed the Covenant of Mayors for Climate and Energy (European Commission 2019b), signalling their engagement to reduce GHG emissions by at least 40% by 2030 (European Commission 2018b).

Decision-makers need to ensure that local government plans can be fully understood, supported and monitored by the general public as well as other administrations. However, often, public decision-makers at the local level lack the necessary tools to support their strategic planning in a quantitative, objective, and transparent manner. Climate change mitigation measures must be based on a rigorous, accurate and up-to-date quantification of GHG sources. This is a basic requirement from the European Commission to support local government administrations (European Commission 2014). Despite this requirement (IPCC 2006), the current GHG calculation methods are best-suited to the national than to the local level (Engo 2019).

Current action plans and measures are based on Base Emissions Inventories (BEI) and Monitor Emissions Inventories (MEI) (European Commission 2019b) most commonly developed with top-down methodologies (Dai et al. 2016). Whilst top-down inventories are rigorous and complete on a year-average and country-wide basis, statistically, its extrapolation to a local scale is often not tenable. Local action also calls for a higher temporal resolution to allow policy measures to be followed and supported by citizens. Spatially and temporally disaggregated emission inventories are specially required for reliable and accurate air quality predictions (Leonidas and Zissis 2019) and GHG monitoring. For example, the emissions' air concentration in an urban hotspot cannot be calculated using year-long average data, since concentrations depend on both to the emission rate profile as well as the weather conditions.

Road transport emissions have important impacts on urban air quality and global warming (Colvile et al. 2001), accounting for about 20% of total fossil fuel consumption (International Energy Agency 2014). In the European Union (EU), road transport contributes one-fifth to total GHG emissions, with passenger cars being the main contributor to CO_2 emissions with 75% of the total (European Commission 2015a, EEA 2012). The transport and mobility sector is furthermore the only major sector in EU that continues increasing its GHG emissions (European Commission 2016c) despite strong political and social mitigation efforts. This highlights the potential of this sector to reducing EU's emissions and deliver to the EU's commitment under the Paris Climate Change Agreement (European Commission 2016d).

To estimate GHG emissions from road transport and mobility, the Intergovernmental Panel on Climate Change (IPCC) puts forward two alternative approaches based on independent data sets: (1) Fuel sold in the field study area and (2) Vehicle Kilometres Travelled (VKT) (IPCC 2006). The first method is a good approach to quantify emissions at wider regional or national levels, whereas the consumed and sold fuel in a specific geographical area may be considered to be approximately equal.

The second method, VKT, needs more variable and data sets to estimate GHG. Typical data needed by these methods includes the number and characteristics of vehicles, the kilometres travelled by each vehicle and how those kilometres were made (velocity, acceleration, etc.). The estimation of GHG can be done both nationally and locally if sufficiently disaggregated data are available. When some of the VKT method inputs are obtained from a statistical sample of observations, the extrapolation of the result to a whole area has been traditionally regarded as a serious limitation to apply the VKT methodology.

In addition to the above mentioned limitations of the two IPCC approaches, traffic variability represents another challenge when using GHG calculation methodologies. Firstly, traffic conditions vary depending on city areas as well as the day times when emissions are measured. In order to meet existing mobility needs, spatial and temporal resolutions of road transport emissions are key not only to assess air pollution (Leonidas and Zissis 2019) and monitor GHG emissions, but also to offer evidence to local policy-makers when preparing proposals for GHG reduction plans or evaluating the already ongoing ones.

IPCC estimations based on the fuel sold in a specific study area lack enough spatial resolution to be effective in city-level GHG calculation. Furthermore, IPCC estimations do not differentiate emissions originated between different type of vehicles. This differentiated information is crucial in regards to urban sustainability policies. Thus, these important limitations call into question the usefulness of this type of estimations at the urban level.

This paper proposes a bottom-up methodology to quantify urban traffic emissions with high spatial and temporal resolution. In addition to this, the proposed methodology addresses the GHG measurement problem at the city level. The recommended method is based on IPCC VKT datasets and the automated information gathering from traffic management systems. The methodology has been applied to Valencia city (Spain) as a proof of concept, which have implied the developing of new tools to acquire and filter the data and to estimate the GHG from the resulting information. The results obtained from the pilot implementation portrays a detailed picture on the spatial and temporal distribution of actual emissions in the city.

The paper is structured in six sections. Following the introduction, a selection of related works is explained and discussed (Section 7.2). The developed methodology is described in Section 7.3, including its implementation in the pilot city. Section 7.4 includes some representative results obtained from the analysis of a four-year dataset (2016–2019) and discusses briefly some of the conclusions that can be outlined. These elements and their representativity are discussed in Section 7.5. Finally, main conclusions and future work are presented in Section 7.6.

7.2 Related works

Road traffic emission inventories can follow either “top-down” or “bottom-up” approaches. These approaches will be used depending on geographical scope, level of data’s detail as well as its availability (Colvile et al. 2001). On one hand, top-down approaches are aimed to high geographic level, e.g. nationwide, using aggregated statistical data. A spatial disaggregation process is necessary to determine local emissions from original spatial level, usually nationwide. Local level data has lower accuracy than nationwide because the approximations used in the disaggregation process. On the other hand, bottom-up approaches require large data sets (total kilometres travelled, number of vehicles, vehicle characterisation, GHG measurements, etc.) and advanced computing processes that summarise the data sets. When data sets are not accessible, several assumptions to get data approximations need to be undertaken affecting whole process accuracy.

In regards to the top-down approach, inventories are the commonly used tools in Europe. These are made mainly using software systems such as various COPERT versions (Computer Program to Calculate Emissions from Road Traffic) (Leonidas and Zissis 2019) and MOBILE (Environmental Protection Agency 2002). COPERT based methodologies have been used to estimate and compare air pollutant emissions in Spain (Burón et al. 2005, Burón et al. 2004), Sardinia (Italy) (Bellasio et al. 2007), Ireland (Kelly et al. 2009) and two different areas in China (Song and Xie 2006). MOBILE has been used to assess the vehicular emissions in Shanghai city (China) (Li et al. 2003).

A hybrid methodology resulting from the two approaches is used in other works to develop air pollutant emission inventories, namely the travelled vehicle kilometres (VKT) from a bottom-up approach and variables from wide areas (e.g, population or road lengths) typical from top-down approaches. Examples of such works are Ramachandra and Shwetmala (2009) and Saija and Romano (2002). In any case, results obtained following this methodology show low spatial resolution.

Several studies using tools for urban simulation of traffic behaviour (to calculate road traffic emissions), adopt a bottom-up approach. For example, Beelen et al. (2009) obtained a mapping of background air pollution across the EU on a 1 × 1 km spatial resolution. De la Hoz et al. (2010) carried out a study on the evolution of CO_2 emissions in Madrid (Spain) defining traffic behaviour based on data from 1990s to plan different strategies at the local level to achieve proposed GHG emission reduction targets aiming to predict several 2030 scenarios. In Iodice et al. (2010), an emissions inventory of the main environmental pollutants in Napoli (Italy) using mobile fleet distribution was obtained using COPERT. Elena and Christidis (2010) propose a unified scheme to assess the GHG emissions impact of road transport infrastructure plans to estimate transport demand with associated energy consumption. This scheme aimed to help decision-makers. The authors used a system based on a Geographical Information System (GIS), origin-destination matrices, length and journey time, and other variables. In Perez-Lopez et al. (2013) the EMEP/EEA Tier 3 methodology is used to determine the evolution of GHG emissions from the road transport sector. Specifically, the study is performed in Spain for the 2005–2010 period quantifying emission of 12 polluting gases according to IPCC standards. This quantification is based on measurements of traffic intensity in stretches, vehicle characteristics of the circulating fleet, driving modes, and VKT.

However, the previous works discussed show different limitations regardless of the approach used such as: (a) the use a fuel balance from national extrapolations to calculate the energy consumption of road transport in a city; (b) the maximum accuracy achieved for observed spatial resolution is square kilometres; (c) emission inventories are made using standardised software for specific periods, not continuously over time; and (d) use of simulations to estimate hard-to-measure variables.

To overcome these limitations, an innovative bottom-up methodology has been developed. The main improvements of the methodology can be summarised as follows:

a. Not based on simulations.
b. Mainly based on actual data, minimising the use of disaggregation processes.
c. Quantify emissions by using a novel calculation model.
d. Quantify emissions by taking into account the local mobile fleet characteristics.
e. The process has to be done in real time, so the model can act on alarm situations in sectors or neighbourhoods of the city.
f. The spatial resolution has to reach a level of accuracy at street level, even distinguishing different sections in the same street.
g. The emissions can be categorised by type of vehicle and type of fuel.

7.3 Material and methods

This section explains the proposed methodology and the pilot test implementation process. As in any other bottom-up methodology, the results of our methodology will be based in fine grain measurements, in our case data from the pilot city traffic control system. This raw data will be filtered to increase its quality and then transformed into equivalent CO_2 kilograms. These data transformations are based on several formulas in which data from other sources will be needed (like vehicle fleet information).

7.3.1 Pilot test city

Valencia city has almost 800,000 inhabitants and is the centre of an extensive metropolitan area with more than one and a half million inhabitants. It is located on the East coast of Spain. 83% of employees in Valencia work in service sectors. However, the city has an important industrial base with 14% of employment.

The pilot city has declared a special interest in the mitigation and adaptation to Climate Change. On February 10, 2009, the municipality of Valencia joined the Covenant of Mayors with a commitment to reduce 40% of GHG emissions by 2030 with respect to the GHG emissions in 2007. Within this policy framework, it must be pointed out that the road transport and mobility sector represent about 60% of the total BEI quantified GHG emissions. However, BEI quantification is based on a top-down approach and aggregated data with low temporal and spatial resolution. This poses a huge limitation to a swift and efficient decision-making. Moreover, the monitoring and control of the implemented measures are highly limited due to the low temporal resolution.

7.3.2 Methods

The process of transforming the traffic data into GHG emissions depends on the circulating vehicles and how they convert fuel into emission. On the other hand, the vehicles circulate on the streets of the city, which will be modelled as a network. The methodology we followed for the data treatment and network definition is detailed in the following subsections.

7.3.2.1 Analysis and categorisation of the vehicle fleet

The requested data for categorising and characterising the units that make up the vehicle fleet are: number of vehicles with their main distinctive features (type of vehicle, engine technology, and fuel category used).

As sources of emissions, only those vehicles that consume one of the various types of fuel (petrol, diesel) and their liquid or gaseous derivatives (biofuels, gas and biogas) are considered.

In the IPCC report (IPCC 2006) the section that covers polluting emissions from transport corresponding to road traffic of vehicles is coded as ”NFR1.A.3.b.i-iv Road transport”. NFR stands for ”Nomenclature for Reporting”, which refers to the format for reporting national data in accordance with the Convention on Long-Distance Transboundary Air Pollution (CLRTAP). In relation with this code there are four different categories of vehicles (see Table 15).

Table 15. Categorization of vehicle types according to NFR code. Source: EMEP/EEA air pollutant emission inventory guidebook 2016, updated July 2018.

NFR category	Title
1.A.3.b.i	Passenger cars
1.A.3.b.ii	Light commercial trucks

1.A.3.b.iii	Heavy-duty vehicles including buses
1.A.3.b.iv	Mopeds and motorcycles

As stated, according to IPCC guidelines we classify the main features of the mobile fleet with three variables for each vehicle: the vehicle type, the fuel used by it and the technological regulations used when manufacturing the vehicle. The available values of these variables are shown in Table 16.

Table 16. The three variables defining the mobile fleet and their values.

Vehicle type	**Technological regulations**	**Fuel type**
Passenger cars	Conventional	Biomethane
Light commercial vehicles	ECE-15.14 and previous	Butane
Light trucks	EURO 1,2,3,4,5	Diesel
Heavy trucks	6-2016, 6-2017 and later	Ethanol
Buses	EURO I,II,III,IV,V	LPG, CNG, LNG
Motorcycles	VI-2016, VI-2017 and later	Petrol
Mopeds		Others
Others		

The database of the Directorate-General for Transport (DGT) statistical portal (DGT 2020) was used to obtain the evolution and particularities of the available attributes of the mobile fleet and its distribution in the timeline of the studied years.

Then, to analyse the temporal variability, an analysis of these data was carried out with monthly granularity and annual aggregations. The available attributes were filtered to obtain an average value of 626 different vehicle categorisations, out of an average fleet of approximately 460,000 vehicles.

The age of the different categories was correlated with the technological regulations that correspond to the specific time range. Following this approach, we managed to reduce the different categorisations to an average value of 136.

Finally, to assign the influence of each vehicle categorisation obtained to the emissions of the pollutants studied, we calculated the relative weights (*RW*) of each one based on their percentage with respect to the total number of vehicles, affected by the average distance travelled by category vehicle on urban roads (%UD).

As a result, we were able to set up a database consisting of vehicle types, fuel, technological regulations, relative weight (RW), and percentage of urban mileage (%UD) for each of the vehicle categories included in our categorisation. Figure 26 depicts the methodological process followed.

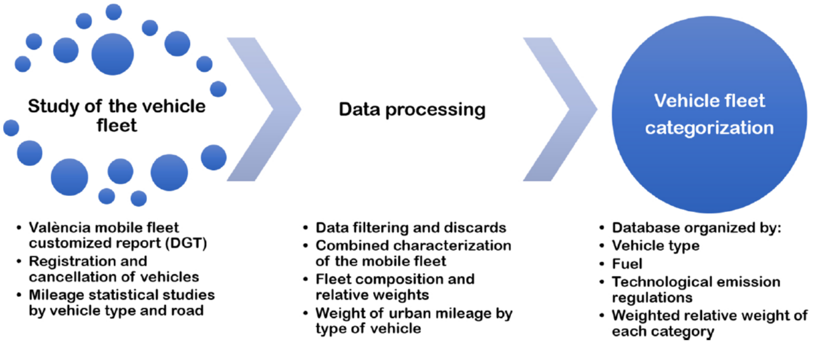


Figure 26. Sequential methodology.

7.3.2.2 Determination of emission factors for pollutants

The Core Inventory of Air Emissions working group (CORINAIR) is considered as a pioneer initiative in analysing emissions at the European level, which consists of developing emission inventory methods. It began in 1987 with the aim of developing a system to determine the appropriate factors to measure vehicle emissions. A computer program, COPERT, was subsequently developed to assist its implementation (Burón et al. 2004, Wang et al. 2018).

A common use of the COPERT methodology is to produce emission inventories generated by road transport based on fuel sales. From a geographical perspective, this criterion is valid for countries or regions (top-down approach) but not for urban settings. In urban settings, an energy balance (bottom-up approach) is more appropriate than a fuel balance to determine the emission factors needed to calculate the CO_2 emissions. These emission factors are derived from different consumption and efficiency factors as follows from the following generic equation (Mahesh et al. 2018):

$$EF = \frac{EC}{CV} \times RATIO = FC \times RATIO \tag{11}$$

Where the EF is the Emission Factor, EC is the Energy Consumption (MJ/km), CV is the Caloric Value of fuel (MJ/kg fuel), RATIO is the proportion of contaminant in fuel (g CO_2/kg fuel) and FC is the Fuel Consumption (kg fuel/km).

This equation is individualised for each polluting gas corresponding to each type of vehicle and fuel, e.g. CO_2 emission factor of the passenger car EURO 6 using diesel, and then applied to each monitored stretch.

To obtain an aggregate, the emission factors obtained must be multiplied with their relative weights (RW) against the total number of vehicles, and by the percentage of urban mileage (%UD) in comparison with the total mileage, of each vehicle category (defined by type of vehicle, used fuel, and technological regulations). Furthermore, to obtain the emissions in equivalent CO_2 the global warming potential (GWP) of each pollutant has to be considered: 1 for CO_2, 28 for CH_4 and 265 for N_2O (these values are extracted from Myhre et al. (2014)).

The above described COPERT-based scheme was used only for the estimation of the emission factors (Figure 27 outlines the flow diagram), but not for the quantification of GHG emissions. To allow quantifying GHG and pollutant emissions, we have developed a new aggregation scheme relying on metrics and data more suited to the urban environment (bottom-up approach) as it will be described in the next subsection.

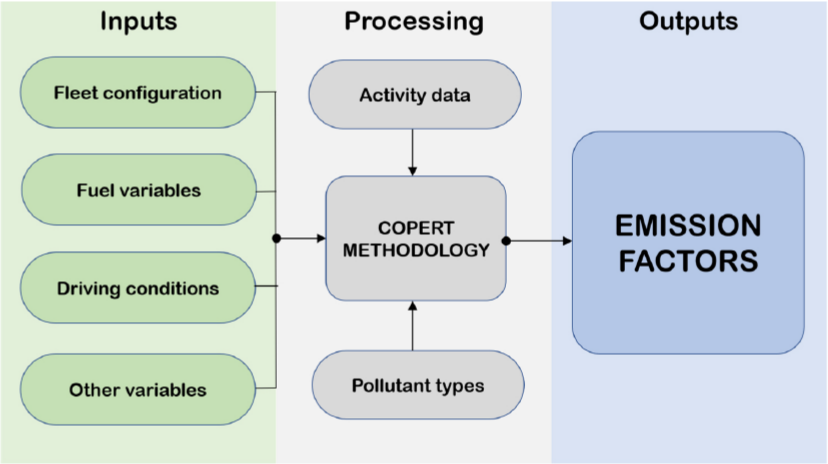


Figure 27. COPERT usage flow chart.

The extensive reviews and cross-checks of the transport data along with the reliability of the data sources, ensure the high quality of the data set obtained for the different emission factors. The emission factors are extracted using a model based on local scope specification, in accordance with the IPCC recommendations for emission inventories (IPCC 2020).

7.3.2.3 Network model description

We have defined the concept of road segment as a road stretch with a given distance between intersections in which the number of input vehicles is equal to the number of output vehicles. The starting point to develop the network of road segment is the traffic control system characteristics. In the pilot city, the traffic control system is made up of 3500 sensors (mainly induction loops) producing data every 10 min (see Figure 28). From the location of those sensors, a total of 1326 measured road segments distributed have been defined across the pilot city.

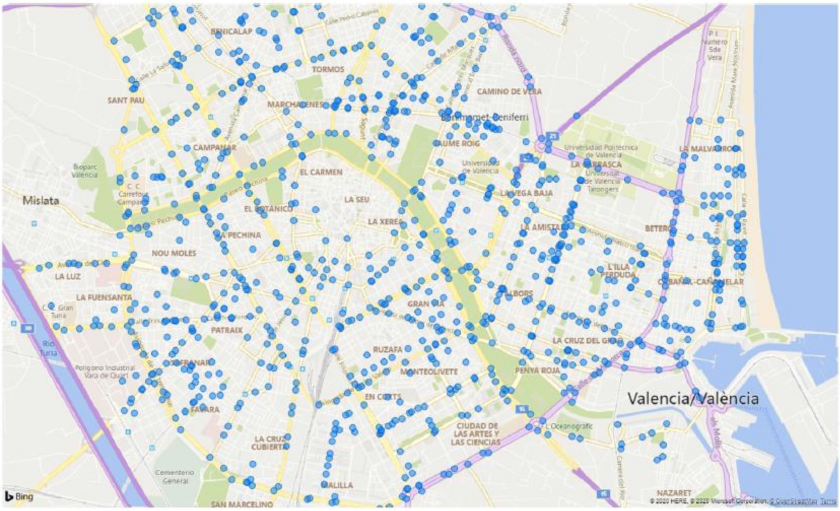


Figure 28. Location of induction loops of traffic control system.

In each monitored road segment *s*, the ITA*s* value represents the number of vehicles that crossed the given segment within a prescribed time window. Each sensor signals contributes to traffic intensity values (ITA) of one or more monitored road segments. This magnitude is described in the following equation:

$$ITA_s = \sum_{i=1}^{n_s} C_{i,s} \times P_{E,i} \qquad (12)$$

Where each measured road segment is affected by a varying number of sensors (n_s), $P_{E,i}$ is the electric output that characterises the response of the *i*th sensor, and $C_{i,s}$ is the coefficient that quantifies the effect of the *i*th sensor on the road segment *s*. Despite the fact that original data have a 10-min period, we have increased the period to 1 h in order to allow a reasonable balance between data manageability and time resolution.

If, as in this case, no specific information is available on the actual vehicle distribution that circulates in a certain road segment *s*, we can mistakenly assume that the distribution is statistically homogeneous and represented by the vehicle category distributions obtained for the whole city. This underestimation would be wrong since the amount of a given type of vehicles within the distribution of categories does not depend on the road segment index s. So, the conversion between intensity data and CO_2 emissions during the prescribed time window results from equation (13):

$$E = \left(\sum_{s=1}^{N} ITA_s \times l_s\right) \times \left(\sum_v \rho_v \sum_g EF_{v,g} \times GWP_g\right) \tag{13}$$

Where the three indices are referred to the target road segment *s*, the vehicle typology *v* and the type of greenhouse gas *g*. *N* is the total number of monitored road segments included in the system.

The different elements of the equation are:

- ITA_s: Vehicle intensity of the road segment *t* in the 1-h time interval (#vehicles/hour).
- l_s: Length of the road segment *s* (km).
- ρ_v: Number of vehicles with the typology *v* (#vehicles).
- $EF_{v,g}$: Emission factor (see Eq. (11)) of the vehicle typology and fuel used *v* for the polluting gas *g* (g CO_2/km).
- GWP_g: Global warming potential of the gas *g*: 1 for CO_2, 28 for CH_4 and 265 for N_2O (Myhre et al. 2014).

7.3.3 Data description

The Smart City Office of Valencia city has provided its dataset for the current study. It compiles four years of measurements of traffic intensity across the city, from January 2016 to December 2019. Originally, the dataset was provided as independent files (one per year), but currently a server system has been prepared to allow a real-time transfer of data.

The dataset is composed by ITA_s (see Section 7.3.2.3) from a total of 1,326 monitored road segments, 10 of which correspond to bus lane-type road segments, 115 to bicycle lanes and the rest to the remaining road traffic. The information from the bicycle lanes was disregarded for this study. Table 17 shows the summary statistics for this dataset.

Table 17. Description statistics of the series in datasets. ITA in vehicles per hour (v/h) and Segments Lengths in meters (m).

Data series	**Min.**	**Max.**	**Mean**	**Median**	**Std. Dev.**	**Variance**
ITA 2016 (v/h)	0	7636	456	233	551	303
ITA 2017 (v/h)	0	7091	458	231	577	332
ITA 2018 (v/h)	0	5543	449	228	543	294
ITA 2019 (v/h)	0	6153	439	222	531	282
Seg. Lengths (m)	17	1343	216	200	134	18

7.3.4 Data processing

The retrieved information had a format that made it difficult to locate each monitored road segment. A first step in the data analysis was to get a precise location of each sensor, with its corresponding latitude and longitude.

In addition to this, raw signals from induction loops can be affected by different errors. The errors must be detected and corrected to eliminate abnormal data with a potentially high impact on the statistical quality of the outcome. The errors may result from sensor failures of any of the loops that contribute to a given road segment, but also to different events such as stretch, physical interventions on the road, closed street, parades, etc. In Figure 29, three typical examples of raw data with errors are shown.

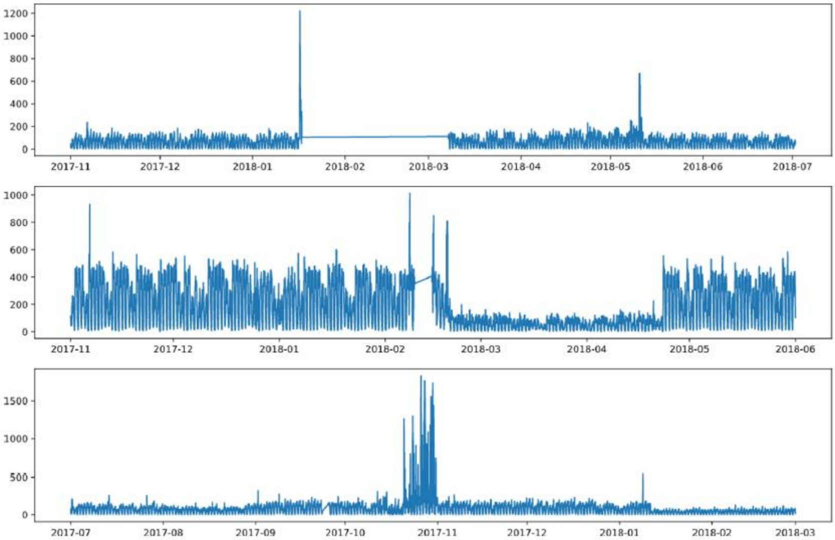


Figure 29. Vehicle intensity of several measurement points showing typical anomalies: missing data (upper and middle graphs) and outliers (in all the graphs).

To discard signals with errors, filtering was performed in those road segments where a high percentage of data is missing over study length. A threshold has been established that allowed us to discard those detectors whose corresponding data set what not complete during the four year survey. Specifically, we used the 95% percentile criterion and, as a result, 468 detectors were found to be non-compliant and subsequently discarded.

Finally, an account assignment was made for the outliers (generated from the average data) and no outliers (obtained for the same stretch at the same month, weekday and hour). The daily seasonality is also taken into account. So, are not included in the calculation of this average. This assumption will be justified in the following section.

7.4 Results

In this section, we will present the main results of the application of our methodology to the complete four-year (2016–2019) dataset of the traffic in the pilot city. The first step is the application of the COPERT-based methodology to collect the emission factors. Emissions have been identified as a result of the filtering procedures described in Section 7.3.2.2. Our analysis allows deriving a timeline and a spatially disaggregated view of the emissions in the city. This view allows drawing an initial preliminary analysis of the observed trends, which can be extremely useful for future decision-making.

A detailed analysis of the resulting information is beyond the scope of this paper, which pays more attention to the methodological aspects of the survey.

7.4.1 Emission factor for pilot city

The value of the average emission factor of the mobile fleet used in this work is 205.47 g CO_2-eq/km. This value has been obtained from the database of the city's mobile park in 2017, the latest update of the vehicle fleet published by DGT (2020). Unfortunately, there is currently no accessible information that allows to link a given road segment traffic intensity with the types of vehicles passing that road segment. Hence, we used the average distribution of vehicle type categories for the whole city.

Regarding the change in the fleet distribution with time, although there is accessible information on an annual basis about registration and removal of vehicles, it was neither possible to determine the type of these vehicles, nor their emission technology, nor the fuel used. Thus, this source of information did not contribute to an improved accuracy of estimations. A basic sensitivity analysis was carried out to see how the EF would have been affected if all the updates had been in the highest and lowest emitting vehicle classes. The results showed no significant differences in average EF value, the one used in the pilot. For this reason, and given that the 2017 data are the most current, it was decided to use that year's fleet composition data for the four years studied (2016–2020).

7.4.2 CO_2 emission results

The model based on the methodology object of this research allows us to obtain GHG emissions from urban road traffic on the measured sections in the pilot city of Valencia. We can disaggregate these values by type of vehicle (see Figure 30) or by fuel used (see Figure 31) for each of the measurement points in the city (see Figure 28). The figures show how emissions from passenger cars and diesel fuel stand out over the rest of the types of vehicles and fuels, with percentages of 62% and 81% respectively.

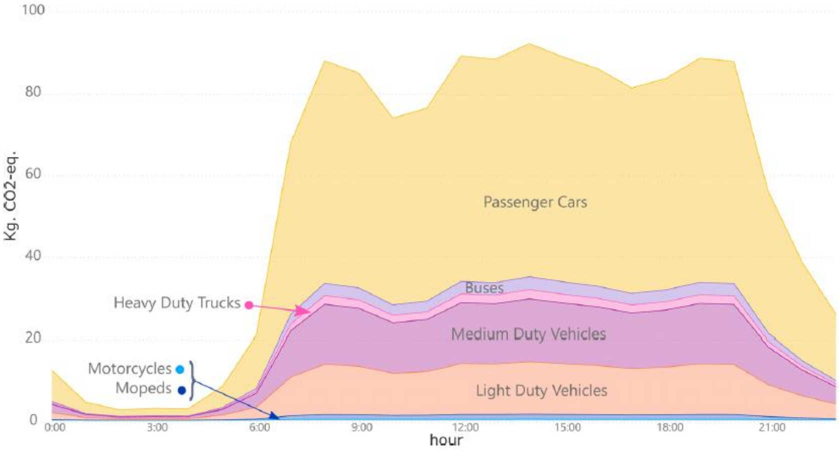


Figure 30. GHG emissions by type of vehicle in one measurement location.

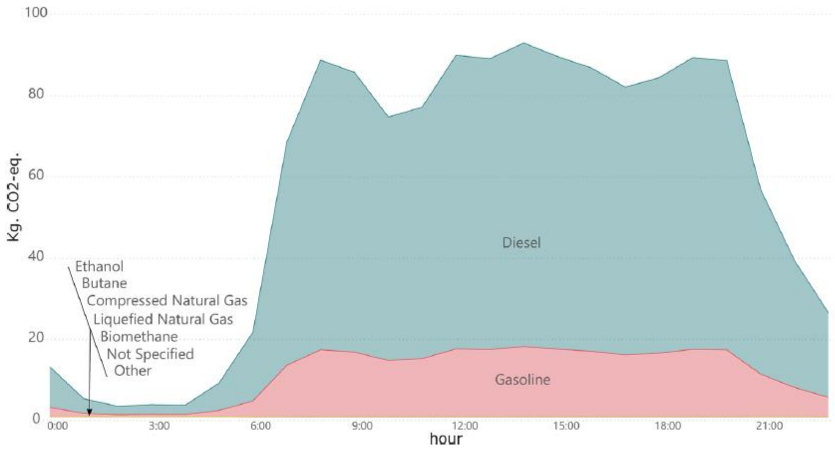


Figure 31. GHG emissions by type of fuel in one measurement location.

After showing the resolution of the graphical representation of results, this section provides an analysis of the CO_2 emissions data that comes from the vehicle detectors available from 2016 to 2019. Bellow, the analysis is organised to observe the annual data following different criteria.

Firstly, Figure 32 shows how CO_2 emissions are influenced by year seasonality. So, they vary significantly throughout the months of the year (each curve represents one specific year). To facilitate the comparison, the time series on the horizontal axis is set from January to December uniformly, while in the vertical axis the daily average of tons of CO_2 equivalent is placed. As can be seen, the monthly changes in CO_2 emissions stay relatively constant throughout the years showing a common pattern.

Figure 33 shows a comparison of average daily emissions during a week for each year. In order to have a better comparison, the time series on the horizontal axis is set from Monday to Sunday uniformly. In contrast, in the vertical axis, the average of tons of CO_2 equivalent is placed. To compare the difference between average emission on working days, weekends and holidays is essential to consider the working days from Monday to Friday; Saturday and Sunday are deemed weekends, and holidays are days off that fall on weekdays. As a general weekly trend, CO_2 emissions show a stable and regular increase throughout the workdays. The increased mobility towards the weekend houses may explain this increase in traffic towards Friday. Weekends, predictably, result in a substantial drop of CO_2 emissions, about 16% and 30% compared to the average of the workdays respectively. Trends and emission values are quite similar along the years allowing to establish patterns and draw conclusions that may be valuable for planning purposes.

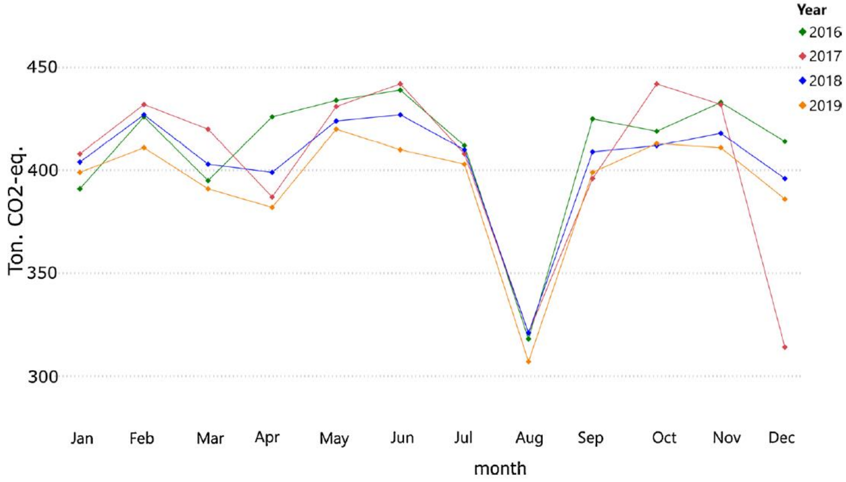


Figure 32. Average daily equivalent CO_2 emission per month for years 2016–2019.

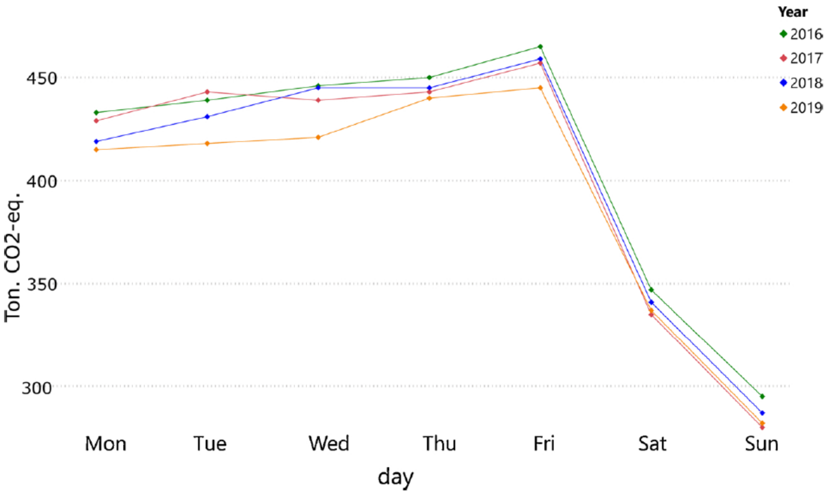


Figure 33. Average daily equivalent CO_2 emission according to the weekday for years 2016–2019.

A similar comparative can be done taking into account the labour characteristic of days. In Figure 34, the boxes represent the graphical representation of CO_2 emissions by different day types: workdays, weekends and holidays. Grey box plots indicate the range of values according to the percentiles and median for each type of day being very similar.

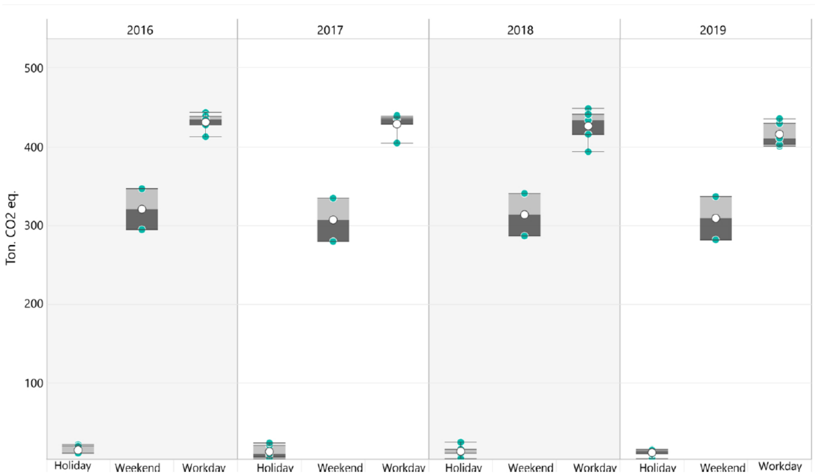
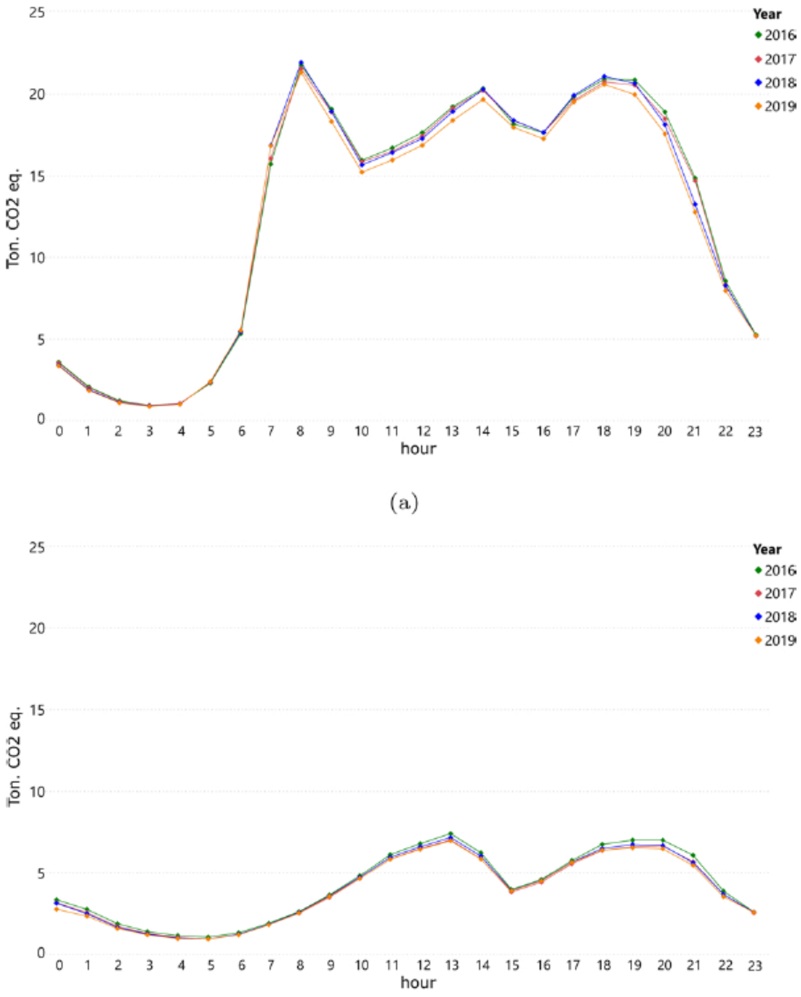


Figure 34. Average daily equivalent CO_2 emission comparison among workday, weekends and holidays.

To compare average hourly emission in a day, Figure 35 shows 24 h of an average day for each workday and non-workday in the horizontal axis. Each curve represents a year. The vertical axis presents the average of tons of CO_2 equivalent. Visual comparison of both plots in Figure 35 indicates that from 00:00 up to 4:59, CO_2 emissions are slighter higher on non-workdays than a working day, but from that moment the emissions are lower on non-workdays.

The previous results show timeline plots in different scales (monthly, weekly and hourly), but the described methodology also allows associating emission to more specific locations within the urban settings, i.e. to study emissions from a spatial perspective.

For a qualitative comparison between the different city areas, we provide a geographic map (see Figure 36 with the total amount of CO_2 emitted in 2016). In order to prevent all areas being associated with the same number of monitored road segments, the total CO_2 emissions were normalised with the total number of kilometres sensorised within each of the areas Ak, k = 1…68 in which the city was divided. This length is given by $L_{A_k} = \sum_{t;t \in A_k} l_t$.



(a)

(b)

Figure 35. Average hourly equivalent CO_2 emission during (a) workdays and (b) non-workdays (weekends and holidays) for years 2016–2019.

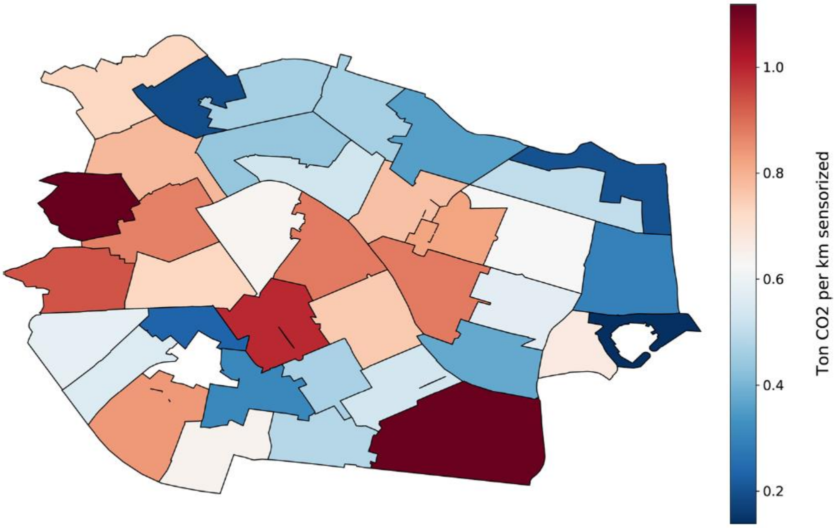


Figure 36. Total equivalent CO_2 per kilometre sensorised for the different zones of Valencia in 2016.

7.4.3 CO_2 emissions trend in Valencia

One of the difficulties to characterise the historical trend of CO_2 emissions in the studied period is the need to define stable criteria or references for enabling an accurate comparison. One possible perspective is shown in Figure 37, where the Cumulative Distribution Function (CDF) of daily emissions is compared on a year by year basis. This allows not only seeing quantitative trends in absolute emissions, but also if the distribution itself is changing. The CDF related to year 2019 is most of the times at left with respect to the rest being 2016 at the utmost right. This clearly outlines that 2019 emissions were lower specially in the range of days in which emissions are statistically higher.

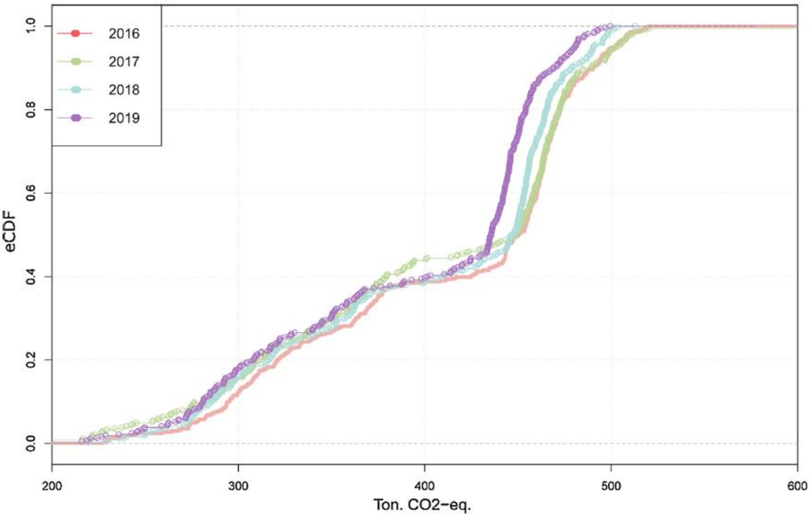


Figure 37. CDF plot for daily equivalent CO_2 emission for years 2016–2019.

In order to check the statistical significance of the outlined trends, a p-value table obtained by means of a Kolgomorov-Smirnov test (Marsaglia et al. 2003) applied to pairs of year checking for equality and order is shown in Table 18. The analysis points out that only in the case of pair 2016–2017, none of the ordering or equality hypotheses can be rejected. In any case, the hypothesis that emissions show a diminishing trend throughout the years is always associated with the highest *p*-value. For the rest of the year pairs, there is a pattern in the test: the years are not coming for same distribution (reject equal null-hypothesis with a *p*-value under 0.05), neither can be the more recent year considered to have a lower distribution than the less recent (reject less null-hypothesis with a *p*-value under 0.05). The conclusion is that there is evidence to suggest, from a statistic viewpoint, that emissions were at steep decline of 95%, as it has been previously argued.

This evolution, from a geographical perspective, is shown in Figure 38. The maps in the figure show the cumulative difference from base year 2016 (Figure 36 shows base year total emissions). The maps show small variation in most of the districts, on the scale red zone if it increases and on the blue if it decreases.

Table 18. Results of Kolgomorov-Smirnov comparison tests for whole year emission.

Compared pairs a vs. b	**Greater a>b**	**Equal a=b**	**Lower a<b**
2016 vs. 2017	0.872	0.497	0.253
2016 vs. 2018	0.976	0.001	0.001
2016 vs. 2019	0.993	3e-13	1e-13
2017 vs. 2018	0.299	0.013	0.006
2017 vs. 2019	0.453	2e-11	1e-11
2018 vs. 2019	1	7e-8	3e-08

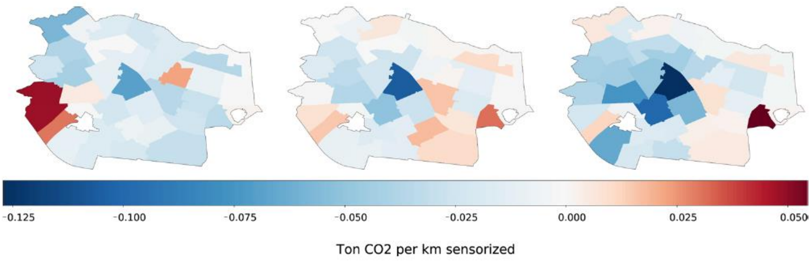


Figure 38. Progression of the total CO_2 per kilometre sensorised for the different zones of Valencia in 2017 (left), 2018 (centre) and 2019 (right), in comparison with the emissions in 2016.

7.5 Discussion

The developed methodology allows real-time monitoring of GHG emissions generated by road traffic in a city with traffic monitoring system, as is the case in the pilot city. Therefore, it is possible to carry out continuous air pollution/quality assessments by city sectors due to the high spatial and temporal resolution of the developed model.

Focusing on CO_2 emissions, we are able to acquire an intensive knowledge on daily emissions with a high degree of hourly granularity, also with high accuracy as in our case, comparative studies can be carried out to determine the most influential factors in the amount of emissions (day of the week, time, etc.) and if these factors are maintained throughout years.

One of the most significant aspects to analyse is the daily emissions profile for each month of the year. The developed methodology and the obtained results shown in Figure 32 demonstrated how these annual profiles are qualitatively similar throughout the series studied between 2016 and 2019. Every year they show the same seasonality pattern as it is expected for the real traffic-related emissions. The most outstanding differences are found in those months in which a larger number of citizens enjoy their work holidays along with their children while they are having their school holidays:

- March: the local festivity in the pilot city of Valencia *Fallas* has a strong impact on the normal functioning of the city between 1st and 19th, and this is more intense from 14th to 19th.
- Eastern Holidays (March–April). Specific dates vary depending on each year’s calendar.
- August: usual summer-holiday-month in the pilot city, which usually lasts from two to four weeks
- December: days 6th and 8th are national holidays. Christmas holidays, at schools from the 22nd until the 7th of January, are 24th, 25th and 31st the most crucial days.

Similarly, the developed methodology and the obtained results allow also demonstrating a clear similarity of the weekly pattern between the different years, with a significantly lower emission values on weekends (Figure 33).

By analysing the results, it becomes clear the difference between work and vacation patterns. This leads us to assume that there might be three categories: working days, weekends, and holidays. As a first step of a more exhaustive analysis, a graphic representation of the data has been carried out in Figure 34. The differences observed between these three types of days are stable throughout the years and are clearly identifiable in the graphs in Figure 35, where the trends between working days and non-working days can be demonstrated on a single scale.

After the descriptive analysis, the interpretation of Figure 35(a) is in accordance with the school and work activity in the pilot city. The start time of these activities is between 7:00 A.M. and 9:00 A.M., a period with increased emissions. The second peak that appears coincides with the end times of the working days and with lunchtime between 1:00 P. M. and 3:00 P.M. Finally, a third less pronounced peak corresponding to the departure from work and/or extracurricular activities between 6:00 P.M. and 8:00 P.M. is again observed, followed by a drop with the shops closing and the end of the working activities.

The pattern shown for non-working days in Figure 35(b) differs significantly from Figure 35(a): it is quantitatively smaller and has a less pronounced profile, showing only two increments and with smoother variations. A delay in the start of activity in the city as well as the influence of a possible leisure factor in the late afternoon can be also observed. The spatial precision of the model allows to assign and represent qualitatively and quantitatively the emissions of the different areas segmented in the city. These results are shown in Figure 36 with data from 2016. There is a clear correlation between the areas that reach higher levels of contamination with city’s main entry and exit routes.

Based on the year 2016, Figure 37 and Table 18 shows the comparison of CO_2 levels with the rest of the years in the time series studied, confirming a steady decline in emissions starting from 2017 until the last analysed year (2019). Finally, the results shown in Figure 38 demonstrated the evolution of emissions spatially, showing the values for the different sectors of the city through the years. Specifically, a clear decrease can be observed in the city centre. One possible cause may be the actions on urban mobility launched by the local administration, such as the creation of new sections of bike lanes and the pedestrianisation of some streets. In the opposite direction, one of the main accesses to the city and the port activity area have increased their emission levels. It should be taken into account that all these observations must be viewed in the broader context of general economic activity indicators that, altogether, will offer a clearer picture about the influences and causes that are on the basis of the observed trends.

Our results are obtained from a hypothesis based on certain initial assumptions. Far from the necessary extrapolations carried out in top-down methodologies, our bottom-up methodology is based on actual traffic measurements within the pilot city and from a specific mobile fleet. In its present form, the developed network model uses the same formulation for all the monitored segments which results in a single average value of the emission factor of 205.47 g CO_2-eq./km. The application of the developed model allows to classifying hours, days and months based on their emissions' patterns, showing that the resulting picture is coherent with the real activity of the pilot city. However, for an absolute quantification of GHG emissions we assume that our procedure involves some uncertainty. This methodology also intends to show polluted areas of the city on a timeline, showing how pollutant and GHG concentrations vary among neighbourhoods or districts.

In summary, applying the methodology developed to the data collected by the traffic management system of the pilot city, we have obtained a series of descriptive methods of analysis of this data, which should support to acquire advanced knowledge and comprehension what agents/variables (instants of time, places in the city, employment patterns, meteorology, etc.) are significant in the traffic behaviour and, therefore, in GHG emissions and other pollutants.

7.6 Conclusions and future work

Tackling climate change is a challenge for society and, therefore, for our cities. Road transport and mobility is a key element to mitigate climate change because it is responsible of more than 20% of total greenhouse gases (GHG) emissions in the EU. This value has been obtained from known and proven measuring processes based on top-down methodologies. Yet, top-down methodologies are not appropriate for local policy-makers due to their very low degree of spatial and temporal resolution.

We have designed, developed and applied a new bottom-up methodology that uses the data from traffic monitoring systems combined with the Vehicle Kilometres Travelled (VKT) methods recognised by the Intergovernmental Panel on Climate Change (IPCC), in order to improve the state-of-the art. IPCC VKT allows getting the factors relating emissions and the specific city mobile fleet. The developed and tested methodology defines how to combine those factors with the data from traffic monitoring systems in order to get GHG emission estimations with high spatial and temporal resolution.

In this research, we have applied the methodology to data from the pilot city. IPCC VKT data gives an average value of 205.47 g CO_2-eq./km for the emission factor. This value has been applied to the data obtained throughout a period of four years from the control traffic system of Valencia.

The results obtained can be used in different scenarios. On one hand, as the spatial distribution of GHG emissions has a good resolution, it allows detecting emission hot-spots in the city or comparing the measures with citizenship perception for social evaluation. On the other hand, the temporal resolution allows detecting emission patterns that can be used to develop or modify the city policies and regulations.

The developed methodology and tools can be used by policy-makers to improve planning and monitoring of climate and mobility policies in a quantitative, objective, and transparent manner. The possibilities of a close-in-time follow up of the effect of traffic related mitigation measures will in particular enable public stakeholders to detect the effects of their city policies in a virtually instant way. Policies enabling a bidirectional feedback between end-users and system managers will be subsequently possible in ways that could not be possible before.

There are still open issues for future research and technological developments. The first challenges we are currently addressing are how to enable a real-time connection between our algorithms and traffic control system. Furthermore, the analysis of data itself is still a pending issue. Third, as discussed in the above paragraphs, the methodology itself has room for improvement and validation in cities with lower degree of traffic sensor systems.

With the development and deployment of new technologies in traffic management (advanced induction-loop sensors, vehicle recognition cameras, etc.), it will be possible to track emissions even more accurately, individualising the category of vehicles circulating in each segment or even their kinematic parameters (velocity, acceleration and stops). Together with the large number of detection loops available, this will allow an accuracy not achieved so far in this type of studies and also to characterise uncertainties associated with the simplifying hypothesis made in our study about the absolute quantities of GHG gases released to the atmosphere.

The real time connection to traffic control system will reduce the time need for evaluating the impact of new regulations, improving the decision making process. Additionally, anomaly GHG emissions levels could be detected making easier their diagnosis.

The results obtained in the pilot city seem to show reductions of the GHG emission year after year from 2016 to 2019, but a deeper analysis of the data is needed to detect what have been the main drivers of these changes and their relative significance.

The application of the developed methodology to other cities and the analysis of the results would enlarge the base of experience in using our method and pave the way to a wider application to mitigate Climate Change.

Finally, our research group is integrating all the tools needed for the methodology with other tools developed to study the GHG emission at local level (building efficiency, renewable energy use and production, etc.) This integration will largely standardise, enable automatism and simplify the process of constructing the emissions inventories at city scale, which is a necessary step forward to mitigate GHG emissions based on solid and quantifiable policies.

8 CAPÍTULO 5 Análisis del potencial forestal mediterráneo para compensar emisiones GEI a nivel regional con resolución a nivel local. Evidencia de Valencia, España.

Potential analysis of Mediterranean forestry for offsetting GHG emissions at regional level.

CAPÍTULO V

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8. CAPÍTULO 5 Análisis del potencial forestal mediterráneo para compensar emisiones GEI a nivel regional con resolución a nivel local. Evidencia de Valencia, España.

Potential analysis of Mediterranean forestry for offsetting GHG emissions at regional level.

8.1 Introduction

Forests play a key role in climate change mitigation by sequestrating atmospheric carbon dioxide (CO_2) in new forestland and in existent forests (IPPC 2001). According to IPPC (2006), carbon stored in terrestrial ecosystems is distributed among three compartments: living plant biomass (stem, branches, foliage, roots), plant detritus (fallen branches and cones, forest litter, tree stumps, tree tops, logs) and soil (organic mineral, surface and deep mineral soil). Terrestrial biosphere has the potential to mitigate between 10 and 20% of the fossil fuel emissions by 2050 (IPPC 2001). Following Vine et al. (1999), forests can tackle climate change in three main ways:

a) afforestation, reforestation or forest management to increase the carbon fixed by forests,
b) bioenergy or biomaterials as substitutive of fossil fuels or more energy intensive materials (IEA Bioenergy 2001, Prato 2015, Wang et al. 2021), and
c) preservation existing forests to avoid or reduce emissions due to anthropogenic disturbances (deforestation) or natural disturbances (pests, hurricanes, snowfalls or wildfires) through preventive and sustainable forest management.

Forest fires have social, ecological and economic costs (Marques et al. 2017). In ecological terms, preserving existing forests is especially important because forests could act as both sinks or sources of greenhouse gas (GHG) emissions (Streck and Scholz 2006, Canadell and Raupach 2008). Natural forest disturbances (mainly wildfires) emit 9 Gt C per year worldwide, which represents approximately 30% more than the GHG emissions from fossil fuels (Binkley et al. 2002). Wildfire risk is clearly the result of the interaction between human activities, ecological domains, and climate (Vigna et al. 2021). In fact, in especially vulnerable areas such as the Mediterranean, wildfire risk is increasing mainly due to three causes (Moriondo et al. 2006):

a) number of years with increased fire risks,
b) season length with severe meteorological conditions that increase fire risks, and
c) extreme events (e.g. total number of days with Fire Weather Index (FWI) >45 and especially episodes with FWI >45 for seven consecutive days) during summer or drought seasons are increasing.

Only in 2009, approximately 434,927 ha were burnt in the EU Mediterranean region (JRC 2009). For this reason, wildfires are one of the most detrimental environmental issues in the Mediterranean basin.

Actually, Mediterranean plant phenology and climatic conditions generate a scenario very prone to large wildfires and consequently large amounts of greenhouse gases emissions. In addition, the accumulation of fuel biomass due to abandonment of traditional forest uses affects severity and magnitude of wildfires, as Marchi et al. (2018) demonstrate in Mediterranean Country, and therefore causes even higher emissions. This abandonment is partly result of the low economic revenues of Mediterranean forests and it could be solved considering the ecosystem services of forests, principally carbon fixation.

There are ways to quantify in terms of money the carbon fixed by forest systems. The most commonly used mechanism is carbon markets (Peters-Stanley et al. 2012). A carbon market is a financial solution for GHG reduction through emissions trading (Kollmuss et al 2008). In other words, it is a market in which carbon credits are obtained and sold within defined standards for GHG prevention or reduction (Ulucak et al. 2019). There are two different types of carbon markets (FAO 2010):

a) regulatory compliance market: used by companies and governments that by law have to account for their GHG emissions. It is regulated by mandatory national, regional or international carbon reduction regimes.
b) voluntary market: carbon credits trade is on voluntarily basis.

In Europe, the most important compliance market is the EU ETS for direct GHG emissions (European Commission 2015b). EU ETS works setting a cap on the total amount of GHG emissions that can be emitted by installations covered by EU ETS and receiving a part of its emissions in free allocate allowances forcing to reduce the rest. At least, half of the auction revenues of EU ETS must be used to reduce GHG emissions for mitigation or adaptation to climate change in the EU and third countries (European Commission 2015b). But even though wildfires can be a major focus of GHG emissions mainly in the European Mediterranean regions, none of this money goes to wildfire prevention (Kollmuss et al. 2008).

On the other hand, most important type of voluntary carbon market is based on forest fixation (Hamilton et al. 2007). The total carbon credits generated in forest based voluntary carbon markets correspond to the difference in carbon stock regarding business as usual (BaU) due to different silvicultural practices (reforestation after clear cutting, tree plantations on former agricultural land etc.). Nevertheless, despite the existence of some preservation actions in same carbon markets (as EU ETS carbon market) (European Commission 2015b), especially aimed at the preservation of tropical forests, most of forest actions to compensate GHG emitted of voluntary carbon markets are limited methodologically to reforestation or tree plantations actions, as for example in Spain (OECC 2019). Nevertheless, this approach does not include, by now, sustainable forest management to reduce wildfire risk, to improve forest health or to provide the sustainability of non-economical ecosystemic services of forests.

Therefore, this actual approach is not useful in large areas of the Mediterranean basin, especially in dry regions with a low rate of forest management due to the low economic value (with high rates of rural abandonment) and yearly accumulation of fuel biomass. These forests are specifically prone to wildfires, even more under severe weather conditions foreseen with climate change that will increase burned area and fire severity (McKenzie et al. 2004, Stephens 2005, Westerling et al. 2006, Miller et al. 2009).

Actually, there is a high potential for annual fixation by Mediterranean forests to mitigate climate change that needs to be estimated and valued because otherwise it can become a great source of GHG emission (Moriondo et al. 2006). But for this, it is necessary to develop a valorisation methodology with a new approach adapted to Mediterranean forest reality, which takes into account prevention measures to reduce GHG emissions by natural disturbances, mainly wildfires.

Thus, the overall objective of this research is to analyse the potential of Mediterranean forestry for offsetting GHG emissions at regional level. To achieve this, the specific objectives are:

1. to identify a case study in a representative Mediterranean region to test a quantification methodology of CO_2 fixation with real data,
2. to quantify CO_2 fixation in the total biomass of forests in the study area under Mediterranean conditions,
3. to develop and to apply a methodology to valorise the CO_2 eq. fixation of forests under Mediterranean conditions,
4. to compare total forest CO_2 fixation with total GHG emissions at regional level in case study region, and
5. to evaluate the potential of Mediterranean forestry for offsetting GHG emissions.

8.2 Materials and Methods

8.2.1 Regional case study

To carry out this research, the Valencia Region in eastern Spain has been identified and chosen as a case study, since Valencia has an important forest area (1.2 million hectares, 57% of the total area) and it is a representative example of Mediterranean forestry (Maroto et al. 2013). Valencia has a population of about 5 million people that live on an area of more than 23 thousand km^2 at the Mediterranean Sea. The majority of the population lives at the coast, where intensive agriculture and industry developed, as well as services, especially tourism. The interior of the region is very mountainous, dominated by an agroforestry landscape, but with a very pronounced rural abandonment during the last five decades, which has led many agricultural lands to evolve into forest without any type of management (Delgado-Artes 2015) by the small rural owners (see Figure 39). Its climate is influenced by the Mediterranean Sea. As all Mediterranean regions, Valencia is classified as one of most negatively affected by climate change in Europe (Giannakopoulos et al. 2005).

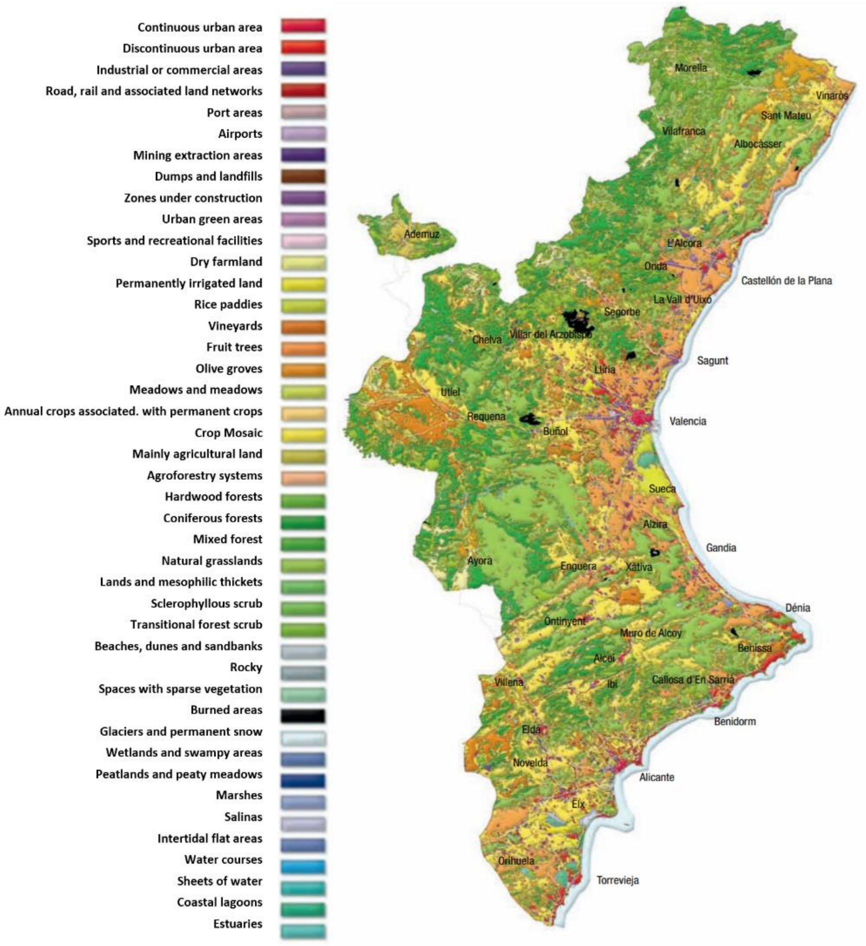

Figure 39. Land cover map of the region of Valencia (Spain) (EEA 2018).

8.2.2 Quantification of carbon fixation in forest biomass under Mediterranean conditions

The quantification of CO_2 eq. fixation in forestry in the regional case study has been focused on the carbon fixation in living plant biomass: stem, branches, foliage and roots. Thus, firstly annual growth in terms of dry weight of biomass has been calculated differentiating between small trees diameters (diameter at breast high (DBH) <7.5 cm) and tally trees (DBH >7.5 cm). The methodology described by (Montero et al. 2005) has been followed to quantify annual growth of small trees. On the other hand, to quantify the annual growth of tally trees, the methodology described by Lerma-Arce (2015) used to calculate cumulative biomass existences has been adapted to calculate the annual growth of biomass (in dry weight). Then, a carbon fraction of dry weight biomass of 0.5 (weight Carbon/weight dry biomass) as the mean value of different authors consulted (IPPC 2006, Montero et al. 2005, McGroddy et al. 2004, Feldpausch et al. 2004, Lamlom and Savidge 2003, Gayoso et al. 2002, Hughes et al. 2000, Andreae and Merlet 2001), has been used. Finally, the stoichiometric relationship between carbon and CO_2 is used to obtain the amount of CO_2 equivalent (CO_2 eq.) that is fixed annually.

The data for the application of these methodologies are obtained from the National Forest Inventory database in Spain (IFN3) (Tragsa 2006). The IFN3 characterizes a number of stands that describe forest ecosystems present in each region, according to the species present, their respective occupations and their age stage (see Table 19). Then, the forest area of the region is divided into different geolocated plots. Each plot is characterized by the stand to which it belongs and its area. Thus, carbon fixation of small and tally trees classified by diametric classes has been quantified per plot.

Table 19. Stands defined to Valencia Region. Source: IFN3 (Tragsa 2006).

Stand	**Dominant species**	**Occupation (%)**	**Stage**	**Canopy cover (%)**
01	*Pinus halepensis*	>=70	Old growth	70-100
02	*Pinus halepensis*	>=70	Old growth	40-69
03	*Pinus halepensis*	>=70	Old growth	20-39
04	*Pinus halepensis*	>=70	Young forest	5-100

05	*Pinus nigra and P. pinaster* or mixed with *Pinus halepensis*	>=70; 30<=Sp.<70	Old growth	40-100
06	*Pinus nigra and P. pinaster* or mixed with *Pinus halepensis*	>=70; 30<=Sp.<70	Old growth	20-39
07	*Quercus ilex* or mixed with *Pinus halepensis* or *Ceratonia siliqua*	>=70; 30<=Sp.<70	Old growth	20-100
08	*Quercus ilex* or mixed with *Pinus spp.*	>=70; 30<=Sp.<70	Young forest	5-100
09	*Juniperus thurifera*	*>=70*	Old growth, Young Forest	20-100 5-100
10	Riverside trees (*Populus spp., Fraxinus spp…*)	>=70; 30<=Sp.<70	All	5-100
11	Scrub	>=70; 30<=Sp.<70	Old growth	5-19

8.2.2.1 Quantification of carbon fixation of small trees

The quantification of the carbon fixed by the small trees diameter (DBH < 7.5cm) is obtained from equation (14):

$$Carbon\ Fixation_{st}\ (t\ C/year)\ = \sum_{plots} AIDWst_k \times Nºst_j \times Area_i \times CF \quad (14)$$

Where:

AIDWst: Annual increment of dry weight of a small tree (DBH < 7.5cm), in tonnes per year.

Nºst: Number of small trees per hectare.

Area: Area of plot in hectares.

CF: Carbon fraction of dry weight biomass (0.5 t C/ t dry biomass).

i: plot.

k: species.

j: stand.

The annual increment of dry weight of small trees is obtained from the models developed by Life Forest CO_2 (2019), which measure the average annual increment of dry weight of different species with DBH < 7.5cm. The number of small trees per hectare are obtained from the characterization of the stand to which that plot belongs in IFN3 (Tragsa 2006) (see Table 20). IFN3 also offers the area of each plot.

Table 20. Example of Forest stands characterization in Valencia. Source: own elaboration based on IFN3 (Tragsa 2006).

Species or group of species	**Nªtt: Number of tally trees per hectare (Nªtt/ha)**	**VWB (m^3)**	**AIVCrt (m^3)**	**Nºst: Number of small trees per hectare (Nºst/ha)**
Pinus halepensis	605.55	67.962	2.349	286.48
Pinus pinaster	1.39	0.305	0.010	3.82
Pinus nigra	0.07	0.015	0.000	0.00
Quercus ilex	3.17	0.108	0.002	38.20
Juniperus thurifera	1.27	0.021	0.001	138.78
Ceratonia siliqua	2.80	0.212	0.002	5.09
Riverside trees (*Populus spp., Fraxinus spp…*)	0.03	0.071	0.001	4.46

Other hardwood trees	2.23	0.075	0.001	12.73
Total	616.51	68.773	2.366	489.56

8.2.2.2 Quantification of carbon fixation of tally trees

The quantification of the carbon fixed by tally trees (BHD > 7.5cm) is obtained from equation (15):

$$Carbon\ Fixation_{tt}\ (t\ C/year) = \sum_{plots} AIVCtt_{j,k} \times BD_k \div \%stem_k \times Area_i \times CF \qquad (15)$$

*W*here:

AIVCtt: Annual increment of volume of the stem of tally trees, in m^3/ha.

BD: Basic density.

Area: Area of plot in hectares.

%stem: percentage of the stem weigh over the rest of the tree biomass (see Table 21).

CF: Carbon fraction of dry weight biomass (0.5 t C/ t dry biomass).

i: plot.

k: species.

j: stand.

The AIVCtt by species is obtained from IFN3 (Tragsa 2006). The percentage of the stem weight over the rest of the tree biomass by species is obtained from the models of (Montero et al. 2005). The area of each plot is also obtained from IFN3. Table 21 shows the relative value in dry weight of each part of the tree adapted from Montero et al. (2005).

Table 21. Relative value that represent the dry weight of each part of the tree. Adapted from Montero et al. (2005).

Aerial biomass							Radical biomass
Species	Stem	Branches			Leafs	Total	
		R > 7 cm	R 2- 7 cm	R< 2 cm			
Pinus halepensis	37%	9.80%	8.40%	21.20%	0%	76.40%	23.60%
Pinus nigra	51.10%	5.40%	8.00%	15.90%	0%	80.40%	19.60%
Pinus pinaster	61.9%	0.9%	4.1%	10.9%	0.0%	77.9%	22.1%
Pinus pinea	36.4%	17.7%	11.4%	13.4%	5.6%	84.5%	15.5%
Pinus sylvestris	56.1%	2.5%	7.0%	7.4%	5.6%	78.6%	21.4%
Populus x euramericana	48.9%	6.4%	6.4%	6.1%	2.3%	76.0%	24.0%
Quercus ilex	18.4%	24.2%	12.2%	8.7%	2.0%	65.4%	34.6%
Quercus faginea	25.1%	24.7%	9.9%	5.5%	3.2%	68.4%	31.6%
Quercus suber	32.4%	30.8%	10.5%	2.4%	1.4%	77.5%	22.5%
Juniperus thurifera	35.8%	7.8%	14.6%	9.3%	8.5%	76.1%	23.9%
Juniperus oxycedrus	-	-	-	-	-	21.8%	78.2%
Ceratonia siliqua	17.7%	13.1%	7.4%	7.7%	5.3%	51.2%	48.8%
Olea europaea	19.6%	25.0%	13.3%	9.3%	1.3%	68.6%	31.4%
Fraxinus excelsior	24.4%	11.7%	11.8%	9.9%	0.0%	57.8%	42.2%

8.2.3 Quantification of total carbon fixed and CO_2 equivalent at regional and local level

The quantification of the total carbon fixed by living plants biomass of forestry is obtained from equation (16):

$$Carbon\ Fixation_{total}\ (t\ C/year) = Carbon\ Fixation_{st} + Carbon\ Fixation_{tt} \quad (16)$$

Then, equation (17) shows how tons of CO_2 eq. are obtained from the amount of carbon calculated in equation (16). Thus, it must be multiplied by the relation between the weight of the CO_2 molecule and the weight of the C atom (44/12):

$$CO2\ eq.Fixation\ (t/year) = Carbon\ Fixation \times \frac{44}{12} \quad (17)$$

The total CO_2 eq. fixation of each geolocated plot is intersected with the local administrative layer of the Geographic Information System (GIS), which includes all the 562 municipalities of the region. With this geographical segmentation, the developed model is able to calculate the total CO_2 eq. fixation of local forests with high spatial resolution.

8.2.4 Valorisation of carbon fixation in Mediterranean forests

To valorise the carbon fixation of the Mediterranean forest, an innovative methodology has been developed. The methodology developed aims to analyse the potential to generate carbon credits as anthropogenic avoided emissions due to reduce wildfire risk compared with a BaU scenario. To achieve this, firstly a literature review to obtain carbon credit price based on existing carbon markets has been carried out. Several forestry-based carbon markets (Life Forest CO_2 2019, WCC 2018, RHC 2020) have been analysed and the carbon credit price has been calculated based on the price of these markets.

Up today, the calculation of carbon credits generated by forestry is based on the difference of the theoretical growth scenario without any type of silvicultural measure (BaU) with respect to a scenario affected by different measures (mainly afforestation and reforestation) (Life Forest CO_2 2019, WCC 2018, RHC 2020). Increasing the number of trees is an adequate measure for forests where the species have an important economic value and therefore product-oriented harvesting is guaranteed, i.e. in central and northern European countries (Carbomark 2011). However, in most southern Mediterranean countries, wood has normally low economic value and consequently low harvesting rates (Croitoru 2007). This low level of management implies the accumulation of combustible biomass, which directly influences a higher vulnerability to fire in the Mediterranean forest ecosystems, especially in times of severe drought (Plana et al. 2016). Actually, the reduction of wildfire risk and magnitude would be a highly effective measure to mitigate climate change, since the emission of a large amount of GHG would be avoided (Moreno et al. 2014). For this reason, the developed methodology calculates the BaU scenario taking into account the wildfires in the region of the last 10 years. This scenario is compared with a simulated scenario without wildfires. The range between the carbon stocks stored in both scenarios represents the number of potential carbon credits that could be generated as anthropogenic avoided emissions in a 10-years period. This period has been chosen in order to avoid excessive influence of anomalous events depending on the moment that the methodology would be applied. For example, in the case of an extraordinary wildfire event in the previous year and taking only this year as BaU scenario, results of carbon credits available would be unrealistic and very influenced by this event. Furthermore, 10 years is the period of time usually used in the forest management plans (Corona et al. 2015).

8.2.4.1 Model for valorisation of carbon fixation in a Business as Usual (BaU) scenario

Equation (18) expresses the developed model for valorisation of carbon fixation in a BaU scenario.

$$f(x) = \frac{(C_{t0} - C_{tm})}{(t_0 - t_m)} \times (x - t_0) + C_{t0} \qquad (18)$$

Where:

f (x): Carbon stored determined by the year (x) in the BaU scenario.

t_0: Base year (first year of the period).

t_m: Any year of the 10-year period.

C_{t0}: Carbon stock in the base year. Calculated following the methodologies described by Montero et al. (2005) and Lerma-Arce (2015). C_{t0} is calculated by the equation (19).

$$C_{t0}\ (t\ C) = Carbon\ Stock_{\ t0,st} + \ Carbon\ Stock_{\ t0,tt} \qquad (19)$$

Where:

Carbon Stock $_{t0,st}$: Carbon stock in the base year of small trees. Calculated by the equation (20).

Carbon Stock $_{t0,tt}$: Carbon stock in the base year of tally trees. Calculated by the equation (21).

$$Carbon\ Stock_{st}\ (t\ C)\ = \sum_{plots} N^{o}st_j \times Area_i \times MC \times \pi \times R^2 \times \ h \times CF \qquad (20)$$

Where:

Nºst: Number of small trees per hectare.

Area: Area of plot in hectares.

CF: Carbon fraction of dry weight biomass (0.5 t C/ t dry biomass).

MC: Morphic Coefficient.

R: Radius in meters (0.025 m based on Montero et al. 2005).

h: Height in meters (1.6 m based on based on Montero et al. 2005).

i: plot.

j: stand.

$$Carbon\ Stock_{tt}\ (t\ C) = \sum_{plots} VWB_{j,k} \times BD_k \div \%stem_k \times Area_i \times CF \qquad (21)$$

Where:

VWB: Volume with Bark of stem in cubic meters (see Table 20).

BD: Basic density.

Area: Area of plot in hectares.

%stem: percentage of the stem weigh regarding the rest of the tree biomass (see Table 21).

CF: Carbon fraction of dry weight biomass (0.5 t C/ t dry biomass).

i: plot.

k: species.

j: stand.

C_{tm}: Carbon stock in the year m, obtained from the equation (22).

$$C_{tm} = C_{t(m-1)} - \overline{C\ burned} - \overline{Cp} - \overline{Cb} + Carbon\ fixation_{total} \qquad (22)$$

Where:

$C_{t\,(m-1)}$: Carbon stock in the year before m.

$\overline{Cp}$: Average of carbon stock extracted from forest to products manufacturing (see Table 22).

$\overline{Cb}$: Average of carbon stock extracted from forest to bioenergy (see Table 22).

$\overline{C\ burned}$: Average of carbon losses by wildfires calculated as equation (23).

$$\overline{C\ burned} = \frac{C_{t0}}{For.Area} * \overline{BA} * \overline{\%BC} \qquad (23)$$

Where:

For.Area: Forestry area of total region in hectares (see Table 22).

$\overline{BA}$: Average of burned area of the 10 years in hectares (see Table 22).

$\overline{\%BC}$: Average of biomass consumed during wildfire due to severity (see Table 22).

C_{t0}: Carbon stock in the base year.

Table 22. Value used in variables to the study case of Valencia.

Variable	**Value**	**Reference**
Average of carbon stock extracted from forest to products manufacturing	417,273 t C/year	Cabanes-Sanchez et al. (2016)
Average of carbon stock extracted from forest to bioenergy	71,300 t C/year	Cabanes-Sanchez et al. (2016)
Forestry area of total region in hectares	1,200,194 ha	Tragsa (2006)
Average of burned area of the 10 years in hectares	9,732 ha/year	MITECO (2020a)

Average of biomass consumed during wildfire due to severity	72.6%	Calculated in REMAS Interreg SUDOE project currently in progress (REMAS Project 2020)

8.2.4.2 Model for valorisation of carbon fixation in a simulated scenario

Equation (24) expresses the developed model for valorisation of carbon fixation in a simulated scenario, which represent a hypothetical scenario without wildfires.

$$g(x) = \frac{(C_{t0} - CSim_{tm})}{(t_0 - t_m)} \times (x - t_0) + C_{t0} \quad (24)$$

Where:

g (x): carbon stored determined by the year (x) in the simulated scenario.

t_0: Base year (first year of the period).

t_m: Any year of the 10-year period.

m: Year.

C_{t0}: Carbon stock in the base year.

$CSim_{tm}$: Carbon stock in the in the year m in a scenario simulated without wildfires obtained from the equation (25).

$$CSim_{tm} = CSim_{t(m-1)} - \overline{Cp} - \overline{Cb} + Carbon\ fixation_{total} \qquad (25)$$

Where:

$CSim_{t\ (m-1)}$: Carbon stock in the year before m in the simulated scenario.

$\overline{Cp}$: Average of carbon stock extracted from forest to products manufacturing (see Table 22).

$\overline{Cb}$: Average of carbon stock extracted from forest to bioenergy (see Table 22).

Thus, the total Potential Carbon Saved (PCS) is calculated with equation (26), being the area between the two scenarios functions f(x) and g(x).

$$Potential\ Carbon\ Saved = \int_{year\ 0}^{year\ 9} [g(x) - f(x)]dx \qquad (26)$$

Therefore, the number of Potential Carbon Credits (PCC) corresponding with potential anthropogenic avoided emissions are obtained from the equation (27):

$$Potential\ Carbon\ Credits\ (PCC) = Potential\ Carbon\ Saved \times \frac{44}{12} \qquad (27)$$

Finally, the number of carbon credits generated (NCCG) will be between 20% and 90% of the amount of Potential Carbon Credits (PCC) (in t CO_2 eq.) in the simulated 10-year period. A maximum of 90% is used because the fire risk cannot be completely reduced (Hurteau et al. 2008). The minimum 20% of the PCC available is due to fuel biomass reduction by fire prevention measures and consequent forest resilience improvement. Therefore, the NCCG will be defined by equation (28):

$$20\%\ PCC \leq \boldsymbol{NCCG} \leq 90\%\ PCC \qquad (28)$$

8.2.5 Comparison between carbon fixation with total GHG emissions

The amount of annual CO_2 fixation has to be compared with the total amount of GHG emissions (direct and diffuse) in the case study region. It is important to differentiate because direct GHG emissions have its own mandatory carbon market (EU ETS), but diffuse GHG emissions could be a potential voluntary carbon market at regional level. So, on the one side, direct GHG emissions of EU ETS industries have been quantified by digitalising the annual GHG emissions notifications of the companies obligated to report their GHG emissions based on 2003/87/EC Directive (European Commission 2003). These notifications were obtained from OECC (2018). On the other side, diffuse GHG emissions have been calculated with national GHG emissions inventory based on a per habitants ratio (MITECO 2020b).

8.2.6 Evaluation of the potential of Mediterranean forestry for offsetting GHG emissions

Finally, the potential of Mediterranean forestry for offsetting GHG emissions through the valorisation of anthropogenic-avoided emissions has been evaluated with the previous expressed models.

8.3 Results and discussion

8.3.1 Total carbon fixation by forest biomass

The results of the application of the methodologies described for the Valencia region show a total amount of annual fixation of 3.16 million t of CO_2 eq. distributed at local level (see Figure 40). This carbon fixation is distributed in 1.52 million t of CO_2 eq. produced by small trees and 1.64 million t of CO_2 eq. produced by tally trees.

CO_2 eq. fixation has been calculated in 473 municipalities with forests, from a total of 542 municipalities in the region. This represents 87.27 % of total municipalities. Table 23 shows the most CO_2 eq. fixation municipalities in the region. These 19 municipalities suppose the CO_2 eq. fixation of 40 % of total fixation. Actually, the higher CO_2 fixation is produced in rural municipalities in the western mountainous areas (see Figure 40), and furthermore less populated. For this reason, the valorisation of the forest services as CO_2 fixation could be a very good option to mitigate and to adapt to climate change and to reduce rural depopulation.

Table 23. Most CO_2 eq. fixation municipalities of Valencia (Spain).

Municipality name	Annual CO_2 eq. Fixation (t CO_2 eq./year)	Relative value regarding total CO_2 eq. Fixation (%)	Cumulative relative value of CO_2 eq. (%)
Morella	269,910	8.53	8.53
Requena	111,459	3.52	12.06
Pobla de Benifassà	93,688	2.96	15.02
Vistabella del Maestrat	93,421	2.95	17.97
Vallibona	78,851	2.49	20.47

El Toro	72,732	2.30	22.77
Ares del Maestrat	66,485	2.10	24.87
Ayora	60,373	1.91	26.78
Villahermosa del Río	56,822	1.80	28.57
Vilafranca	44,387	1.40	29.98
Venta del Moro	43,399	1.37	31.35
Castellfort	40,518	1.28	32.63
Cortes de Arenoso	40,414	1.28	33.91
Zorita del Maestrazgo	37,056	1.17	35.08
Chelva	36,819	1.16	36.24
Culla	36,259	1.15	37.39
Benassal	30,870	0.98	38.37
Andilla	30,498	0.96	39.33
Tuéjar	28,774	0.91	40.24

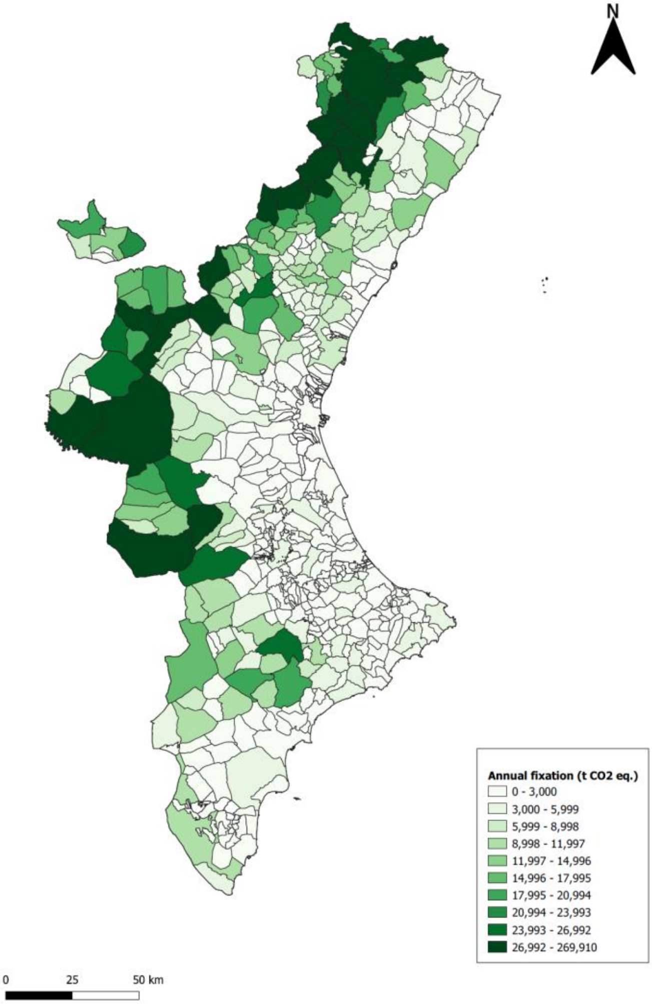

Figure 40. Spatial distribution of annual CO_2 eq. fixation at local level in Valencia (Spain).

8.3.2 Value of carbon fixed by Mediterranean forests

The average carbon credit price calculated for year 2020 based on the forest carbon markets analysed (Life Forest CO_2 2019, WCC 2018, RHC 2020) is 16 €/t CO_2 eq. Thus, this price has been used to estimate the valorisation of GHG emissions balance at local and regional level.

Then, the results of carbon stored in a BaU and in a simulated scenario for the 10-years period analysed in the pilot region can be seen in Table 24.

Table 24. Results of carbon stored quantification in BaU and simulated scenarios.

BaU Scenario		
2006	C_{t0} (t C)	18,877,336
2007	C_{tm} (t C)	19,123,160
2008		19,368,985
2009		19,614,810
2010		19,860,634
2011		20,106,459
2012		20,352,284
2013		20,598,108
2014		20,843,933
2015		21,089,758

Simulated Scenario		
2006	C_{t0} (t C)	18,877,336
2007	$CSim_{tm}$ (t C)	19,234,277
2008		19,591,219
2009		19,948,161
2010		20,305,103
2011		20,662,045
2012		21,018,986
2013		21,375,928
2014		21,732,870
2015		22,089,812

Thus, the total Potential Carbon Saved (PCS) is 4.5 million of t C, being the area between the two scenarios functions f(x) and g(x) (see Figure 41).

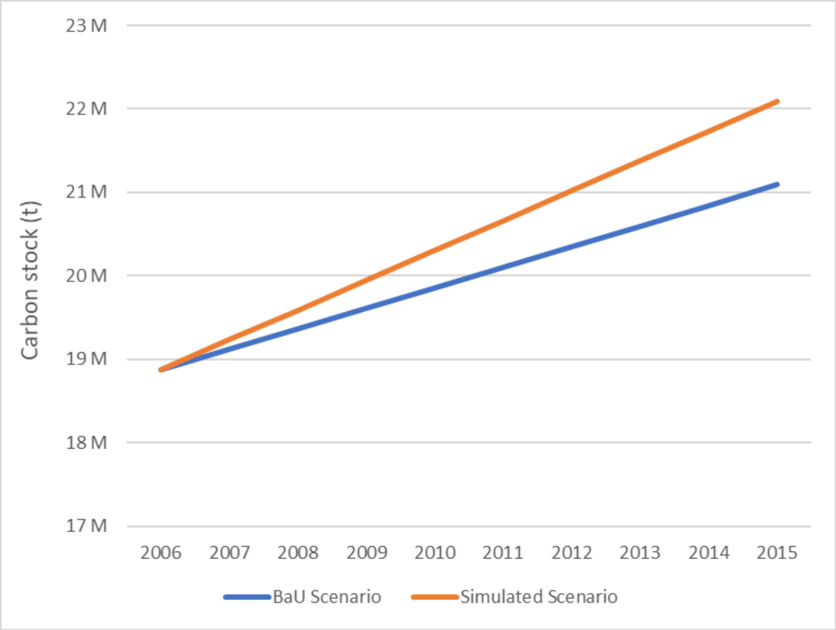

Figure 41. Graphical representation of f(x) and g(x) functions of BaU and simulated scenarios respectively.

Then, the number of Potential Carbon Credits (PCC) is 16,500,898, which correspond to potential anthropogenic avoided emissions in terms of t CO_2 eq. Therefore, the number of carbon credits generated (NCCG) will be between 3,300,179 and 14,850,808 (equivalent to t CO_2 eq.) in the simulated 10-years period in the region. Thus, the valorisation of the calculated NCCG in the region based on carbon price of forestry carbon markets analysed is between 55.5 and 250 million €.

8.3.3 Carbon fixation in relation to total GHG emissions

The estimation of total growth GHG emissions in Valencia is 35.5 million t CO_2 eq. divided in direct and diffuse GHG emissions. Most emitter sector is “Energy” with around 75%, followed by “Industrial processes and product use” and “Agriculture” with 10% each one and “Waste” with 5%.

Direct GHG emissions composed by 178 EU ETS facilities in the region emit 8.9 million t of CO_2 eq. (OECC 2018). The main contributor is the ceramic sector with 33% of the total direct emissions followed by the clinker sector with 21% and electricity generation with 18%.

Diffuse GHG emissions are estimated in 26,622,550 t CO_2 eq. distributed by every municipalities of the region in dependence of the inhabitants. Therefore, the annual CO_2 fixation by living biomass in forests suppose 9% of total growth GHG emissions and 15% of diffuse emissions that have no compensation carbon market nowadays.

8.3.4 Potential of Mediterranean forestry for offsetting GHG emissions

The number of carbon credits generated (NCCG) calculated by the application of the methodology developed for the regional case of Valencia, would allow to compensate between 330,018 and 1,485,080 t CO_2 per year. This would suppose a compensation potential between 1.2 and 5.6% of total diffuse GHG emissions.

Finally, regional compensation of GHG emissions would produce a lot of positive benefits for society and environment at local and regional level: creation of jobs linked to rural activities (rural development), minimizing natural disaster risks, conservation of biodiversity and natural habitats, revaluation of the territory and its resources, promotion of low-carbon value chains (bioeconomy), climate change mitigation and adaptation and the reduction of a lot of damages produced by wildfires in economic, social and environmental terms.

8.4 Conclusions

A quantification of CO_2 fixation by living plant biomass of forestry sector has been done with high spatial resolution in a representative Mediterranean region with a clear lack of forest management (Valencia in Spain).

The methodology developed has allowed to valorise CO_2 fixation by forests with a new approach adapted to Mediterranean conditions, which takes into account the anthropogenic avoided emissions by sustainable forest management to active wildfire prevention. In this way, a simulated scenario with forest management has been used to calculate the generation of carbon credits of avoided CO_2 eq. emissions and to compare with a business as usual scenario. In addition, a literature review of the existing forest-based carbon markets has been carried out to estimate an average carbon credit price equivalent to one ton of CO_2 eq.

The application of this methodology to the study case of Valencia region has allowed to obtain a total valorisation of between 55.5 and 250 million €, corresponding to 16.5 million of potential carbon credits generated equivalent to anthropogenic avoided emissions of a 10 years period in terms of t CO_2 eq.

Finally, the comparative of carbon credits generated with total GHG emissions has allowed to show the potential for offsetting between 1.2 and 5.6% of diffuse GHG per year (emissions without regulated carbon market nowadays) at regional level.

As future work, a quantification improvement of diffuse GHG emissions at local level is necessary to enable the establishment of a voluntary carbon market in Mediterranean forest regions. On the other hand, the fixation produced by the soil (organic mineral, surface and deep mineral soil) and plant detritus (fallen branches and cones, forest litter, tree stumps, tree tops, logs) should be added to the quantification of the carbon fixation of the forest land. Finally, most efficient silvicultural measures to enhance carbon sequestration and reduce wildfire risk should be studied and quantified in order to reduce the uncertainty range of Number of Carbon Credits Generated (NCCG) with respect to the Potential Carbon Credits (PCC) calculated.

9 CAPÍTULO 6 Análisis de la contribución de las áreas verdes urbanas para la consecución de los Objetivos de Desarrollo Sostenible (ODS). Estudio de caso en Valencia (España).

Contribution of green urban areas to the achievement of SDGs. Case study in Valencia (Spain).

CAPÍTULO VI

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9. CAPÍTULO 6 Análisis de la contribución de las áreas verdes urbanas para la consecución de los Objetivos de Desarrollo Sostenible (ODS). Caso de studio: Valencia (España).

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9.1 Introduction

Sustainable Development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs (United Nations 2021). This idea, concept or goal has been treated and debated in depth in the most important international policy forums since its introduction in the Brundtland report by the World Commission on Environment and Development (WCED) (United Nations 1987). Since then there have been great approaches towards the assumption of international commitments in relation to sustainable development, the definition of concrete goals and ways of evaluating their achievement such as the Rio Declaration on Environment and Development (1992), the Millennium Declaration, the World Summit on Sustainable Development (2002) or the United Nations Conference on Sustainable Development (Rio+20) in 2012. It was finally in 2015, when 193 member states of the United Nations unanimously agreed on the Agenda for Sustainable Development 2030 (United Nations 2015). This agenda is made up of the 17 Sustainable Development Goals (SDGs) (inspired by the millennium goals) that humanity will have to meet by 2030.

However, the progress made to date on the SDGs has demonstrated the need to address them at the local level, specifically at urban level. Most of the population in the world will live in cities (Ritchie and Roser 2018). In Europe, 83.7% of the population will live in cities in 2050, in comparison with 74% in 2018 (United Nations 2018). Furthermore, Adelphi and Urban Catalyst (2015) indicate that 65% of the SDG agenda may not be fully achieved without the involvement of urban and local actors. Moreover, about one third of the 232 SDG indicators can be measured at the local level, making it an important unit for action and tracking of progress towards sustainable development (UN-Habitat 2018).

Cities are the places where the positive interlinkages amongst the SDGs are boosted (Siragusa et al. 2020). Therefore, involving local authorities in the implementation of the 2030 Agenda is crucial (Bentz 2020). For this reason, the Joint Research Centre of the European Commission (JRC) published a European Handbook for Local SDGs with quantifiable and comparable indicators to configure voluntary local reviews in order to monitor progress and maintain the transformative action of local actors towards the achievement of the SDGs (Siragusa et al. 2020). Nevertheless, a global assessment at the city level allows to check the level of achievement but not to improve it efficiently, since it does not allow to identify and locate potential areas for improvement. Thus, an evaluation of the SDGs achievement at the sub-city scale or even sub-neighbourhood scale would not only make it possible to evaluate the SDGs level of achievement, but would also allow to identify areas with potential improvement. In addition, a granularity greater than city scale also allows to ensure equitable sustainable development in order to all citizens can be benefited from sustainable development. Green Urban Areas (GUA) have great relevance and are a key element in the achievement of the SDGs in cities (Elgizawy 2014). They provide a great ecological, aesthetic and recreational value to cities and also act as bioclimatic regulators on humidity and temperature that makes them a key urban infrastructure in promoting quality of life and public health for the citizenship (Siragusa et al. 2020). In addition, lignocellulosic material of urban green areas acts as a carbon sink by storing atmospheric CO_2 during photosynthesis (Strohbach et al. 2012). Therefore, it is necessary to appropriately manage and protect these spaces and ensure the access of the population to these islands of tranquillity within the urban hustle and bustle of cities (Watts et al. 2013). However, according to

United Nations (2019), most cities have difficulty ensuring that their populations have easy access to GUA. In this survey, from 220 cities of 77 countries, only 21% of the population has easy access to GUA in 2018. This could be due to two reasons: the lack of GUA or their unequal distribution.

Following the European Handbook for Local SDGs (Siragusa et al. 2020), GUA contribute directly to three SDGs at urban level:

a) ODS 11 “Sustainable cities and communities”: also known as the “Urban Goal”, calls for making cities and human settlements inclusive, safe, resilient and sustainable.
b) ODS 13 “Climate action”: take urgent action to combat climate change and its impacts, and without a doubt, protecting and promoting carbon sinks such as GUA is a mitigation and adaptation action against climate change.
c) ODS 15 “Life on land”: aims to protect, restore and promote the conservation and sustainable use of terrestrial, inland-water and mountain ecosystems. From a planning point of view, the public character of GUA is significant, since it is considered to contribute to the quality of life. On the other hand, the preservation of GUA represents a value to preserve of biodiversity, reduce of the heat island effect, increase the permeability of the soil, and reduce the flood risk (Siragusa *et al*. 2020).

The evaluation of these three SDGs from the point of view of GUA has been carried out at different scales by many authors in recent years using different indicators. JRC (2020) propose an indicator to evaluate the contribution of GUA to SDG 11 “Sustainable cities and communities” based on the methodology presented by Poelman (2018), which considers the spatial distribution of both population and GUA throughout the cities' territory, and produces also indicators about the proximity of the GUA to the citizenship. In addition, United Nations (2019) proposes an indicator that considers that a citizen has easy walking access to a GUA when the distance that separates them is less than 400 meters from home. On the other hand, Casado (2015) presents an indicator that considers both conditions of distance to the

GUA and the GUA size to determine the level of desirable access to it. Moreover, another proposal for evaluating this SDG is through an indicator that measures the GUA area and sports facilities per inhabitant (Sánchez et al. 2018). Finally, Fox and Macleod (2019) defined another approach for the city of Bristol (United Kingdom), which assesses social behaviour and the use made of GUA through indicators such as trips to parks or walking areas, use of outdoor spaces for sporting purposes or healthy or even percentage of people who visit a park at least once a week.

The evaluation of SDG 13 "Climate Action" with regard to greenhouse gases (GHG), affects all sectors and sources of GHG emissions, not only the fixation caused by GUA. Several authors propose methodologies for evaluating the positive impacts of urban vegetation on climate change that could be used as an indicator for evaluating this SDG (McPherson et al. 1998, Nowak and Crane 2002, Yang et al. 2005, Nowak et al. 2006, Zhao et al. 2010, Escobedo et al. 2011, Weissert et al. 2014). Following these authors, GUA influence climate change through two impacts:

1. Carbon fixation by urban carbon sinks: the amount of fixed carbon depends mainly on growth rates (fast-growing trees initially capture more CO_2 than slow-growing ones), (Chaparro and Terradas 2009), age (young individuals retain carbon at higher rates than mature trees) and life expectancy because when the tree decays, carbon is released into the atmosphere, either by burning of the residual biomass or by biodegradation (Stoffberg et al. 2010). There are different methodologies to calculate the carbon capture and storage carried out by vegetation in GUA (Mijangos-Hernández 2015), even at a local scale (Garrido-Lauranga et al. 2009; Guarín-Villamizar et al. 2014).
2. Indirect reduction of GHG emissions caused by the influence of GUA due to three factors related to energy consumption in buildings: a) due to the reduction of heat absorbed and stored in buildings by the shade provided by urban trees (Akbari et al. 1997, Romero-Lankao and Gratz 2008, Nowak et al. 2010); b) due to the decrease in air temperature caused by the

evapotranspiration of the foliage humidity (Huang et al. 1990, Kurn et al. 1994, Romero-Lankao and Gratz, 2008, Nowak et al. 2010); c) due to the decrease in the frequency and intensity of the winds that causes a decrease in heat losses caused (Huang et al. 1990, Nowak et al. 2013).

Finally, to evaluate the contribution of GUA to SDG 15 “Life and land”, Siragusa et al. (2020) proposes as indicator the total amount of green area in square meters as approximated by the Normalized Difference Vegetation Index (NDVI) based on satellite imagery. Another method is described by the Cabot Institute for the Environment of the University of Bristol (Fox and Macleod 2019) that assesses social behaviour using an indicator that measures the proportion of respondents who visit GUA at least once a week. Generalitat Valenciana (2018) proposes indicators such as number of urban or periurban Protected Natural Areas, percentage of managed urban forest area, ownership of urban forestland, and forest area affected by fires or pests. However, most of these indicators are difficult to adapt to the urban scale. Finally, Sánchez *et al*. (2018) and Ajuntament de Barcelona (2019) propose two similar indicators, but with a slight nuance between them. These authors propose as indicator the natural area per capita and the area of GUA per capita.

After analyse the state of the art, we can conclude that none of the described studies carried out by other authors analyse the specific and direct contribution of GUA to the SDGs of a city at sub-neighbourhood level. This would allow to have a quantified global vision of its importance in society, as well as to identify opportunities for improve it efficiently based on observed weaknesses in order to ensure an equity sustainable development in the different areas of the city. Therefore, our research analyses the direct and specific contribution of GUA to the achievement of three SDGs at sub-neighbourhood level. To do this, the indicators that have been considered most appropriate have been selected, adapted and applied to evaluate the contribution of GUA to SDG 11 "Sustainable Cities and Communities", SDG 13 "Climate Action" and SDG 15 "Life and Land" in the study case of the city of Valencia (Spain). The results allow to identify potential areas of the city to improve the sustainable development regarding to GUA, and to analyse the level of equity in the sustainable development between different parts of the city to promote the environmental justice of the city.

9.2 Methods

9.2.1 Pilot city for the case study

Valencia city council and Joint Research Centre have a Collaboration Agreement signed to use Valencia as a City Lab under the framework of the Community of Practice on CITIES (JRC 2020), to identify new approaches in the areas of urban indicators and Sustainable development goals. Thus, the city of Valencia (Spain) has been selected as a case study to carry out the evaluation of the contribution of GUA to the achievement of the SDGs. The city of Valencia is located in the Valencian Community in the Eastern part of Spain. Currently, Valencia city has 764,000 inhabitants and is the third biggest city of Spain. The metropolitan area, which includes other municipalities adjacent to the city, reaches more than 1,500,000 inhabitants. The city of Valencia is administratively divided into 19 districts, subdivided into 88 neighbourhoods, which are subdivided into 606 census sections, as shown in Figure 42. Census sections of the centre of the city have less population density due to the age, size and type of building, as buildings of the centre of the city is generally buildings with lower heights where less population lives. This directly affects population density. However, as you go away from the centre, some census sections have greater separation between buildings or higher buildings where the population density may differ between adjoining census sections (Figure 42).

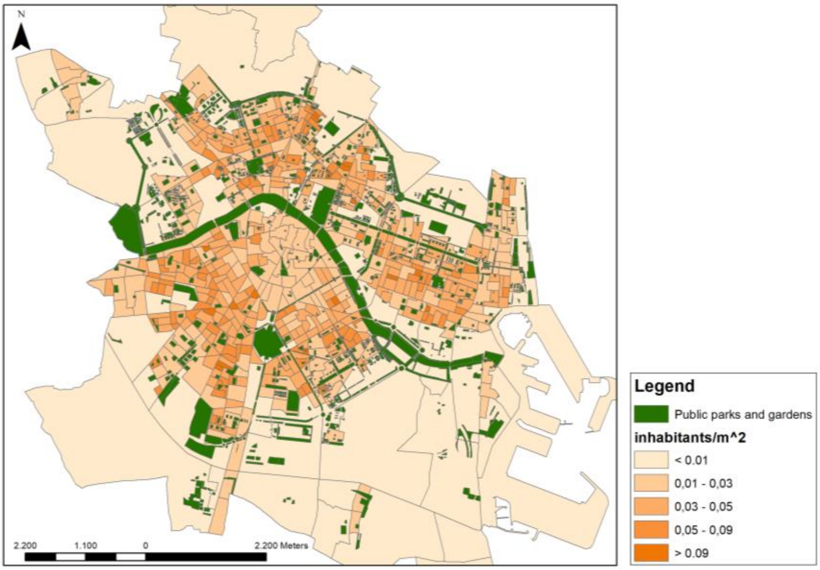

Figure 42. Geographical distribution of the Green Urban Areas in the city of Valencia and population density of the city of Valencia

A Geographic Information System (GIS) has been used for the calculation of the indicators and the graphic representation of the results to obtain the maximum spatial resolution in the evaluation and analysis of the results, thanks to zoning the city into 606 different polygons. The GUA of the municipality of Valencia are georeferenced and represented by a polygon with attributes of the area of the polygon, the number of trees and the species. Additionally, a census population layer is also used for each census section downloaded from the Valencia City Council Smart City Platform (Ajuntament de València 2019).

9.2.2 Evaluation of GUA to achieve SDG 11 “Sustainable Cities and Communities”

The contribution of GUA to the achievement of the Sustainable Development Goal 11 "Sustainable Cities and Communities" has been evaluated using two indicators, which assess the percentage of the citizenship that has access to GUA from two different approaches.

9.2.2.1 Population without desirable access

The definition of “desirable access to GUA” is an adaptation obtained from the different degrees of compliance that Casado (2015) uses to evaluate access to GUA at the city scale. Casado (2015) classifies as "desirable" when 100% of the population meets the four conditions described below, "acceptable" when 100% of the population meets three conditions and "unacceptable" when less than three conditions or less than 100% of the population meets three conditions. However, these evaluation parameters have been adapted at the sub-neighbourhood level, evaluating only how much population has “desirable access”.

Thus, the condition proposed by Casado (2015) to have desirable access to a GUA occurs when the following conditions are met simultaneously:

- It is located at less distance than 200 meters (walking distance) from a GUA larger than 1,000 m^2.
- It is located at less distance than 750 meters (walking distance) from a GUA larger than 5,000 m^2.
- It is located at less distance than 2 kilometres (commuting by bicycle) from a GUA larger than 1 hectare (10,000 m^2).
- It is located at less distance than 4 kilometres (travel by public transport) from a GUA larger than 10 hectares (100,000 m^2).

Therefore, the polygons of GUA are divided into 4 different categories according to the mentioned intervals of their area and those under 1,000 m^2 are excluded from the calculation for this indicator. After that, a buffer is made with the aforementioned distance from the centre of each polygon depending on the category to which each polygon belongs. After that, the following equation is applied:

$$\%PWDA = \frac{\sum_{CS} CS_i population \times \frac{CS_{iPWDA} area}{CS_i area}}{\sum_{CS} CS_i population} \times 100 \qquad (29)$$

Where:

PWDA: Population without desirable access

CS_ipopulation: Population of the census section i

CS_iarea: Area of the census section i

PWDAarea: Area not covered by buffer of influence of GUA (area without desirable access).

CS_{iPWDA}area: Area of the census section i without desirable access to GUA.

CS_i: Census section i

9.2.2.2 Population without easy walking distance access

For the evaluation of easy walking distance access, the indicator proposed by Siragusa et al. (2020) has been used. This indicator is calculated considering an area of easy walking distance approximately of 10 minutes of walking time. In order not to give the same weight to very small GUA as to the rest, areas smaller than 1,000 m^2 have also been excluded. In addition, the same but more restrictive indicator has also been applied using an area that is easier walking distance access, considering 5 minutes of walking time.

Thus, influence buffers are calculated to represent the distance that can be reached from parks in a specified period of time using the Network Analyst extension of the ArcGIS software. Assuming that a citizen walks at 3.5 km/h (considering that the speed of an older person or child is less than an adult), the areas of influence of 5 and 10 minutes have been achieved. Next, a network of the streets of Valencia is configured from *pgrouting* in *Postgis*. From this network, the time of each street is calculated in a new field. Finally, the necessary layers are added to the network to achieve the polygons of areas of influence at the speed set to obtain the areas of influence according to the architecture of the streets.

After that, equation (30) is applied to the new buffer generated to calculate the Population without easy walking distance access.

$$\%PWEW = \frac{\sum_{CS} CS_i population \times \frac{CS_{iPWEW} area}{CS_i area}}{\sum_{CS} CS_i population} \times 100 \qquad (30)$$

Where:

PWEW: Population without easy walking distance access.

PWEWarea: Area not covered by buffer of influence of GUA that represent 10 or 5 minutes trip by foot.

CS_{iPWEW}area: Area of the census section i without easy and easier walking distance access of GUA.

9.2.3 Evaluation of GUA to achieve SDG 13 “Climate Action”

The evaluation of the contribution of GUA to SDG 13 “Climate Action” has been done by quantifying carbon fixation (expressed as CO_2 equivalent) by the vegetation (mainly trees and palm trees) of the GUA through the photosynthesis activity. For the calculation, the values of annual growth described by Montero et al. (2005) have been used. After that, a value of carbon fraction of dry weight biomass of 0.5 (weight carbon / weight dry biomass) has been applied as mean value of different authors consulted (IPCC 2006, Montero et al. 2005, McGroddy et al. 2004, Hughes et al. 2000, Feldpausch et al. 2004, Andreae and Merlet 2001, Gayoso et al. 2002, Lamlom and Savidge 2003). Finally, the stoichiometric relationship between carbon and CO_2 is applied to obtain the total CO_2 eq. fixed annually. Thus, the calculation of CO_2 eq. fixed is calculated by the following equation:

$$Fixed\ CO_2\ eq. = \sum_i n_{ij} \times AG_j \times CF_j \times \frac{44}{12} \qquad (31)$$

Where:

Fixed CO_2 eq.: Total amount of CO_2 eq. fixed by photosynthesis of trees and palm trees. (in kg CO_2 eq.)

n_{ij}: Number of trees of the species j in the polygon i

AG: Annual growth of dry weight in kg per year.

CF: Carbon fraction of dry weight biomass (0.5 kg C / kg dry biomass)

i: polygon

j: species

44/12: Stoichiometric relationship CO_2-C.

GUA of the pilot study of Valencia are composed by 322 different species. The bibliography consulted does not have data for all these species. Therefore, a simplification has been made by cataloguing all the species without exact referenced data for the species in three types: coniferous, broadleaves and palm trees. Thus, an average value for each type has been calculated based on the species that we do have data in the bibliography. Thus, the annual growth values (in kg dry biomass/year) used for the species without referenced data are: coniferous 3.07; broadleaves 5.08 and palm tree 2.71. These values were calculated in TRUST 2030 strategic cooperation project of The Valencian Innovation Agency (AVI TRUST 2019). Thus, annual growth values were calculated based on statistics of Valencia city (number and spices of the trees) (Ajuntament de València 2019) with coefficients used by Montero et al. (2005).

9.2.4 Evaluation of GUA to achieve SDG 15 “Life and Land”

Finally, the evaluation of the contribution of GUA to the SDG 15 “Life and Land” has been carried out using the indicator used by Sánchez et al. (2018) and Ajuntament de Barcelona (2019) that calculates the GUA per capita. Thus, the indicator used is calculated using the following equation:

$$GUA\ per\ inhabitant = \frac{\sum_{CS} CS_i GUA}{\sum_{CS} CS_i population} \qquad (32)$$

Where:

GUA: Green Urban Area

CS_ipopulation: Population of the census section i

CS_iGUA: Green Urban Area (in m^2) of the census section i

In addition, the calculation of this indicator has been carried out in every census section individualized to achieve more spatial resolution in the analysis and to be able to identify which census sections of the city have the worst results or the most opportunity for improvement.

9.3 Results and discussion

9.3.1 Contribution of GUA to achieve SDG 11 “Sustainable Cities and Communities”

9.3.1.1 Population without desirable access

The combination of the four influence buffers of the GUA categories allows to identify the area of population without desirable access to GUA (blue area of Figure 43). Figure 43 shows which parts of the city meet the criteria described of desirable access or do not meet them. It can be seen that the peripheral areas of the city have a large area considered as "without desirable access to GUA". However, these areas are outside the urban nucleus where there is almost no GUA because little or no population lives here. These results show that the distribution of GUA in the city is generally equitable. Only the blue area of the city centre has worse results. This is because it is the oldest area of the city and has fewer GUA spaces. Thus, the results of the applied indicator show 70,497 inhabitants without desirable access to GUA because they are living in areas that do not comply with the distances described in the four categories of access to GUA, simultaneously. This means 9.23% of city inhabitants do not have desirable access to GUA. The specific analysis of the central area of the city where more space is identified as “without desirable access” is analysed more in detail in Figure 44.

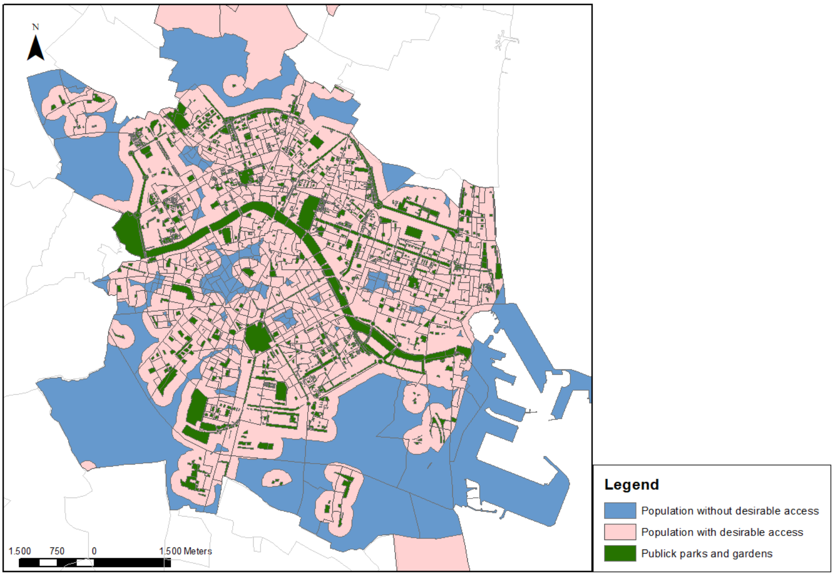

Figure 43. Population without desirable access to GUA in the city of Valencia.

Figure 44 shows the part of the city with the highest population without desirable access to GUA. This is the southwest area of the city, where the neighbourhoods of the districts of Patraix, Ciutat Vella and Extramurs are located. This zone lacks GUA less than 200 meters away and therefore does not meet the first condition of accessibility (see section 9.2.1.1).

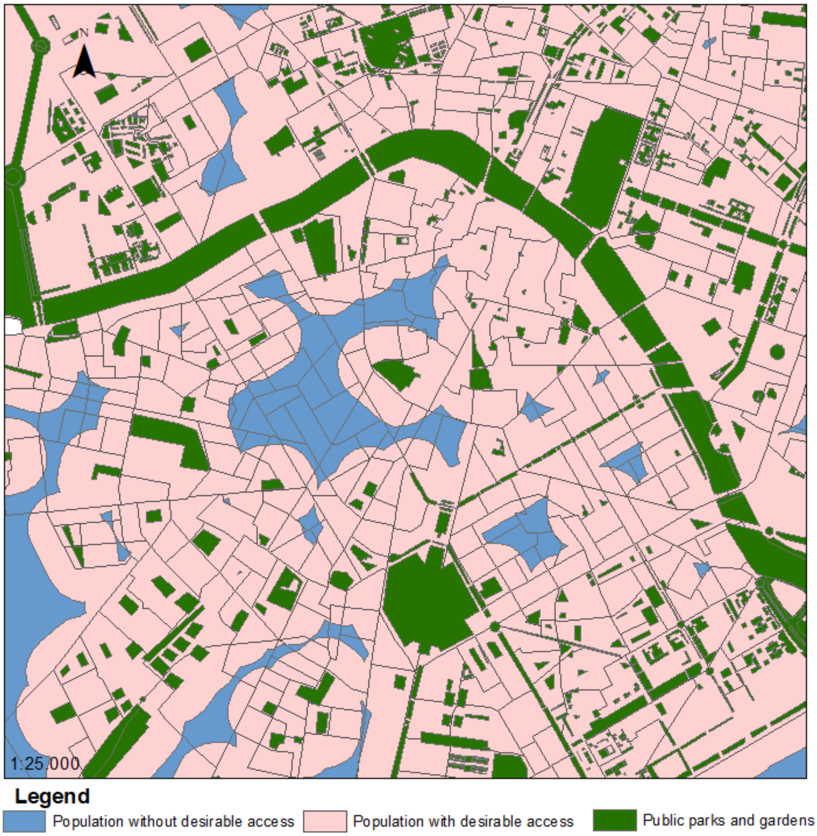

Figure 44. Population without desirable access to GUA in the city of Valencia. Zoom detail of southwest area of the city.

9.3.1.2 Population without easy walking distance access

The application of second indicator to evaluate the contribution of GUA to the achievement of SDG 11 can be observed in Figure 45. In Figure 45, the purple area represents the area with easy walking distance access to a GUA and the pink area represents the area without easy walking distance access to GUA. Thus, the analysis of these results shows a total of 20,885 citizens without easy walking distance (PWEW). This supposes 2.73% of the total population of Valencia city. Most of the population without easy walking distance access to GUA is located in the south of the city. Nevertheless, compared with other municipalities of Spain, the city of Valencia has less population without easy walking distance access to GUA than e.g. Madrid (14.41% PWEW), Barcelona (17.6% PWEW) or Bilbao (10.26% PWEW) according to the results of Sánchez et al. (2018). However, these results are very sensitive to assumptions made to apply the methodology. For example, the speed of walking or even the layout of the streets have a significant influence on the results. Thus, Sánchez et al. (2018) obtained a result of 26.69% without easy walking distance access in the municipality of Valencia instead of the 2.73% that we have obtained. One of the reasons is also due to the fact that we have applied the indicator to the city of Valencia, excluding the outside neighbourhoods of the North and South of districts “Poblats del Nord” and “Poblats del Sur” respectively for being far away of the urban area and close to natural areas (beaches or forests). Nevertheless, the districts excluded represent less than 3% of Valencia municipality population. Thus, in our case, the differences observed regarding Sánchez et al. (2018) results are due to the assumption made in terms of speed of walking and the specific application of the methodology (for example the road streets characteristics or the location of entrances to the park that determine the length of the journey by foot).

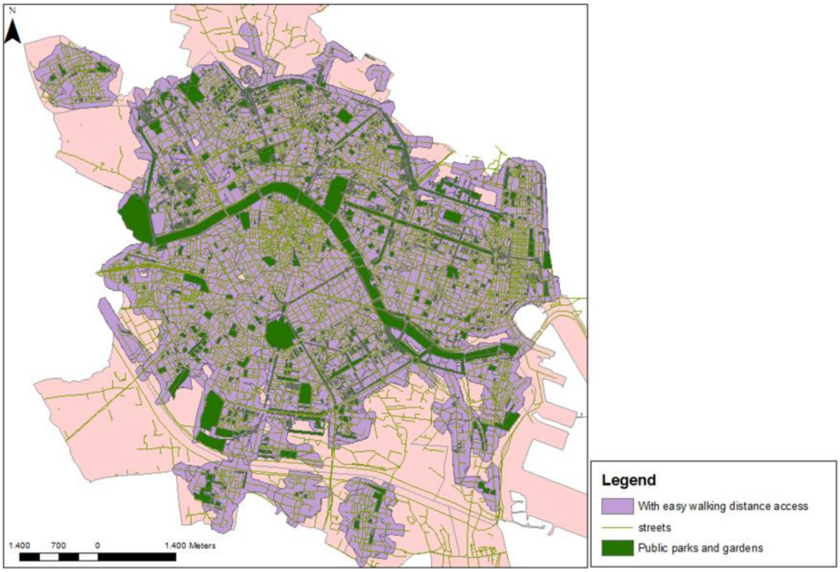

Figure 45. Population with easy walking distance access to GUA in the city of Valencia.

Figure 46 shows the result of the application of the same indicator, but more restrictive as people without easier walking distance access. This indicator calculates the easier walking distance access considering 5 minutes of walking time. In Figure 46, purple area shows the area with easier walking distance access calculated by criteria described in section 9.2.2.2 and pink area represent the zones of the city where people do not have easier walking distance access. The result shows a total of 154,062 citizens without easier walking distance access that suppose the 20.17% of the population of Valencia city. The zone with worst results is again the southwest area of the city where the neighbourhoods of the districts of Patraix, Ciutat Vella and Extramurs are located. In this area of the city, two factors occur at the same time that justify this poor result, it is an area with few nearby GUA and also has a high population density. Some of the city centre neighbourhoods apparently close to GUA appear as "without easier walking distance access". This is because the influence buffer depends as much on road streets characteristics as the location of the entrances to the specific GUA polygons. Therefore, some large GUA polygons with the entrance located in a part of the polygon, just going around the polygon or following the route described by the road streets layer to the entrance can suppose more than 5 minutes of walking time. This means that some areas of the centre near large GUA have been considered as “Without easier walking distance access”.

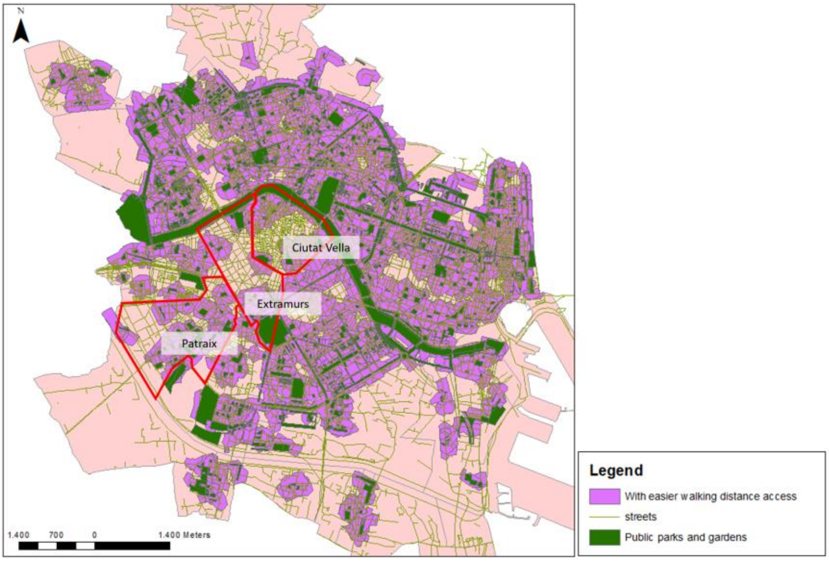

Figure 46. Population with easier walking distance access to GUA in the city of Valencia.

9.3.2 Contribution of GUA to achieve SDG 13 “Climate action”

The 901 GUA with available data in Valencia fix 812,230 kg CO_2 eq. annually. The results are shown in Figure 47, which represent the carbon fixation of each GUA. The maximum amount of CO_2 eq. fixed is 49,505 kg CO_2 eq. and correspond to the park “Jardines del Real Viveros”. There are also polygons with low carbon fixation due to contain very little vegetation or the presence of non-arboreal or shrub vegetation, which is not quantified in this study (such as meadows).

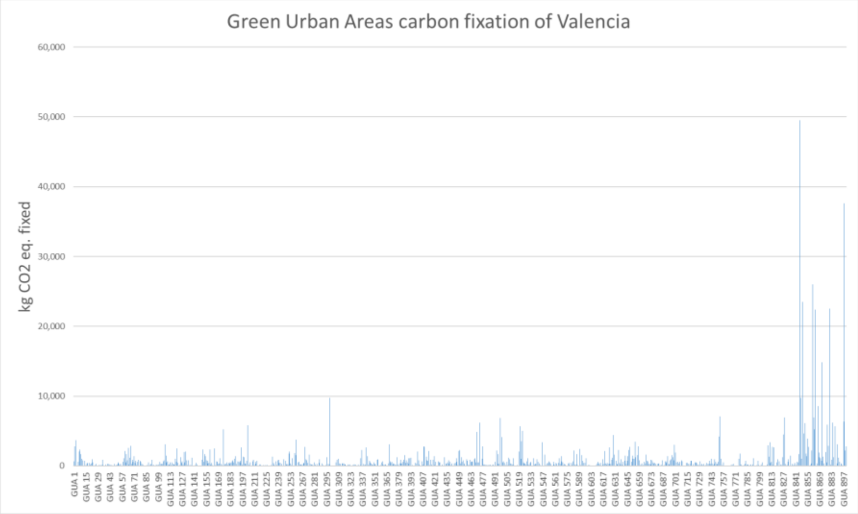

Figure 47. Carbon fixation per GUA of the city of Valencia.

The geolocation of public parks and gardens and its importance as carbon sinks, can be observed in Figure 48. As can be seen, the biggest carbon sinks green urban areas are in a linear green infrastructure that crosses the city from east to west through the centre. This linear green infrastructure offers a strategic location that allows most areas of the city to have good access to GUA.

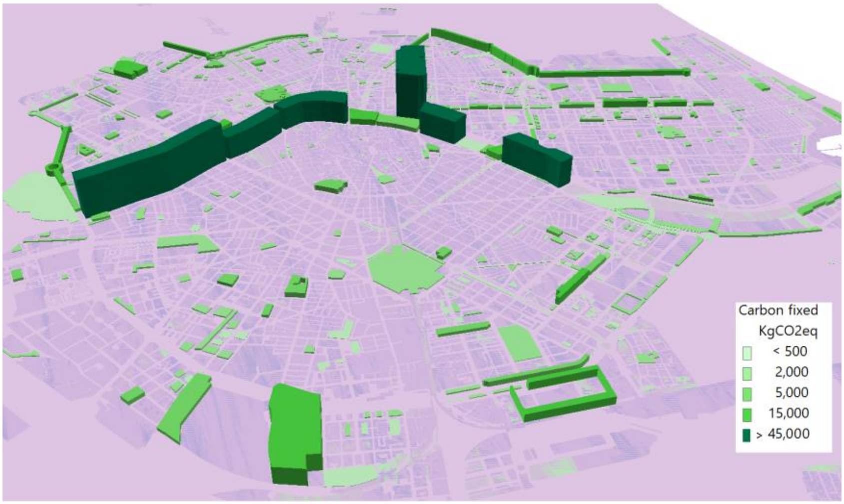

Figure 48. Location of GUA with extrusion proportional to their fixed carbon value of the city of Valencia.

We have to consider that the results obtained correspond to the quantification of CO_2 eq. fixed only by public parks and gardens. Thus, the CO_2 eq. fixation of the vegetation of the individual trees in pits on sidewalks of some streets as well as private parks and gardens are outside this quantification. However, the monitoring of this indicator allows evaluating it annually to check and monitor its evolution. Despite this, we have compared this result with the city of Torrent (Spain), which is smaller city in the same region (Torrent has 69.32 km2, and Valencia has 134.6 km2). Thus, Ajuntament de Torrent (2015) quantified a CO_2 sequestration of 590 tCO_2/year by GUA. The carbon fixation of the GUA of Torrent is equivalent to 0.18% of its gross emissions according to its Sustainable Energy Action Plan (Ajuntament de Torrent 2015). In Valencia, however, the total CO_2 fixation quantified is equivalent to 0.04% of total gross GHG emissions according to the Sustainable Energy and Climate Action Plan (Ayuntamiento de València 2019). Sustainable Energy Action Plan has a common methodology that allows us to compare objectively two cities of very different sizes. Thus, the Valencia's assessment of the GUA's contribution to SDG 13 “Climate Action” is worse than Torrente's.

9.3.3 Contribution of GUA to achieve SDG 15 “Life and Land”

The contribution of GUA to the achievement of SDG 15 “Life and Land” has been evaluated calculating the green urban area per capita. Thus, the overall result shows 10.03 m^2/inhabitant to the city of Valencia (Figure 49). This result shows that Valencia is slightly above the minimum amount of 9m^2 of green open space per person recommended by WHO (2009).

Valencia surface area of green urban area per capita is above than other Spanish cities such as Sevilla (8.57 m^2 GUA/inhabitant), Barcelona (7.00 m^2 GUA/inhabitant) or Bilbao (9.30 m^2 GUA/inhabitant) evaluated by Sánchez et al. (2018). However, the result of Valencia is far below others such as Madrid (20.9 m^2 GUA/inhabitant), Córdoba (34.01 m^2 GUA/inhabitant), Cartagena (24.42 m^2 GUA/inhabitant) or San Sebastián (39.72 m^2 GUA/inhabitant) according to the same author.

In comparison to other cities in Europe, EGCA (2013) reports 57 m^2 GUA/inhabitant for Nantes and 18.85 m^2 GUA/inhabitant for Amsterdam, 22.73 m^2 GUA/inhabitant for Berlin, 19.23 m^2 GUA/inhabitant for London, 13.61 m^2 GUA/inhabitant for Roma and 7.6 m^2 GUA/inhabitant for Athens according to Maes et al. (2019). Valencia is above the average value obtained for European Southern countries of 4.84 m^2 GUA/inhabitant according to Kabisch et al. (2016) but below the European average value of 18.2m^2 of publicly accessible green space per inhabitant (Maes et al. 2019). On a worldwide level, Geotab (2019) reports 13.14 m^2 GUA/inhabitant for New York, 21.52 m^2 GUA/inhabitant for New Dehli (Ramaiah and Avtar 2019) and 1.13 m^2 GUA/inhabitant for Marrakech (Bounoua et al. 2020). So, we can consider that the results obtained for Valencia are in medium range in comparison with other large cities.

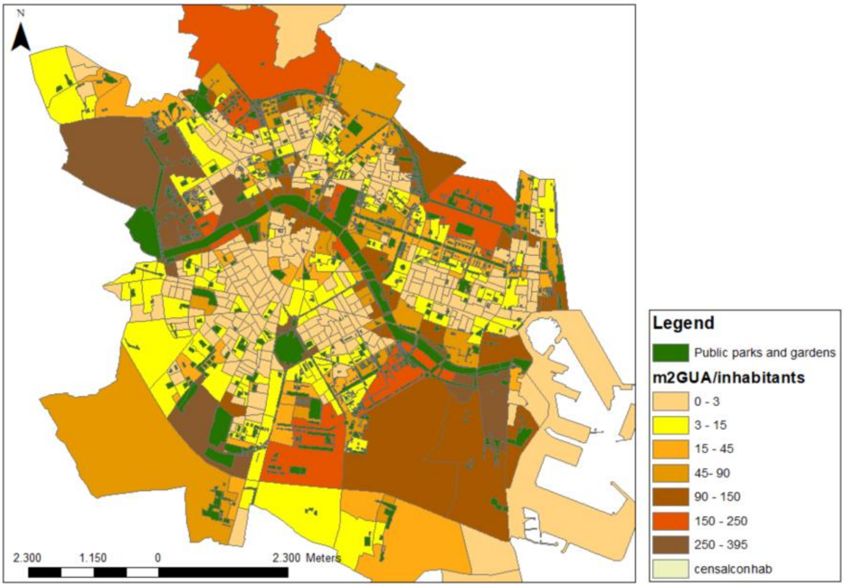

Figure 49. Green urban area per capita in each census section of the city of Valencia.

In addition, the green urban area per capita has been calculated in each census section (Figure 49) to evaluate the sustainable development equity, regarding GUA per inhabitant, between the different zones of the city. Thus, the worst results correspond to the neighbourhoods of the districts of Patraix, Ciutat Vella and Extramurs, like the results of the evaluation of SDG 11 obtained in the section 9.3.1.1. Nevertheless, in this indicator the neighbourhoods of the district of Eixample present also very bad results, as can be observed in a detailed view in Figure 50.

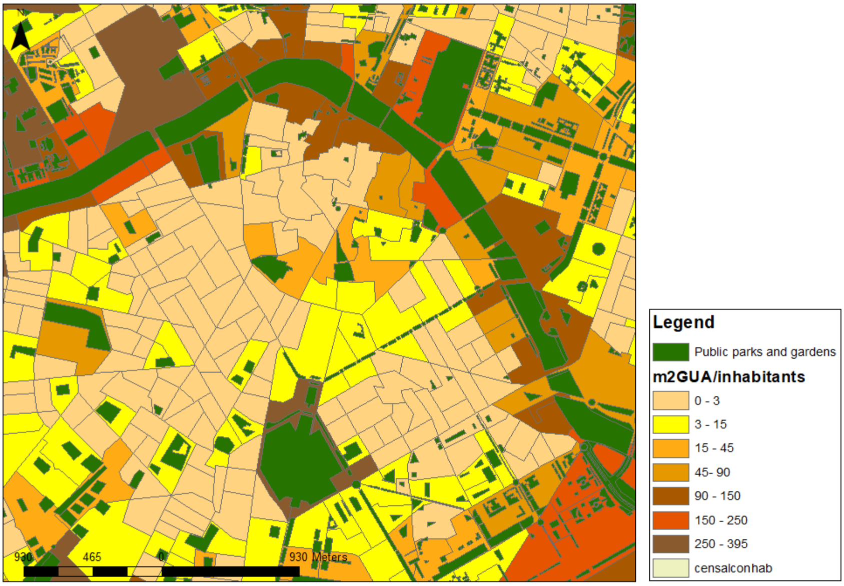

Figure 50. Green urban area (GUA in m^2) per capita (inhabitants) in each zone (divided by census section) of the city of Valencia. Zoom detail of southwest and south centre area of the city.

Finally, the results of the GUAs' contribution to the achievement of SDG11, SDG15 and SDG13 at the sub-neighbourhood level show that equitable sustainable development must simultaneously ensure that the GUA have adequate location, size, quantity and quality (quantity and type of vegetation). Therefore, proper planning of GUAs in cities must take into account all these factors in order to have equitable sustainable development among all areas of the city.

9.4 Conclusions

The contribution of public green urban areas (GUA) to the achievement of three Sustainable Development Goals (SDGs) and the sustainable development equity between 606 different zones have been evaluated in a case study in the city of Valencia (Spain). Specifically, the SDG 11 “Sustainable Cities and Communities”, SDG 13 “Climate Action” and SDG 15 “Life on Land” have been analysed and evaluate with a Geographic Information System (GIS). For this, four different indicators have been applied in the 606 areas into which the city has been divided. The evaluation of SDG 11 “Sustainable Cities and Communities” offers a result of 9.23% of the citizens with difficult access to GUA and 2.73% without easy walking distance access. However, applying a more restrictive criterion to the indicator described as population without easy walking distance access, which quantifies the distance based on 5 minutes walking time instead of 10 minutes, the result worsens to a total of 20.17% of the population without easier walking distance access. The GIS analysis has allowed to identify the least equitable zone of the city with the worst results. Thus, the southwest zone of the city has obtained the worst results due to two causes overlapped, on the one hand the low number of GUA and on the other hand the high population density. Consequently, the methodology designed and applied and the results obtained show that future green infrastructure expansion programs should focus on these less favoured areas of the city, in order to comply with this SDG ensuring equity between the different areas of the city, specifically in the application of the Urban 2030 Agenda for a sustainable city. Moreover, the calculation methodology for the two indicators that have been defined and applied to assess the influence of GUA on SDG 11 can be considered as very appropriate and easy to apply for their follow-up and monitoring in a Smart City platform. However, these indicators need to be improved, for example by fine-tuning the age groups (elderly people and children) as well as disabled people. Currently, our research group is working on the integration of these data to refine the indicators, in order to obtain models and practical solutions for the better access of these groups to the GUA, as well as to facilitate decision-making by local administrations in urban, environmental and social planning of the GUA in cities.

The contribution of GUA to SDG 13 “Climate Action” has been evaluated calculating the carbon fixed by public GUA. The result shows that carbon fixed by GUA is equivalent to 0.04% of total gross GHG emissions of the city. The spatial resolution of the calculation allows identify the parks and gardens that most contribute to mitigate climate change. Thus, in the case of the city of Valencia, the main urban carbon sink is located in a large linear green infrastructure that crosses the city from east to west through the centre. The location of this large green infrastructure has proven to be strategic, not only for the achievement of this SDG but also of the other SDGs evaluated. However, it is important to note that the structure of each type of park or garden significantly influences the carbon fixation capacity of the vegetation that composes it. Thus, young trees and shrubs are capable of absorbing more carbon due to their rapid growth, while mature trees are already declining in their growth and, consequently, in their fixing capacity. It must also be taken into account that meadows or grasslands do not have a significant capacity for carbon fixation. Therefore, we consider that this is another factor to take into account when planning the green infrastructure of cities. With all this, after this research we can affirm that the methodology designed and applied allows us to obtain an indicator of the contribution of GUA to the mitigation of Climate Change through carbon fixation that is easy to record, evaluate and monitor, also for inclusion in a Smart City platform. However, in order to improve the accuracy of this indicator, our research group is refining this indicator by including both the linear trees in the sidewalk pits and also by introducing the emissions derived from the cultural treatments of the GUA (fuel consumption for tillage machinery and soil improvement, nutrient contributions through fertilization, pruning, final felling, irrigation facilities, etc.) in the calculation of net carbon fixation.

The evaluation of SDG 15 “Life and Land” by applying the indicator of green urban area per inhabitant offers a result of 10 m^2 GUA per inhabitant. This result places Valencia in a medium/low level in comparison with other large cities in Spain, and in a medium range level in comparison with other large cities in Europe or even worldwide. After the investigation, it can be concluded that the methodology designed and applied allows evaluate the sustainable development equity of the different zones of the city thanks to obtaining results with high spatial resolution. Thus, the results of this indicator make it possible to identify with very high precision the areas, neighbourhoods and districts where GUA are clearly insufficient for the well-being and health of citizens. Therefore, this indicator is key for planning future green infrastructures in cities.

In the case study of the city of Valencia, after the evaluation carried out, we can conclude that the GUA that exist today sufficiently fulfil their environmental and social functions in terms of accessibility and quantity and quality of green urban areas close to citizens. Regarding the applicability of the methodology, we can conclude that the four indicators defined and applied are very appropriate for evaluating the contribution of GUA to the three SDGs analysed. They are therefore quantitative indicators, easy to understand and interpret by citizens and their public decision-makers, with a clear methodology, with sufficient spatial and temporal resolution, and easy to monitor and include in a Smart City platform. They are, therefore, key indicators for planning a sustainable city and for the fulfilment of a Sustainable Urban Agenda 2030 in an equitable way between all areas of the city. Finally, the inclusion of additional parameters related e.g. to the age structure of citizenship, typology of accessibility difficulties due to disabilities, more accurate information on structure and composition of parks and gardens and their cultural treatments, will allow us to further refine the calculation, measurement, evaluation and monitoring of these indicators and their degree of compliance with the SDGs in cities.

10 CONCLUSIONES

El diseño de la investigación y el análisis de los resultados obtenidos en esta tesis han fluido en el desarrollo de una herramienta integral de gestión de gases de efecto invernadero (GEI) para la toma de decisión contra el cambio climático a nivel regional y local. Para ello se ha desarrollado un sistema informático basado en agentes para poder sistematizar y digitalizar las metodologías desarrolladas a fin de poder aprovechar al máximo el potencial que ofrecen las Tecnologías de la Información y las Comunicaciones (TIC), concretamente la tecnología *Big Data*. Finalmente, la herramienta se ha implementado a diferentes escalas, sobre sectores clave como son el sector edificación, el sector transporte y el sector forestal y parques y jardines urbanos.

Así, tras evaluar y discutir los resultados obtenidos en la totalidad de la investigación, se pueden extraer las siguientes conclusiones:

1. El sistema de información territorial y sectorial desarrollado (SITE) para el seguimiento de las emisiones de GEI es válido como herramienta de gobernanza climática local y regional. Este sistema permite integrar los enfoques descendente y ascendente (o *top-down* y *bottom-up*) con un enfoque híbrido innovador que permite cuantificar las emisiones de GEI de todos los indicadores del municipio de manera eficiente, con un alcance completo y asegurando la estandarización con las métricas e indicadores del Panel Intergubernamental de Cambio Climático. La implementación del sistema desarrollado a la Comunitat Valenciana ha permitido priorizar los indicadores de emisión para optimizar y adaptar al contexto local las estrategias y planes de acción regionales y locales contra el cambio climático, identificando los focos de emisión más relevantes de cada territorio para invertir los recursos disponibles en aquellas las medidas de mitigación que resultan más eficientes. De este modo, SITE ha permitido cuantificar las emisiones de GEI de un total de 162 indicadores en toda la región (aproximadamente 5 millones de habitantes distribuidos en 542 municipios). Además, la distribución territorial de las

emisiones ha permitido identificar que tan solo 10 municipios (1.8%) emiten el 34.45% del total de emisiones brutas y que el 34% de los municipios de la región (185 municipios) se comportan como sumideros netos de carbono al fijar más GEI de los que emiten, y su ubicación es principalmente el interior de la región. Esta distribución territorial desequilibrada de emisiones y sumideros de carbono es muy representativa para varias regiones de Europa, especialmente en los países mediterráneos, donde la actividad socioeconómica se concentra principalmente en la costa o en grandes áreas urbanas.

Por otro lado, la distribución sectorial de las emisiones ha permitido identificar que el 20% de los indicadores cuantificados son responsables del 85% del total de las emisiones y también ha identificado aquellos indicadores que se repiten dentro de los 10 indicadores más emisores en el mayor número de municipios de la región analizada. Esta información es valiosa para la gobernanza climática regional ya que permite planificar una estrategia regional colaborativa contra el cambio climático, pero atendiendo las necesidades de cada ciudad o municipio en particular. Finalmente, la implementación del enfoque metodológico híbrido ha mejorado la precisión de la cuantificación de las emisiones de GEI de dos indicadores relevantes y muy importantes (“Quema de combustible en el sector residencial” y “Emisiones derivadas del consumo eléctrico en el sector residencial”). de los municipios de la región del estudio de caso con variables atributivas disponibles (aprox. 50% del total de municipios). Esto demuestra que SITE permite desarrollar una estrategia colaborativa de cuantificación de emisiones de GEI a nivel regional para optimizar al máximo los recursos disponibles.

2. La estructura informática que da soporte a esta herramienta de gestión de emisiones a nivel local se basa en agentes lo cual permite aprovechar al máximo el potencial que ofrecen las Tecnologías de la Información y las Comunicaciones (TIC) y el Big Data. Este sistema permite digitalizar y sistematizar los procesos de recopilación de datos, tratamiento de datos y almacenamiento de la información de manera que pueda

automatizarse las metodologías desarrolladas descritas en el capítulo uno, así como las metodologías específicas de los sectores edificación, transporte y sector forestal y áreas verdes urbanas que se desarrollan en los capítulos 3, 4, 5 y 6. Con este análisis y evaluación sistemáticos, la herramienta posibilita los procesos de toma de decisiones sobre las acciones más eficientes contra el cambio climático. El sistema informático propuesto permite una constante mejora a partir de resultados de las diferentes aplicaciones descritas. Además, gracias a la estandarización seguida en la estructura del inventario de emisiones seguida en base a la propuesta por el IPCC, la implementación de la herramienta es escalable y extrapolable a otras ciudades y regiones, así como a otros países.

3. La primera aplicación sobre el sector edificación, ha permitido implementar una metodología basada en un sistema de información geográfica (SIG) para mapear no solo las emisiones de GEI de los edificios, sino también el consumo de energía primaria. La alta resolución espacial de la metodología desarrollada permite apoyar a la toma de decisión contra el cambio climático a escala distrital o de edificio. De esta manera, las autoridades locales y los tomadores de decisiones públicos pueden identificar los edificios o distritos con mayores emisiones de GEI y, en consecuencia, enfocar sus esfuerzos y recursos para mitigar estas emisiones con un alto nivel de eficiencia. Su implementación sobre una ciudad piloto representativa de tamaño medio (Quart de Poblet, Comunitat Valenciana) ha permitido integrar una gran cantidad de datos heterogéneos (bases de datos locales, catastro nacional, bases de datos externas y auditorías energéticas propias) para lograr cuantificar las emisiones de GEI y el consumo de energía primaria de sus edificios con un buen nivel de representatividad de la ciudad. Finalmente, el modelo de datos desarrollado ha sido adaptado a la directiva Europea INSPIRE integrando datos alfanuméricos y geográficos para garantizar la interoperabilidad y por tanto la replicación y extrapolación a otras ciudades de la Unión Europea.

4. La segunda aplicación de la herramienta sobre el sector transporte rodado, ha permitido implementar una metodología *bottom-up* para cuantificar las emisiones de GEI del tráfico urbano con alta resolución espacial y temporal. En este caso, la metodología desarrollada ha permitido mejorar el estado del arte utilizando los datos de los sistemas de monitoreo de tráfico (espiras electromagnéticas) combinados con los métodos de Kilómetros de Vehículo Recorridos (VKT) reconocidos por el Panel Intergubernamental sobre Cambio Climático (IPCC) para poder llevar a cabo una cuantificación de emisiones de GEI a escala de tramo o calle urbana. La implementación de la metodología desarrollada ha demostrado tener gran potencial de ayuda en la toma de decisión contra el cambio climático. En primer lugar, ha permitido identificar puntos calientes donde se den grandes cantidades de emisión en la ciudad y poder así optimizar estas ubicaciones para reducir las emisiones con gran eficiencia. Además, la resolución temporal ha permitido detectar patrones de emisión que se pueden utilizar para desarrollar o modificar las políticas y regulaciones de la ciudad, así como para realizar un seguimiento cuantitativo, objetivo y transparente, sobre el impacto de medidas de mitigación de emisiones que afecten al tráfico de la ciudad.

   Finalmente, el modelo desarrollado permite la posibilidad de despliegue de nuevas tecnologías en la gestión del tráfico (espiras electromagnéticas dobles, cámaras de reconocimiento de vehículos, etc.) que haría posible monitorear las emisiones con mayor precisión, individualizando la categoría de vehículos que circulan en cada tramo o calle, o incluso parámetros de su cinemática (velocidad, aceleración y paradas). Su inclusión, ofrecería aún mayor potencial a la hora de realizar análisis de sensibilidad sobre estos parámetros para simular como variarían las emisiones específicas del municipio ante la reducción de la velocidad máxima, la disminución del número de paradas o la variación en la composición del parque móvil circulante.
5. La tercera aplicación de la herramienta ha permitido analizar el potencial forestal mediterráneo para compensar emisiones GEI

a nivel regional con resolución a nivel local. Esto ha sido posible gracias a la cuantificación de la fijación de carbono en biomasa vegetal viva realizada en el sector forestal. La metodología aplicada ha permitido cuantificar las emisiones fijadas al año y el stock de carbono almacenado en cada parcela forestal de la región. Además, se ha desarrollado y aplicado una metodología para valorizar la fijación de CO_2 por los bosques con un nuevo enfoque adaptado a las condiciones mediterráneas, que tiene en cuenta las emisiones antropogénicas evitadas por la gestión forestal sostenible para la prevención activa de incendios forestales. Su implementación ha permitido generar un escenario simulado para calcular los créditos de carbono generados calculando la reducción de emisiones de GEI derivadas de incendios forestales que podrían evitarse mediante tareas silvícolas. La aplicación de esta metodología al caso de estudio de la Comunitat Valenciana ha permitido estimar un potencial total de 1.65 millones de créditos de carbono (en t CO_2 eq.) al año. Gracias a la implementación del sistema desarrollado en el Capítulo 1 de esta tesis, sabemos que esto equivale al 5.5% del total de emisiones brutas al año de la Comunitat.

6. Finalmente, la aplicación simplificada de la metodología implementada en el Capítulo 5 de esta tesis, ha servido como indicador de la contribución directa y específica de las Áreas Verdes Urbanas (AVU) a la consecución del Objetivo de Desarrollo Sostenible 13 "Acción Climática". La herramienta ha permitido cuantificar la fijación anual de los 901 polígonos de AVU de la aplicación piloto en la ciudad de Valencia. La resolución espacial obtenida ha permitido identificar las AVU que más contribuyen a mitigar el cambio climático, así como identificar las zonas con mayor potencial de mejora. La metodología aplicada ha permitido monitorear y evaluar un indicador de la contribución de las AVU a la mitigación del cambio climático. Esta información pretende ayudar a los tomadores de decisión local a la hora de planificar la infraestructura verde de las ciudades.

Como conclusión general de la investigación, la herramienta desarrollada ha demostrado ser de gran ayuda para la toma de decisión contra el cambio climático a nivel regional y local ya que permite optimizar los recursos disponibles tanto para la monitorización como a incrementar la eficiencia de las medidas a adoptar para la mitigación de las emisiones GEI. Las diferentes implementaciones tanto a nivel regional en la Comunitat Valenciana como a nivel local en municipios grandes (València) y medianos (Quart de Poblet y Llíria) han demostrado el potencial de adaptación territorial y sectorial que tiene la herramienta. Las metodologías desarrolladas para los sectores específicos de tráfico rodado, edificación o forestal, ofrecen una resolución espacial con gran capacidad de optimizar las políticas locales. Por tanto, la herramienta cuenta con un gran potencial de escalabilidad y gran capacidad de mejora continua mediante la inclusión de nuevos enfoques metodológicos, adaptación de las metodologías a la disponibilidad de datos, metodologías concretas para sectores clave, y actualización a las mejores metodologías disponibles en la comunidad científica.

11 TRANSFERENCIA DE LOS RESULTADOS DE LA INVESTIGACIÓN

11.1 Publicaciones científicas de impacto

Como principales resultados de transferencia del conocimiento adquirido en la presente Tesis Doctoral, cabe destacar que se han presentado tres artículos científicos y un capítulo de libro como primer autor y un artículo científico como segundo autor que han sido publicados en revistas indexadas por el Journal Citation Report (JCR).

Los artículos científicos son:

1) Lorenzo-Sáez, Edgar; Oliver Villanueva, José Vicente; Coll-Aliaga, Eloína; Lemus Zúñiga, Lenin Guillermo; Lerma Arce, Victoria and Reig Fabado, Antonio (2020). Energy efficiency and GHG emissions mapping of buildings for decision-making processes against climate change at local level. *Sustainability*, 7 (12), 1 - 17. https://doi.org/10.3390/su12072982

2) Lorenzo-Sáez, Edgar; Oliver Villanueva, José Vicente; Lemus Zúñiga, Lenin Guillermo; Urchueguía Schölzel, Javier Fermín and Lerma Arce, Victoria (2022). Development of sectorial and territorial information system to monitor GHG emissions as local and regional climate governance tool: case study in Valencia (Spain), *Urban Climate*, Volume 42, ISSN 2212-0955, https://doi.org/10.1016/j.uclim.2022.101125.

3) Mateo Pla, Miguel Ángel; Lorenzo-Sáez, Edgar; Luzuriaga, Jorge E.; Mira Prats, Santiago; Moreno-Perez, Juan-Antonio; Urchueguía Schölzel, Javier Fermín; Oliver Villanueva, José Vicente and Lemus Zúñiga, Lenin Guillermo (2021). From traffic data to GHG emissions: a novel bottom-up methodology and its application to Valencia city. *Sustainable Cities and Society*, 12643 (66). https://doi.org/10.1016/j.scs.2020.102643

4) Lorenzo-Sáez, Edgar; Oliver Villanueva, José Vicente; Lerma-Arce, Victoria; Yagüe-Hurtado, Celia and Lemus Zúñiga, Lenin Guillermo (2021). Potential Analysis of Mediterranean Forestry for Offsetting GHG Emissions at Regional Level: Evidence from Valencia, Spain. *Sustainability*, 8 (13), 4168. https://doi.org/10.3390/su13084168

5) Lorenzo-Sáez, Edgar, Oliver-Villanueva, José-Vicente., Luzuriaga, Jorge Eloy, Mateo Pla, Miguel Ángel, Urchueguía, Javier F. and Lemus-Zúñiga, Lenin G. (2019). A Cooperative Agent-Based Management Tool Proposal to Quantify GHG Emissions at Local Level. In: Jezic G., Chen-Burger YH., Howlett R., Jain L., Vlacic L., Šperka R. (eds) Agents and Multi-Agent Systems: Technologies and Applications 2018. KES-AMSTA-18 2018. Smart Innovation, Systems and Technologies, vol 96. Springer, Cham. https://doi.org/10.1007/978-3-319-92031-3_24

6) Lorenzo-Sáez, Edgar; Lerma-Arce, Victoria; Coll-Aliaga, Eloina and Oliver Villanueva, José Vicente (2021). Contribution of green urban areas to the achievement of SDGs. Case study in Valencia (Spain). *Ecological Indicators*, 131, 108246, ISSN 1470-160X, https://doi.org/10.1016/j.ecolind.2021.108246.

11.2 Comunicaciones en congresos científicos

Otros resultados de transferencia del conocimiento adquirido son las comunicaciones en congresos científicos tanto nacionales como internacionales, que son:

1) Lorenzo-Sáez, Edgar; Oliver Villanueva, José Vicente; Lemus Zúñiga, Lenin Guillermo; Urchueguía Schölzel, Javier Fermín; Luzuriaga, Jorge E.; Brunet-Navarro, Pau (2018). CMI-SimBioTIC: herramienta avanzada para Llíria como Smart City

frente al Cambio Climático. EN Small & Medium Smart Cities Congress 2018. (20 - 31). Alcoi, Spain: Universitat Politècnica de València.

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cambio climático. (147 - 148). Calp, Spain: Universitat de València.

11.3 Participación en Seminarios y Jornadas de Transferencia

Además de las comunicaciones en congresos científicos, los resultados que se ha ido obteniendo durante el desarrollo de la tesis ha sido también presentados en los siguientes seminarios y jornadas:

1) Participación en calidad de ponente en el seminario de investigación “Gestión, aprovechamiento y uso de la biomasa forestal” celebrado en Cámara de Comercio de Valencia, el 20 de diciembre de 2017. Título de la ponencia “Bioenergía forestal: Gestión Integral de las emisiones”. Interreg Med Project ForBioEnergy.

2) Participación en calidad de ponente en el seminario de transferencia de conocimiento “Evaluación de oportunidades y beneficios del aprovechamiento de biomasa forestal” celebrado en Universitat Politècnica de València, el 13 de abril de 2018. Título de la ponencia “Herramientas TIC interactivas en el cambio de la bioenergía forestal y la mitigación del cambio climático”. Interreg Med Project ForBioEnergy.

3) Participación en calidad de ponente en el seminario de transferencia de conocimiento “Planificación de la biomasa con fines energéticos” celebrado el 22 de febrero de 2019. Título de la ponencia “Herramienta de gestión de las emisiones de Gases de Efecto Invernadero (GEI) como Smart City frente al Cambio Climático”. Interreg Med Project ForBioEnergy.

4) Participación en calidad de ponente en la I Conferencia sobre Transición Energética, Digitalización y Cambio Climatico de la Cátedra de Transición Energética de la Generalitat Valenciana

en la Universitat Politècnica de València, el día 21 de Noviembre de 2019. Título de la ponencia: “Taller Gestión del cambio climático y transición energética a nivel local”.

5) Participación en calidad de ponente la III Jornada de Investigación Universitaria sobre Cambio Climático, el día 29 de Octubre de 2020. Bloque III Acciones transversales para la transición energética. Título de la ponencia: “Sistema de Información Territorial de Emisiones (SITE)”.

6) Participación en calidad de ponente en las Jornadas “PROGRAMA CAPACITACIÓN DOCENTE ENERGÍA DISTRITAL EN CHILE Y EL MUNDO” organizadas por Dirección Sectorial Energía y Sustentabilidad – SEREMI de Energía Maule – INACAP TALCA los días 6 y 7 Octubre de 2021. Título de la ponencia: “Casos prácticos aplicados. Emisiones y sistema territorial para monitorización de emisiones”.

7) Participación en calidad de ponente en las Jornadas “La UPV responde a la misión València Ciutat Neutra” celebradas en la Universitat Politècnica de València los días 7-8 Octubre de 2021. Título de la ponencia: “Reto 2: Emisiones Cero para la ciudad Neutra”.

11.4 Proyectos y transferencia a administraciones públicas y empresas

Durante el desarrollo de la tesis, el doctorando ha participado en los siguientes proyectos de investigación:

1) SimBioTIC. Infraestructura pública avanzada de TIC para la transición y ahorro energéticos en Llíria (València). SimBioTIC es un proyecto integral de la UPV al Ayuntamiento de Llíria con el objetivo general de desarrollar y dotar de herramientas

basadas en las nuevas tecnologías de la información y la comunicación que permitan al municipio de Llíria y a sus ciudadanos luchar contra el cambio climático. 2017-2019.

2) AVI TRUST 2030. Transición Urbana Sostenible utilizando indicadores en conjunto con herramientas de big data para la toma de decisiones. TRUST tiene como objetivo colocar a la Comunidad Valenciana a la vanguardia del conocimiento sobre huella ecológica para la mitigación del cambio climático en el medio urbano y la transición hacia una economía sostenible a nivel nacional y europeo. 2018.

3) EU Interreg Sudoe REMAS (SOE3 / P4 / E0954) Gestión de riesgos de emisiones de GEI en incendios forestales. 2019-2022.

4) EIT Climate KIC VALVOLCAR. VALencia VOLuntary CARbon market. Objetivo: analizar las posibilidades de la creación del primer mercado voluntario de carbono de la Comunidad Valenciana, permitiendo a las empresas compensar sus emisiones a través de acciones que reviertan positivamente en el medioambiente. 2019

5) Investigación en Extinción de Incendios Forestales. Año 2021. Consultorías, estudios técnicos y asesoramiento. AGENCIA VALENCIANA DE SEGURIDAD Y RESPUESTA A EMERGENCIAS.

Finalmente, las metodologías y modelos matemáticos desarrollados en esta tesis doctoral se han transferido a la empresa GEMINIS Tools S.L. mediante un convenio de colaboración entre el grupo de investigación ICTvsCC del instituto ITACA de la UPV y la empresa para el desarrollo de un software de gestión de emisiones.

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