# Modelling Actions at the Building Stock Level for Decision-Making Towards Carbon-Neutral Cities

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## Abstract

The building sector plays a major role in terms of energy consumption and consequently carbon emissions in a city. In a typical European city, the share of $CO_2$ related to this sector is around 40-50%, being the most impacting one. In this context, characterised by high complexity, it is necessary to develop manageable, science-based models that policymakers can use to design and simulate the impact of feasible decarbonisation actions over space and time.

This paper presents a simulation platform capable of modelling actions for city decarbonization, particularly focusing on the building sector. Each action is modelled in terms of primary energy exploitation (type and quantity) and its impacts on energy consumption and emissions using a tailored set of metrics. This involves considering the unique characteristics and challenges of the city, such as its existing infrastructure, building stock, energy sources, and policy context.

The proposed approach is applied to a real European city to demonstrate its feasibility and assess its effectiveness in achieving emissions reduction targets. The results provide effective support to the municipality in setting up the city action plan towards climate neutrality.

## 1. Introduction

Climate change is a global problem, but attention should be focused on the city context. Despite occupying only 2% of the Earth's surface, cities are responsible for more than 70% of global emissions and consume 2/3 of global energy (Zapata Arango et al., 2024; Hoornweg et al., 2020). Additionally, they offer a favourable context for implementing targeted actions, leading to significant results, not only in emission reductions, but also in air pollution, biodiversity loss, and energy poverty reduction. Scaling down further, the building sector alone is responsible for 37% of global $CO_2$ emissions and 34% of energy demand. This creates an urgent need to decarbonize and improve the energy performance of the urban built environment (Hoornweg et al., 2020) searching for cost-optimized solutions (Ferrara et al., 2018). This paper proposes a science-based approach to achieving these goals, focusing on the macro-actions needed to make existing buildings near-zero energy buildings (NZEBs) (Ferrara et al., 2015; Jaysawal et al., 2022), considering climate change and creating useful tools for policymakers facing these challenges.

### 1.1 Scope of the Work

This paper aims to present a simulation platform capable of modelling actions for city decarbonization towards carbon neutrality (Anselmo et al., 2023), particularly focusing on actions related to the building sector. This was created in the context of the EU Mission "100 carbon-neutral cities by 2030" (The 100 Climate-Neutral and Smart Cities by 2030, 2024) aiming to support cities in defining their path towards carbon neutrality.

## 2. Materials and Methods

### 2.1 Conception of the Simulation Platform

The primary goal of a city should be to reduce GHG emissions from anthropogenic activities within a

Part of
Pernigotto, G., Ballarini, I., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2025. Building simulation applications BSA 2024. bu,press.
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well-defined city boundary. To achieve this crucial goal, it is essential to have a complete understanding of the starting point, i.e., the emissions produced by the city in a specific year considered as a baseline, and then to define a timeframe to achieve the set targets.

This process implies a thorough analysis of the key sectors within the urban environment that contribute significantly to emissions, enabling the definition of a list of effective "macro-actions" that can guide decision-makers who will then select more specific actions to be implemented, moving from a general to a particular view.

Understanding the impact of these macro-actions is crucial as it helps create emission reduction scenarios that are both reasonable and effective.

To provide real support to policymakers, it is planned to formalise these actions and link them to the "city's ontology" (Fig. 1). The ontology maps the logical relationships between various entities and forms the basis for defining individual actions and all 'what if' analyses. The goals are to:

- Formalise the correlations and interactions between entities in the City;
- Understand how actions generate a change in the state of the city.

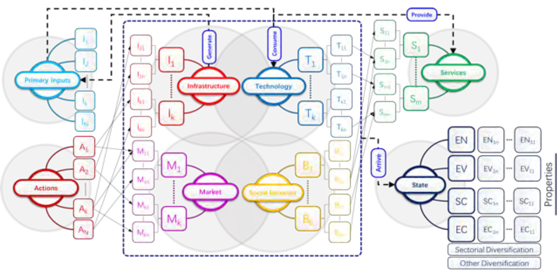

Fig. 1 – Conceptual scheme of the City Ontology, EST Lab

By creating a Python code, accompanied by a formal document specifying all the data, primary and secondary, used and the mathematical approach behind the functions, it will be possible to quantitatively evaluate the impacts of the considered actions. By defining then an "Action Type" and characteristic parameters linked to it through a Json file, it will be possible to establish new, more sectorial and specific actions, linked to the city context (Fig. 2).

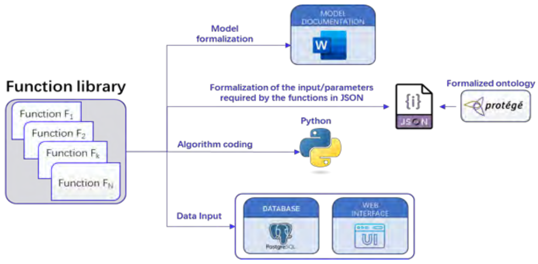


Fig. 2 – Functional scheme of the function libraries

This concept is the foundation of a new interactive simulation platform named CLICC, where various actors in a city can enter the actions that have been conceived, implemented or are underway, leading to a reduction in $CO_2$ emissions and defining a path towards carbon neutrality.

City system data are automatically and systematically organised into an ad hoc data room, based on a data lakehouse architecture, with web crawlers and automatic validation systems.

Furthermore, the platform is particularly useful for monitoring the current situation thanks to an interactive dashboard, which allows users to:

- track the evolution of the city systems with respect to climate neutrality goals;
- monitor the trend of GHG emissions (CO2, N2O, F-gases, SF6 , NF3 , CH4 ), in terms of current value, current target and final target;
- monitor the overall investments, in terms of current value, current target and final target;
- graphically see the evolution of normalised emissions and investment over the whole-time horizon.

Therefore, policy decision-makers can easily understand the evolutionary trajectory of the systems and the potential need for corrective actions to accomplish the final goals.

In addition, an interactive tool supports this by allowing users to explore the city, understand its main peculiarities, and access several georeferenced data. In particular, it permits:

- Exploring each building on a 2D/3D map, obtaining information on the building type, surface area, heating system, solar PV producibility and Energy Performance Certificate (EPC).
- Geolocating all the generation plants (PV, hydro, and traditional non-res) and the city's feeders, primary and secondary substations.

- Exploring the main energy infrastructures of the city (e.g., electricity distribution lines).
- Graphically selecting areas or groups of buildings on the map for simulating specific policy actions.
- Monitoring public and private transport through parameters such as kilometres travelled and fuels used.

The platform also manages financial aspects (time horizon, funder, amount of investment), details ("what" and "where"), co-benefits, and barriers of each action.

All necessary methodologies are included in the platform (Fig. 3), from identifying the baseline inventory of the city's GHG emissions (by type of gas and by sector) to combining actions, identifying relevant time horizons and impacts in terms of GHG reductions compared to the baseline inventory, and including investment details over the time horizon for each action included in the pathway (both in absolute value and as a percentage of the total) and the relevant financiers.

With these tools, the decision-maker can combine the actions inserted in the platform into different scenarios and evaluate the most appropriate one for the city. This decision-making process is complemented by a cost/benefit analysis of these scenarios, considering all possible barriers but also the co-benefits.

Another crucial aspect is the opportunity for citizens to be an integral part of the city's reality, thanks to access to general evolutionary tracking information. In this way, citizens become active participants in the community's growth and development, encouraging a sense of shared responsibility.

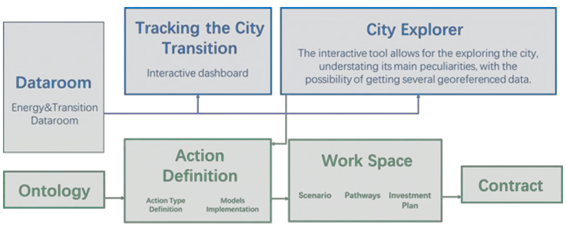


Fig. 3 – Platform scheme

## 2.2 Function Modelling

A function is the formalization and implementation of a model that allows the computation of its outputs for given inputs and parameters (in terms of $CO_{2eq}$ avoided, in general whichever outcome of the action). The functions reported in this paper focus on reducing emissions in the built environment sector.

The first step towards this goal was to select and analyse all implementable actions in the built environment sector, starting with a study based on data provided by the International Energy Agency (IEA), which examined the main sources of $CO_2$ emissions in the life cycle of buildings (Italy 2023, 2023).

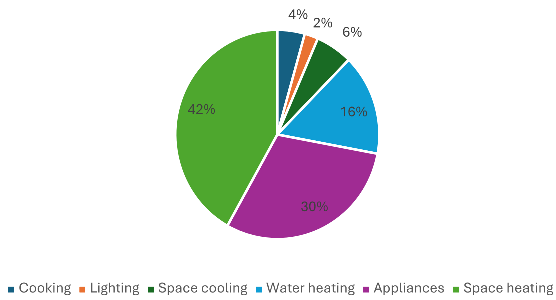


Fig.4 – Emissions of GHG from Building's activities in 2021 (Italy 2023, 2023)

The analysis showed that most $CO_2$ emissions came from the operational use of energy in buildings, including daily activities such as heating, cooling, lighting and using household appliances. In particular, space heating and household appliances are the main emitters.

The first general step, common to all actions, is to create a detailed GHG inventory. This inventory must report all emissions broken down by sector, according to the Global Protocol for Community-Scale GHG Emission Inventories (GPC), complying with the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines (GHG Protocol for Cities, 2024).

In some situations, cities may use direct measurements of GHG emissions (e.g. through the use of continuous emission monitoring systems in power plants), resulting in a highly accurate inventory. However, for most emission sources, cities will have to rely on estimates. In general, a quantity referring to human activity, responsible for the emissions to be estimated, is combined with a coefficient to quantify emissions per unit of activity. The first quantity is called Activity data (AD) while the coefficient is identified as Emission factor (EF), as follows:

$$Emissions = AD \cdot EF[tCO_{2eq}] \quad (1)$$

Therefore, the generic Eq. 1 provides cities with a systematic method for evaluating greenhouse gas emissions. This procedure requires the accurate acquisition and analysis of data on the activity in focus and the detailed implementation of appropriate emission factors.
Based on this, models for the different macro-actions identified for a specific context can be developed, as described below.

### 2.2.1 Increasing The Number Of Connected Users And Optimising The DH Network

This action evaluates the GHG emissions that can be avoided by replacing traditional, fossil-fuelled domestic heating systems with a connection to the district heating network. The environmental benefit comes from switching from multiple heat generation units distributed throughout the municipality to a few centralised combined heat and power generation sites.

$$Vol_{DH_{new}} = Vo\frac{l_{DH_1} * k_{new}}{k_1} \quad (2)$$

Where $k_{new}$ is the percentage of the total volume of buildings connected to district heating and $k_1$ is the percentage of buildings connected in the reference year.
Accordingly, a proportion is also implemented for the calculation of new MWh installed:

$$E_{DH_{new}} = \frac{E_{DH_1} * Vol_{DH_{new}}}{Vol_{DH_1}} \quad (3)$$

If $\Delta E_{DH,S} < E_{DIESEL,S}$ the district heating will be used to connect buildings with an existing diesel heating system, where

$$\Delta E_{DH_S} = E_{DH_{new_S}} - E_{D1_S} \quad (4)$$

So, the reduction of emissions will be:

$$\Delta CO_{2_{DIESEL}} = \Delta E_{dh_s} * (f_{DIESEL}) \quad (5)$$

$$\Delta CO_{2_{Tot}} = \Delta E_{dh_s} * (f_{DIESEL} - f_{DH_{new}}) \quad (6)$$

If $\Delta E_{DH,S} > E_{DIESEL,S}$ the district heating will be also used to connect buildings with an existing natural gas heating system, starting from those in class G and F (the energy provided by district heating will be equally distributed to class G and F - this will be used for following actions).

$$\Delta CO_{2_{GN}} = (\Delta E_{dh_s} - E_{DIESEL}) * (f_{GN_1}) \quad (7)$$

$$\Delta CO_{2_{ToT}} = E_{DIESEL_S} * (f_{DIESEL} - f_{DH_{new}}) + (\Delta E_{dh_s} - E_{DIESEL_S}) * (f_{GN_1} - f_{DH_{new}}) \quad (8)$$

### 2.2.2 Improvement Of Thermal Insulation

The model function evaluates avoidable GHG emissions as a result of improved thermal insulation of buildings. In particular, the function evaluates the difference in emissions that would occur if no improvements were made, and the emissions related to buildings after increasing their energy performance.
When a building carries out this intervention, it makes a jump in energy class. Consumption, and consequently also emissions, are calculated according to the change from a lower to a higher energy class and thus the reduction in average thermal energy as defined by the EPA. First of all, the new area is calculated for each energy class in the final year: the example represents the transition of buildings from class E to class D and the respective reduction in consumption of the next class.
The following equations must be applied separately for the industrial, residential and tertiary sectors.

$$HFA_{CLD,new} = HFA_{CLD,1} + HFA_{CLE} - HFA_{CLD,eff,new} \quad (9)$$

Where $HFA_{CLD,1}$ is the heated floor area of the current class D, $HFA_{CLE}$ is the area of the class E buildings that with the thermal insulation action move to class D, and $HFA_{CLD}$ is the area of the class D buildings that move to class C. These values can be calculated considering a percentage of building for the class that has to be renovated with thermal insulation:

$$HFA_{cl,eff,,new} = k_{Cl} \cdot HFA_{CL,1} \quad (10)$$

With $k_{Cl}$ the percentage of buildings for a class that we want to renovate (from 0 to 100%);(the default values are listed in the tab7: Renovated surfaces by energy class and sector) this calculation has to be done using the same renovation rate for both for buildings with natural gas heating system and for buildings connected to district heating because the specific thermal energy per class is different.

The consumption for each class is obtained as follows (this is an example for class D).

$$E_{th,Cl,D,,1}=Q_{h,D}\cdot HFA_{CL,D,1} \quad (11)$$
$$E_{th,Cl,D,new}=Q_{h,D}\cdot HFA_{CL,D,new} \quad (12)$$

where $Q_{h,D}$ is the average thermal energy, obtained from APE data. The total amount of energy per class is calculated as follow:

$$E_{th_GN_{new}} = \sum E_{th_{Cl_{GN_{new}}}} * x \quad (13)$$
$$E_{th_DH_{new}} = \sum E_{th_{Cl_{new}}} \quad (14)$$
$$E_{th_GN_1} = \sum E_{th_{Cl_{GN_1}}} * x \quad (15)$$
$$E_{th_DH_1} = \sum E_{th_{Cl_{DH_1}}} \quad (16)$$

With $\sum E_{th_{Cl_{GN}}}$ and $\sum E_{th_{Cl_{DH}}}$ respectively the amount of energy consumption for all the classes for the gas-supply buildings and the district heating and χ the scaling factor due to an overestimation of the natural gas emission with the APE compared to the baseline.

For calculating the emissions reduction directly affected due to the action of thermal insulation we calculate the reduction of energy consumption.

$$\Delta E_{th_{GN}} = E_{th_{GN_{new}}} - E_{th_{GN_1}} \quad (17)$$
$$\Delta E_{th_{DH}} = E_{th_{DH_{new}}} - E_{th_{DH_1}} \quad (18)$$

And the reduction of emissions is:

$$\Delta CO_{2_{GN}} = \Delta E_{th_{GN}} * f_{GN_1} \quad (19)$$
$$\Delta CO_{2_{DH}} = \Delta E_{th_{DH}} * f_{DH_1} \quad (20)$$

With $f_{GN}$ and $f_{DH}$ respectively the emission factor of natural gas and district heating.

### 2.2.3 Heat Pumps And PV Installation

The model function estimates the avoidable greenhouse gas emissions as a result of installing heat pumps in buildings. The heated floor area of buildings for an energy class in which we want to install a heat pump is equal to:

$$HFA_{HP_{Cl}} = k_{Cl,HP} * HFA_{GN_{Cl}} \quad (21)$$

With $k_{Cl,HP}$ is the percentage of buildings with natural gas heating systems that we want to replace and $HFA_{GN\_Cl}$ is the floor area for the class of buildings that have a gas heating system. The energy to be supplied by heat pumps is equal to the annual thermal energy demand of the building to which is added that for the production of domestic hot water, and is equal to:

$$E_{nd_{HP_{ClD}}} = HFA_{HP_{ClD}} * EPH_{nd_{ClD}} + HFA_{HP_{ClD}} * EPW_{nd_{ClD}} \quad (22)$$

Where $HFA_{HP,ClD}$ is the floor area of buildings that are installing a heat pump and are upgrading to another class, $EPH_{nd\_ClD}$ is the useful thermal performance index for heating, and $EPW_{nd\_ClD}$ is the useful heat performance index for domestic hot water production.

The new gas consumption will be:

$$E_{th,GN,ClD,new}=E_{th,GN,Cl,D}-E_{th,HP,Cl,D} \quad (23)$$

Where $E_{th,GN,ClD}$ is the thermal consumption of the class equal to:

$$E_{th_{GN_{ClD}}} = Q_{H_{GN_{ClD}}} * HFA_{GN_{ClD}} \quad (24)$$

Where $Q_{H,GN,ClD}$ is the average thermal energy supplied to the heating system for class D, taken as a general example and $HFA_{GN,ClD}$ is the natural gas-heated floor area of the class before the installation of heat pumps.

$$E_{th_{HP_{ClD}}} = \frac{E_{nd_{HP\,ClD}}}{\eta_{imp}} \quad (25)$$

With η_imp the seasonal average efficiency of a gas heating system. However, the installation of the heat pump implies an increase in electricity consumption, which must be evaluated according to the change in class of the building.

$$E_{el,HP_{Cl_{A1}}} = \frac{E_{nd_{HP_{ClD}}}}{COP} \quad (26)$$

With $E_{el,HP,ClA1}$ the new electrical consumption of Class A1 due to heat pumps, COP, coefficient of performance, which represents the efficiency of a heat pump, that is the ratio of heat delivered to the room to be heated to the electrical energy consumed, taken equal to 3.

To calculate the new gas consumption, the total increase in electricity consumption and the total heat energy supplied by the heat pumps, we will sum the gas consumption, the increase in electricity consumption and the heat energy supplied by the heat pumps for all classes.

$$E_{th_{GN_{2030}}} = \sum E_{th_{GN_{Cl_{2030}}}} \quad (27)$$

$$E_{el_{HP_{new}}} = \sum E_{el_{,HPCl}} \quad (28)$$

$$E_{th_{HP_{new}}} = \sum E_{th_{HP_{Cl_{new}}}} \quad (29)$$

If the energy would be taken by the national grid there will be to consider a new emission factor of the electricity $f_{el,new}$, so the equation would be:

$$\Delta CO_2 = E_{th_{HP_{new}}} * f_{GN_1} - E_{el_{HP_{new}}} * f_{EL_{new}} \quad (30)$$

A scenario is also proposed in which a photovoltaic system is also installed at the same time, so that the energy supplied to the heat pumps is generated directly by the photovoltaic panels, with no emissions generated.

$$\Delta CO_2 = E_{th_{HP_{new}}} * f_{GN_1} - E_{el_{HP_{new}}} * f_{El\,PV} \quad (31)$$

Where $E_{th,HP,new}$ is the thermal energy supplied by heat pumps in the year in which it is wanted to evaluate the emission reduction for all energy classes and $f_{GN,1}$ is the natural gas emission factor in the reference year and $f_{EL,PV}$ the emission factor of PVs, assumed equal to 0.

PV panels are dimensioned depending on how much energy should be consumed by heat pumps; considering that these panels are discontinuous in that production, which is greatest in the middle of the day, when solar irradiation is at its highest and lower in the morning, evening and cloudy days, the installation of a storage system was also assumed. Considering a self-consumption of less than 100 per cent, the photovoltaic panels are sized to generate more energy than is needed to run the heat pumps. This energy will be recovered with a storage system. Thus, the electricity per class produced by the photovoltaic panels is equal to:

$$E_{el_{PV}} = \frac{(EPH_{nd} + EPW_{nd}) * HFA_{eff_{Cl}}}{k_a * COP} \quad (32)$$

Where $E_{el,PV}$ is the energy generated by PVs, EPH_nd and EPW_nd are the useful thermal performance index for heating and the useful thermal performance index for domestic hot water production respectively, COP is the average efficiency of the heat pump, and $HFA_{eff\_Cl}$ is the heated surface area of a class in which is installed a heat pump, $k_a$ is the auto consumption.

### 2.2.4 Electricity Storage

The purpose of storage systems connected to photovoltaic systems is to store the electricity produced by photovoltaic panels during periods of overproduction and to release it when solar production is lower than demand; this system improves the efficiency of the system and allows a more stable energy supply.

This scenario assumes the installation of a storage system in buildings that already have a heat pump and consequently a photovoltaic system installed. The storage system makes it possible to use the energy generated by the photovoltaic panels even at times when production is lower and thus to increase self-consumption, to achieve 100 per cent self-consumption.

It is assumed that the energy to be supplied by the E_st storage system is equal to the electricity generated by the photovoltaic panels that is not self-consumed.

$$E_{st} = (1 - k_a) * E_{el_{PV}} \quad (33)$$

The storage action will have an impact on the reduction of emissions because the energy that is autoconsumed during the hours when PVs cannot supply the energy needed, would be lost. So, the reduction is equal to:

$$\Delta CO_2 = E_{st} * f_{el_1} \quad (34)$$

Where $f_{el,1}$ is the electricity emission factor in the baseline year.

We can also consider buildings, which have installed photovoltaic panels and a storage system, as a result of the action of thermal insulation and the installation of heat pumps, can be considered to be in class A4 as the non-renewable primary energy index will be close to 0.

### 2.2.5 Energy Class of Appliances

The model function calculates the reduction in emissions resulting from the use of more efficient appliances and electronic devices in buildings, evaluated considering the new energy labels defined for the most frequently used appliances.
The consumption for electrical devices in an household would be equal to

$$E_{el_x} = E_{el_{sector_1}} * \beta_x \tag{35}$$

Where $E_{el,sector}$ is the electrical consumption of each sector in the baseline year, and $\beta_x$ is the percentage of electrical consumption per use referring to the total.
The action will reduce the electrical consumption as follows:

$$E_{el_{dev-improved_{new}}} = \alpha * E_{el_{dev_{new}}} \tag{36}$$

With $\alpha$ the percentage of buildings that we want to improve.
So, for each sector we have a reduction equal to:

$$\Delta E_{el} = E_{el_{dev-improved_1}} - E_{el_{dev-improved_{new}}} \tag{37}$$

The emission reduction due to the reduction of electrical consumption is equal to:

$$\Delta CO_2 = \Delta E_{el} * f_{el} \tag{38}$$

## 2.3 The Case Study and the Decarbonisation Scenario

The proposed methodology was applied to the practical case of the city of Turin, one of the 100 cities selected by the European Commission in the context of the mission '100 climate neutral and smart cities by 2030'. A decarbonization scenario was simulated, considering 100% of buildings in classes G, F and E retrofitted (45% of buildings), extending the goal included in the proposal for the recast of EPBD (Energy Performance of Buildings Directive), which mandates that all residential buildings reach at least class D by 2033. The percentage of renovated floor surfaces would be 65.1% of residential, 46.3% of tertiary and 81.1% of industrial buildings. Additionally, heat pumps will be installed in 45% of buildings that are not connected to the district heating network, with electricity demand entirely covered by PV with storage systems. Then the proposed plan involves converting all buildings with oil systems to district heating, with the remaining volume comprising buildings with natural gas systems, covering 70% of the total built environment volume. The recovery of waste heat from data centres is also considered, providing a new source of clean energy for district heating.

# 3. Results

## 3.1 The CLICC Platform

The CLICC platform allows the results of the proposed decarbonisation scenario to be tracked. It monitors the trends of GHG emissions and investments, showing their current value, current target and final target (Fig. 5).

Fig. 5 – CLICC Interactive dashboard

The platform can automatically calculate the emission reduction in [t/y] referring to each action that the policy maker selected during the creation of the pathway, and evaluate their combined effect on the value of the emission factors (Fig. 6). The proposed actions reduce the emission factors of the different commodities used and this leads to a significant reduction in emissions.

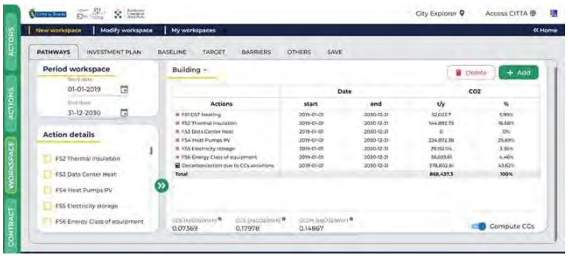

Fig. 6 – CLICC Workspace – Built environment action results

Moreover, thanks to its data management and visualisation system, it is possible to keep the entire built environment of Turin under control, through a digital twin of the city (Fig. 7).

Fig. 7 – CLICC City explorer– Built environment in Turin

## 3.2 Decarbonisation of the Building Sector

Another important result of this modelling is the decarbonisation of the city's built environment (Fig.8). In fact, the proposed actions, in a first analysis, succeeded in reducing emissions by approximately 37% in 2019, the baseline year chosen by the city.

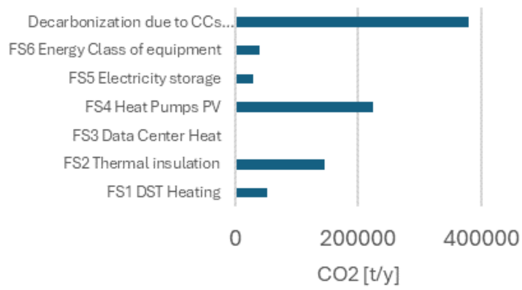


Fig. 8 – $CO_2$ avoided due to actions related to the building sector

# 4. Conclusions

This research demonstrates the feasibility of decarbonising cities through a scientific approach, providing models and a simulation tool to assess the impact of proposed decarbonisation actions. The construction of an automated simulation platform facilitates the complex process of city energy transition, allowing real-time monitoring and modification of actions to align with set targets. The study also emphasises the importance of the building sector and how interventions in this area can significantly contribute to urban decarbonisation and serves as a starting point for further future developments based on data with greater granularity and, therefore, a lower degree of uncertainty. Specific actions implemented in Turin demonstrate the effectiveness of such interventions, but these are only indicative results aimed at demonstrating the effectiveness of the model, and require further steps to obtain actual decarbonisation results. However, this shows that the application of the method is adaptable to the data available as well as to different levels and in different cities and contexts, extending to other sectors such as transport and industry, in support of a comprehensive approach to urban transition.

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# Nomenclature

## Symbols

| | |
|---|---|
| AD | Activity Data |
| f | Emission Factor |
| k | Share of buildings’ volume connected to DH network |
| E | Energy consumption |
| HFA | Heated Floor Area |

| | |
|---|---|
| $k_{Cl}$ | Share of building renovation |
| $E_{th}$ | Thermal energy |
| $\chi$ | APE scaling factor |
| $EPH_{nd}$ | Heating performance index |
| $EPW_{nd}$ | DHW performance index |
| $Q_{H,GN,Cl}$ | Average thermal energy supplied to the heating system |
| η_imp | Gas heating system seasonal average efficiency |
| COP | Coeffient of Performance |
| $k_a$ | Share of autoconsumption |
| $E_{el}$ | Electrical consumption |
| $\beta_x$ | Share of electricity per use |
| $\alpha$ | Percentage of buildings with renovated electrical appliances |

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