A life cycle assessment method to support cities in their climate change mitigation strategies

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Abstract

National climate change mitigation objectives must be translated to the city level and to specific sectors, with locally-relevant policy measures. However, assessing the decarbonization value of these measures is a challenge for local policy makers and few local consumption assessment studies integrate a systemic vision. This research presents a multi-criteria city-scale Life Cycle Assessment method focusing on the three largest carbon-emitting sectors in cities: food, residential buildings and daily mobility, with an original combination of databases and models. For food, databases were used to evaluate environmental impacts based on socio-demographic characteristics. For building and mobility, modeling tools were used and adapted at different scales: with local spatial refinement for mobility and the creation of archetypes representing the city's most common residential buildings. A demonstration of this new cross-sectoral method was conducted on Montreuil city in the Parisian region, to 1) evaluate the current greenhouse gas emissions (GHG), and 2) test the possible reductions following different measures. The developed assessment framework provides various interpretation, with disaggregated contribution, mapping, and scenario analysis. For instance, the application of ambitious measures and important lifestyle changes reduced GHG in these sectors by 30%, far from the French government's ambitions of a 55% reduction by 2030.

Keywords: life cycle assessment, carbon footprint, lever for change, city scale, urban sustainability, consumption footprint, cities

1 Introduction

To limit the multiplication of the upcoming climate disasters announced by the latest IPCC report (IPCC, 2021), countries around the world aim to respect the 2015 Paris Agreement. This agreement aims to limit global temperature increase to 1.5°C by 2050 compared to 1990. To achieve this, each state has set targets for reducing these carbon emissions into the atmosphere. For example, the European Union has set an objective of carbon neutrality in 2050 and a 55% reduction in its greenhouse gas (GHG) emissions by 2030 (EU, 2020). These objectives have been replicated at other levels: countries, regions and cities have adapted these objectives to their own scale. . Carbon emission diagnostics became mandatory in France, although territorial leaders are not required to prove that their measures will reach the set objectives (EU, 2019; France, 2015). Some territories like the C40 Cities group or the Grenoble urban area are voluntarily starting to set ambitious targets by proposing measures that are likely to reduce GHG emissions, but without knowing the real consequences or effectiveness of these measures. Although sector-based tools exist to evaluate many of these measures (i.e. building, transport and consumption models, material and energy flow analysis), combination of these models and analyses are complicated and rarely done, due to the multitude of data required and their lack of a systemic vision in regard to urban systems complexity (Mirabella et al., 2018).

The environmental assessment of cities represents an important challenge for urban development, and for leaders aiming to improve their cities' sustainability. Such environmental assessments are challenging because cities represent complex systems, where multiple and diverse anthropogenic activities interact with significant concentration of people, companies, energies and resources (Moine, 2006; Wegener, 1994). While this density can be seen as an opportunity to implement efficient environmental measures, as claimed by the C40 cities network, it also makes cities dependent on external ecosystems to provide resources and energy, and to treat waste and to absorb pollution (Jenks and Jones, 2010). Given these complex fluxes, numerous urban environmental assessment methodologies rely on the Urban Metabolism concept (i.e. reviews: (Mirabella et al., 2018; Zhang et al., 2015)), which considers the input and output flows associated to resources and energy necessary for the proper functioning of cities (Pincetl et al., 2012). Because cities outsource a significant part of their emissions, carbon assessment methods must overcome the limits related to territorial inventories and pure geographic production-based accounting by using consumption-based approaches (Athanassiadis et al., 2018; Dias et al., 2018). Depending on the characteristics of the urban area, the difference between territorial-based and consumption-based assessments can be significant for carbon, energy or resource issues, highlighting the importance of both scope and geographic boundary definitions (Heinonen et al., 2020). Among the nine main tools for the environment assessment of territories listed by Loiseau et al. (2018) only four rely on the metabolism concept with flow analysis: Material Flow Analysis, Substance Flow Analysis, Physical Input-Output Table and Ecological Network Analysis.

Process-based, bottom-up Life Cycle Assessment (LCA) for cities represents a useful alternative to top-down Input-Output-based analyses, because it considers physical consumption of materials to quantify environmental impacts (Dias et al., 2018; Loiseau et al., 2018). Nonetheless, the use of LCA methodology, initially design for products, for a territorial scale raises new challenges such as multifunctionality and the collection and spatialization of local data (Loiseau et al., 2018). To overcome these issues, many LCAs at the urban scale focus on specific sectors (building, energy, water, transportation, waste ...) or combine LCA with others approaches—in particular Urban Metabolism and geographical information system (GIS). The unit of assessment—called the functional unit (FU) in LCA—varies among urban LCAs depending on sectors assessed, the scale, and the goal of the study. LCAs of urban systems have used FUs such as “the neighborhood”, “the inhabitant", "the household", and "m² of living space" (Lotteau et al., 2015). These FUs often don't encompass the multifunctionality of cities, but methods are being developed to include more urban functionalities such as the city prosperity index (Albertí et al., 2019) or the population equivalent (Mirabella and Allacker, 2021).

In the life cycle inventory phase, highly-granular, city-specific data are valuable, and the quality and quantity of collected primary data make LCA studies more representative and more able to identify precise hot-spots. For each urban sector the capability to collect specific data is different and the source of secondary information varies (Mirabella et al. 2018). Building sector LCAs are based on bottom-up approaches with important level of description (ground plan, materials characteristics …) and dedicated models for thermal simulation. Nonetheless, building assessments face issues regarding system boundaries, with additional systems and potential interactions with energy, mobility, waste, water or green infrastructure sectors (Petit-Boix et al., 2017). On the other hand, the transportation sector does not usually rely on specific process data, and rather uses transport surveys, models, and GIS analysis to represent mobility flows (Mirabella et al., 2018). The environmental assessment of the consumption of goods depends on consumer habits that can be measured through national expenditure statistics or local surveys. The impacts of measures taken at the local level are often assessed for separate sectors, with building retrofitting policies (Marique and Reiter, 2014), new transports technology (Lausselet et al., 2020), transit-oriented districts (Kimball et al., 2013) and food and diet-related strategies (Barbour et al., 2021; Candel, 2020). To achieve significant mitigation results, these policies should be carried out and assessed simultaneously , but this raises issues on the implementation in specific neighborhoods (Pulselli et al., 2019) and rebound effects (Ottelin et al., 2018).

The objective of this research was to propose a multi-sector life cycle environmental modeling method at the city scale. The interest of this model-based methodological framework was to 1) facilitate the environmental assessment of the current state of food, mobility, and residential building use 2) evaluate the outcomes of climate change mitigation measures. With this framework, the specific territorial and spatial characteristics of cities can be considered in an evaluation.

The main contributions are (i) proposing a coherent LCA environmental assessment method for three of the most GHG-emitting sectors in France: food, buildings and daily mobility, (ii) an innovative method designed for use at the city scale, (iii) evaluation of the impact of climate change mitigation measures through a multi-criteria LCA and (iv) a case study on a city of 110,000 inhabitants that illustrates the method and the implementation of several measures in the three sectors studied.

The different research fields mobilized in this study are at different levels of maturity in the quantification of environmental impacts. If the modeling of the thermal of buildings and the modeling of transport allow to quantify environmental impacts from physical models, in the food sector the use of statistical models is still necessary. The knowledge of each of these research fields was thus mobilized to evaluate the environmental impacts at city scale and integrated in coherence in a LCA. More precisely, (i) the data on the city's buildings and their construction systems was used to create archetypes of buildings representative of the city's constructions. The thermal simulation of these archetypes and their environmental assessment allowed to estimate the balance at the city scale and by neighborhood. (ii) the transportation models used by large cities to plan their future infrastructure were used as a basis for quantifying the movement of the city's population at the city neighborhood level. Thus, an inventory for assessment in LCA was derived. Finally, (iii) the characteristics of the city's population coupled with consumption inventory databases provided an estimate of the food consumption by city's residents. Consistent with a carbon footprint approach, we evaluated only the impacts of the city's residents and not those of non-resident users (i.e. commuters). By cross-referencing these results by food type with an LCA impact database for food, we obtained the environmental assessment of this sector. Finally, the aggregation of these environmental results provided comparisons at city and neighborhood scales, but also for an average Montreuil resident.

The rest of the article is composed as follows. The second section details the methodology for calculating LCA impacts as well as the types of data needed. The third section presents the case study of a municipality in the Paris region, Montreuil, with the specificity of the databases used in a French context. Finally, the last section demonstrates the environmental assessment based on our methodology on the city of Montreuil, as well as the implementation of measures at the city-scale to lower the GHG emissions.

2 Methods

2.1 General

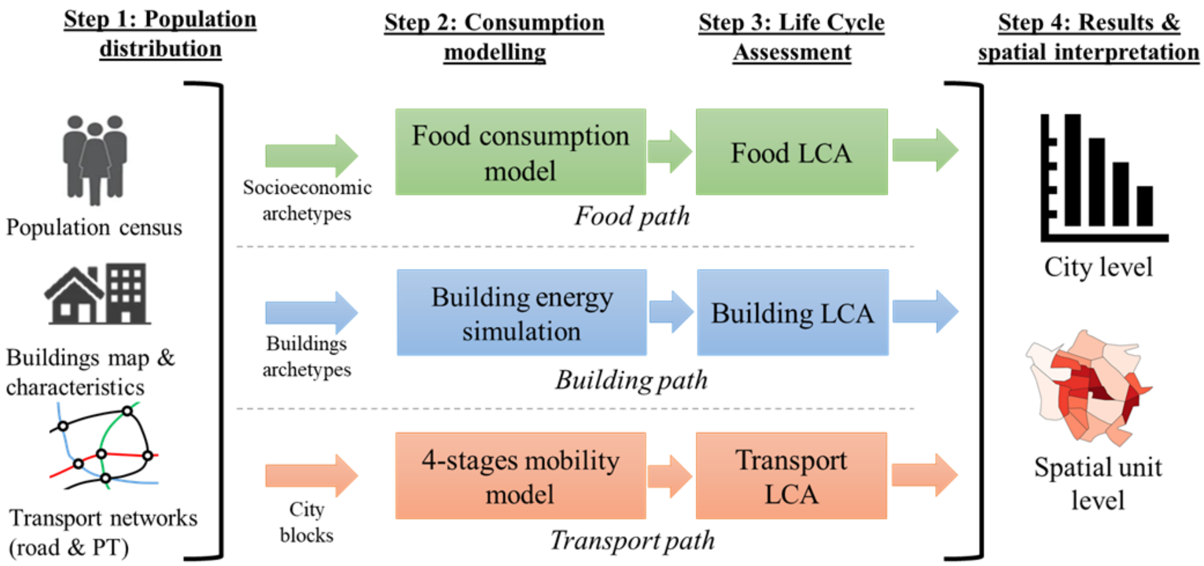

Figure 1: Methodological framework for the city LCA.

(Loiseau et al., 2018; Mirabella et al., 2018) T Three consumption sectors were included to represent major environmental impacts of the residents: food consumption, residential building and daily mobility. These three sectors were found to be highly impactful in a review of urban metabolism studies by Goldstein et al. (2017). Depending on the study approach adopted (production-based, consumption-based or geographically-based), cumulative contributions of mobility, buildings and food sectors vary but stay significant, from 50% to 80%. All three sectors were handled separately in our study with distinctive models, datasets and calculations developed and executed in different manners. Nevertheless, the spatial and socio-economic information related to the population was processed jointly to properly characterize and disaggregate individuals into various spatial units (census sectors, city blocks, buildings). The smallest spatial unit used was the building one. The population description was known at a sub-municipal scale (IRIS census tracts), with precise information on individual archetypes collected in the national census. An intermediate scale was built to better represent traffic flow, and it corresponded to city blocks delimited by road and intersections. Then, the population disaggregation was based on the residential space known for each building, with a distinction between detached home and multi-unit dwelling, which have different densities. Buildings, mobility and food impacts were represented with building, city blocks and IRIS scales, respectively. The map representation of these spatial units associated to the case study is filed in the Appendix.

2.2 Life cycle assessment

Processes-based life cycle assessment was the main methodology of environmental assessment used in this study, and its principles and framework were applied for all urban sectors considered as illustrated in Figure 1. The goals of the LCA were to 1) model environmental impacts of the current consumption levels in the food, building, and transport sectors at the city level, and 2) model potential reductions in climate change impacts from mitigation measures considered by elected officials. The definition of the scope and the boundaries is a challenge for territories, and it leads to different approaches for data collection and allocation (Loiseau et al., 2018; Mirabella et al., 2018).The system boundary here included all upstream and downstream processes needed to produce the materials and energy used in the three sectors studied. According to life cycle thinking, processes located outside of the city were included, such as energy production, agriculture, and trips between cities. Details regarding what was included for each sector are provided in the following sections. The functions of the three sectors are to provide food and beverages, residential building energy, and daily transport to residents of the city. We considered two functional units: provisioning of these functions to the entire city for one year, and provisioning of these functions per person per year. Calculation of the reference flow—the amount of material and energy needed to fulfill these functions—was a major part of this work, and steps for calculating the reference flow of each sector are described below.The same life cycle impact assessment (LCIA) method was used for all three urban sectors, which came from a specific tool for building assessments. 12 categories compose the LCIA method, mainly derived from CML2001 (Guinée, 2002) but completed with the water use from the AWARE method (Boulay et al., 2018), with a bulk waste and a radioactive waste categories from EDIP 2003 method (Potting and Hauschild, 2004) and with two endpoint indicators for the human health and the ecosystem quality from eco-indicator 99 (Goedkoop and Spriensma, 2001). To simplify analysis, our study focused mainly on Global Warming Potential (GWP) and presented results for primary energy demand, land use impacts and bulk waste production in the article, and all other impact categories are presented in the Supplementary Material. For each sector, we analyzed the contribution of different processes to the impacts, the spatial variability and the impacts of alternative scenarios representing actions cities may take to reduce GHG emissions. Then we combined results of all sectors to obtain city-scale results, where we highlighted the hotspots, the territorial heterogeneity and the potential environmental improvements and deteriorations.

2.3 Food sector

To calculate the environmental impacts of food consumption, we first modeled the amount and type of food consumed in the city. We based this information on national consumption surveys, as has been done in numerous other studies (Ramaswami et al., 2017). However, food consumption patterns can vary largely within a country, and in the context of this work focused on environmental impacts and levers at the city scale, we sought to improve the local precision of this data. Diets vary largely by socio-economic factors, and three key factors defining categories of consumer are identified: age, sex, and level of education (or for children, level of education of parents) (ANSES, 2017). The typical annual diet for each socio-economic category was compiled, based on a national food consumption survey which contained socio-economic data for each respondent. We then identified the number of consumers belonging to each category in the case study city and scaled up the typical annual individual diet by the number of individuals in each category, to obtain the total amounts of different food products consumed by residents of the city in one year. The system boundary included agricultural production, processing, distribution, and preparation of the food.

Due to the nature of the survey data, this study considered the consumption of all food by residents, regardless of whether consumption occurs in the case study city or in another location. For example, commuting to a nearby city for work and eating lunch was included here. Because the scope of our research was consumption of residents, we excluded food consumed by commuters who do not reside in the city.

2.4 Building sector

The method used for the environmental assessment of buildings was based on numerous studies applied at the neighborhood level (Ballarini et al., 2014; Reinhart et Davila, 2016). The use stage accounts for the majority of the life cycle environmental impacts of existing buildings, so it is necessary to calculate accurately the energy consumptions. The chosen approach consisted in modeling buildings and determining their energy performance. However, building energy simulation (BES) requires numerous detailed data and is time-consuming on a large scale. Archetypes were then created to represent the building stock, and modeled on the BES software Pleiades[1], which aids in the eco-design of buildings and optimization. The dynamic building energy simulation model COMFIE (Peuportier and Sommereux, 1990) was used to evaluate heating loads, and environmental impacts were calculated over the building life cycle including stages of construction, use, renovation and end of life, with the LCA tool EQUER (Peuportier et al., 2013; Polster, 1995; Popovici, 2005). The use stage contained impacts associated to energy consumptions according to the energy production, while domestic waste and transport of occupants were not considered in the buildings modeling. Indeed, occupants' transport and food are assessed in the corresponding sections, so including them in the building section would involve a double counting. Finally, all buildings of the residential stock were divided into the 14 archetypes defined on the previous step, and the city's

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[1] https://www.izuba.fr/

buildings were allocated to these archetypes, based on similar thermal properties. Results were then extrapolated to the city level.

2.5 Transport sector

The basis of our method used a traditional 4-step transportation model (Trip generation, trip distribution, modal split and traffic assignment) to simulate the daily trips of residents (Meyer and Miller, 1984). Using urban land use and transport supply data, we simulated the trip patterns of users by mode. Thus, the distances per mode were quantified for each territorial zone defined in the model. The method used to calculate environmental impacts is described in previous work (Kotelnikova-Weiler et al., 2017a, 2017b). Kotelnikova-Weiler et al. (2017a) described the use of a transportation model to simulate the daily trips of the inhabitants at district level through a spatial refinement to accurately represent the trips within the territory but also the behaviors of users. This refinement consists not only of finely dividing the classical zones of a transport model into finer blocks, but also of better representing the transport network at the city scale than it is at the agglomeration scale. Kotelnikova-Weiler et al. (2017b) explained the method of attribution to the origin or destination location while transportation models classically attribute impacts to a trip (Bouzouina et al., 2013). For each block in the study area, the distance of each resident's trips that have their residence as origin or destination was associated with each resident. Thus, for each block of the study area, the number of kilometers travelled by the inhabitants for each mode of transport was calculated for one working day from their residence. The conversion to a yearly basis was done using ratios calculated from the household travel survey of the study area.

After representing the mobility and distance travelled in each spatial unit of the city, our transport methodology converted these distances into environmental impacts. The technology description of transport modes is essential when processing transport LCA. Then, we described the individual car fleet based on regional data, leading to a lower diesel rate than the national fleet. The car fleet LCA calculator, ModEm-ACV (François, 2022), was used to get unitary environmental impacts associated to the regional fleet. This calculator crosses LCA database and emission models to assess the exhaust, the fuel production, the vehicle life cycle (production, maintenance and end-of-life) and the road infrastructures impacts, while considering road and speed conditions (François et al., 2017). The environmental impacts were obtained per spatial unit by multiplying unitary impacts related to the car fleet, expressed per vehicle.kilometer, by car travelled distances. The impacts of public transit use were not considered in this study for several reasons. First, transportation models are fairly consistent for longer distances, but not so much for local trips that correspond to bus use. Second, LCAs of transport modes such as the metro are still very unreliable. Third, the public transit system is managed at the regional/metropolitan level, so the municipality has no opportunity to improve its carbon balance. Finally, the contribution to the carbon impacts of daily public transport remains quite low in European cities (Anderson et al., 2015; François et al., 2021; Le Féon, 2014).

3 Case study city and data sources

3.1 Montreuil, a town in the Paris region

To illustrate our methodology, we applied it to the Paris-adjacent city of Montreuil. The population of this city is around 110 000 inhabitants and more than 50 000 jobs for a total area of 8.92 km². It is characterized by a high variability of density and wealth, with the West part being wealthier and less dense with low-rise housing, compared to the East part with high-rise housing. Public transport accessibility is important in this territory, with three subway lines and a regional train connection.

3.2 Demographic data sources

The population description was central to estimating building occupancy, mobility patterns and food consumption related to every spatial unit that composed Montreuil. The French national census from 2015 was the main source of demographic data, with details on population, job location, and socioeconomic characteristics. The French statistical agency, INSEE, is in charge of the census and it localizes individuals and jobs at a spatial unit named IRIS. There are 41 IRIS units in Montreuil. Because building and mobility sectors require finer localization of individuals, we distributed the population into buildings and traffic blocks based on the BDTopo database, from IGN (The French national institute of geography). Montreuil has 112 traffic blocks and around 20,000 buildings, and the exhaustive road network is also available on this database (map in annex, Figure 7).

3.3 Transport data sources and models

The DRIEA's MODUS model is a transportation model that simulates the daily trips of residents in the Paris region according to the transportation networks and the distribution of jobs and populations by geographic sector defined for the model (DRIEA Île-de-France, 2021, 2012). For our study, the distribution was retained for the whole urban area except for Montreuil, for which the distribution was refined by block as explained above. In the model, only a selection of the main roads constituted the network. In the same way, we specified all roads at the scale of the city using the base of the road sections of the BDTOPO of the IGN. The MODUS model thus simulated for all users of each block the daily modal share (public transport, private car, bicycle, or walking). Assessed distances travelled by private cars are also modeled.

The environmental impacts of personal vehicles were calculated based on the regional car fleet composition described in the regional mobility surveys. The most recent mobility survey for Paris was in 2010, and described a car fleet with 64% of diesel and 35% of gasoline cars and an average age of vehicle around 7 years. Then, through ModEm-ACV calculator (François, 2022), emissions and consumptions of vehicle use were first estimated based on Copert model (Ntziachristos et al., 2020). Next, LCA impacts related to vehicle manufacturing and maintenance, fuel production and road construction were added from the EcoInvent database (Wernet et al., 2016). Detailed ModEm-LCA parameters, including car fleet description, are presented in the Supplementary Material. Finally, LCA impacts per vehicle.kilometer were crossed with private car daily distance for each city block to assess Montreuil mobility.

3.4 Food data sources

The INCA3 survey was used to determine the average amount and type of food consumed for each socio-economic group per year in metropolitan France (ANSES, 2017). This survey was done by the national government agency ANSES, and surveyed over 5,800 individuals in 2014 and 2015, and was published in 2017. Data from the French census were used to determine the number of inhabitants in Montreuil corresponding to each socio-economic group. The breakdown of the population in each socio-economic category for the city is provided in the supplementary material (Annex_FOOD.xlsx). We combined the individual consumption data and the population data of the city to calculate the mass of food consumed from 44 different food categories. Life cycle inventory data for average food products consumed in France came from the AgriBalyse database, which draws from the LCA database EcoInvent (Asselin-Balençon et al., 2020). The software OpenLCA was used to perform the life cycle impact assessment.

3.5 Building

3.5.1 Data sources

Following the disaggregation presented in the previous sections, the number of inhabitants of individual and collective housing properties was known. To evaluate the environmental impact of the city's buildings, we created archetypes representing the housing stock to avoid modeling each building in the city. Archetypes were based on key characteristics identified through the study of several complementary databases giving information on buildings, such as the type of residence, the construction period or the type of energy production. This data collection took place during the pre-modeling stage, and the studied databases are presented in Table 1.

Database	**BD TOPO**	**DPE**	**Census**	**TABULA**	**ROSE**
Administrator	IGN	ADEME	INSEE	IEE	Paris region
Reference	Building	Wall	Neighborhood	Time period	City
Data	Construction period, materials, area, building typology	HVAC system, materials of walls, roof and glazing	Population, Building type distribution	Building standard, time period, renovations	Energy consumption of municipalities

Table 1: Databases used to model residential buildings

3.5.2 Modeling building archetypes

- Building archetypes were determined from the analysis of these databases, according to the three main criteria of the French database BD TOPO, detailed hereafter. This standard national map database for France is used in various sectors, such as improvement of the Global Positioning System (GPS) (Bétaille et al., 2015) or urban heat island studies and climate modeling (Emery et al., 2018; Richard et al., 2018). Its level of details enables the creation of archetypal building envelopes representative of the city. The buildings are also differentiated by their heat production system, mainly represented by electric and gas heating The archetypes were based on: type of residence (individual housing, small collective residence i.e. from 2 to 9 dwellings, and large collective residence – more than 10 dwellings)
- Construction date, divided into four periods (before 1945, 1946-1970, 1971-1990, after 1991)

- Wall and roof materials

Building characteristics used to create the archetypes are the averages of data associated with the real representative of each archetype in the databases. These data were used as Pleiades inputs in order to process to BES and LCA. Given the variability of building characteristics (materials, heating production and different envelopes), energy efficiency of the building stock was heterogeneous. . Heat production for heating and domestic hot water was split between gas and electricity for each archetype, with ratios coming from the French database TABULA. Only multi-family dwellings built before 1945 were considered to be heated solely by gas. At the city level, 60% of the heat production comes from gas boilers, and 40% from electricity. Details regarding building archetypes (envelope and roof type, proportion in the city and heat production) are specified in the supplementary data: Annex_Build.xlsx)

The most common archetypes were the four buildings presented in Table 2. They were modeled in Pleiades.

Individual housing		Collective housing	
Before 1945	1946 - 1970	1946 - 1970	1971 - 1990
			
			

Table 2: Pictures and 3D representation of the most common archetypes

4 Results

First, we validated the consumption amounts that we calculated for each sector, which were the reference flows for the LCA: food consumption, energy use, and transport. The next section details the climate change impacts by sector. Finally, we present the effect of GHG reduction measured on each of the studied sectors, and on the entire city.

4.1 Validation of consumption amounts and reference flows

4.1.1 Validation of food consumption

The amount of food and drinks consumed in the city per adult (18-79 years old) was the same as the national average (2.96 kg/day in Montreuil compared to 2.94 kg/day in France), and drinks made up 58% of this in Montreuil vs 60% in France. Most of the differences in diet patterns between our model of Montreuil and the national average consumption were in food groups making up less than 1% of the total mass of food consumed. Differences for adults between foods that made up more than 1% of the diet were the category of sandwich, pizza, tarts, and pastry, which was 11% higher in Montreuil than the national average and made up 5.4% of the mass of food consumed in Montreuil. Other notable differences included smaller soup consumption (8.4% less, making up a total of 7.4% of consumed food) and smaller milk consumption (5.7% less, making up a total of 5.7% of consumed food). Among children (age 0-10 years old) there were notable differences in consumption of milk, which was 7.5% higher in Montreuil and made up 9.7% of children's diets; and fruits, which was 5.5% higher in Montreuil and made up 6.8% of children's diets. There were not substantial differences between Montreuil and the national average for beverage consumption among adults, food and beverage consumption among adolescents, or beverage consumption among children. A table of the total food consumption and differences from the national average are in the Supplementary Material (Annex_FOOD.xlsx).

4.1.2 Validation of building energy consumption

Building energy simulations of each archetype were performed to calculate energy consumption. Results were then extrapolated to the city scale to represent all energy consumption. To validate the method chosen to create the archetypes, these simulated consumptions were compared to real energy consumption. The reference for the real consumptions is the French database ROSE which collects numerous energy data as energy, energy indicator, energy bill etc. This indicates energy consumption of the residential housing of the town. According to our calculations, Montreuil's residences consumed 774 GWh/year, with 445 and 329 GWh/year for respectively gas and electricity, while the reference value was 731 GWh/year according to the ROSE data of 2017. The gap of 6 % between simulated and calculated final energy consumptions can be considered as acceptable and validated the choice of the methodology.

4.1.3 Validation of transport behaviors

There is no mobility survey available at the city of Montreuil scale. Only the 2010 Household Travel Survey (EGT, Ile De France Mobilité) at the Ile de France level allows us to verify the order of magnitude of the general indicators that characterize daily mobility. First, the ratio between the number of trips linked to the residences of Montreuil and the sum of the population is 3.7 trips per inhabitant per day. At the Ile de France level, the EGT gives 3.8 trips per resident. The modal share of Montreuil residents and workers can be compared with the modal share of the residents surveyed in the inner ring (the first ring of cities around Paris). The proportion of private cars in Montreuil is 43% (34% in the EGT and 42% in the city carbon diagnostic (Montreuil, 2013)) and 27% in public transport (22% in the EGT and 20% in (Montreuil, 2013)). Finally, the average distance per trip by car for residents is 5.4 km (6.1 km in the EGT for residents of the inner ring). The public transport breakdown by sub-modes (bus, train, subways, tramways), with distinct trip distances and vehicle occupancies, are not defined in this study at local scale, only statistics at regional scale are known (OMNIL, 2021).

4.2 Environmental assessment results

Impacts from the three sectors combined were 4.1 t CO_2 eq/cap/a. Food consumption contributed the most to climate change impacts (44%), followed by buildings (34%) and then daily mobility (22%).

4.2.1 Environmental impacts from food

Food and beverage consumption in Montreuil were responsible for 196 kt CO_2 eq per year, and 1.79 t CO_2 eq per habitant per year. Most of the climate change impacts came from solid foods (and milk) (88%), and 12% came from beverages as shown in Figure 2. Meat was the most impactful food category, contributing 38% of the climate change impacts. This contribution was especially notable considering the relatively small proportion of the diet that meat makes (4% by mass of total consumption, 9% of solid foods). This was followed by the sandwiches, pizza, tarts, and crackers category, with 6% of the climate change impact and 2% of the mass of total diet. Hot drinks were the next most impactful, contributing 5% to total diet related climate change impacts. We grouped the 44 products into 11 solid food categories and 6 beverage categories to facilitate interpretation of the results. Among these categories, the most impactful were meat (38% of climate change impacts), cereals and prepared foods (14%), and dairy products (13%).

These results were in line with other studies measuring climate change impacts from food consumption per capita per year. (Goldstein et al., 2017) reviewed urban food consumption impacts from 16 assessments, and found average impacts were 2.1±1.1 t CO_2 eq/cap/a. They also found that meat and dairy were major contributors to climate change impacts. Similar values were found in more recent studies, including 1.87 t CO_2 eq/cap/a in Madrid, Spain (González-García et al., 2021) and 1.83 t CO_2 eq/cap/a in Almere, Netherlands (Stelwagen et al., 2021). The French environmental agency ADEME calculated impacts for food consumption in France, which we divided by the population and found 2.43 t CO_2 eq/cap/a (Barbier et al., 2019). Pernollet et al. (2018) found that most impacts for food consumption in France came from the farm stage (57% for climate change), followed by at-home food waste (17-22% of all impact categories).

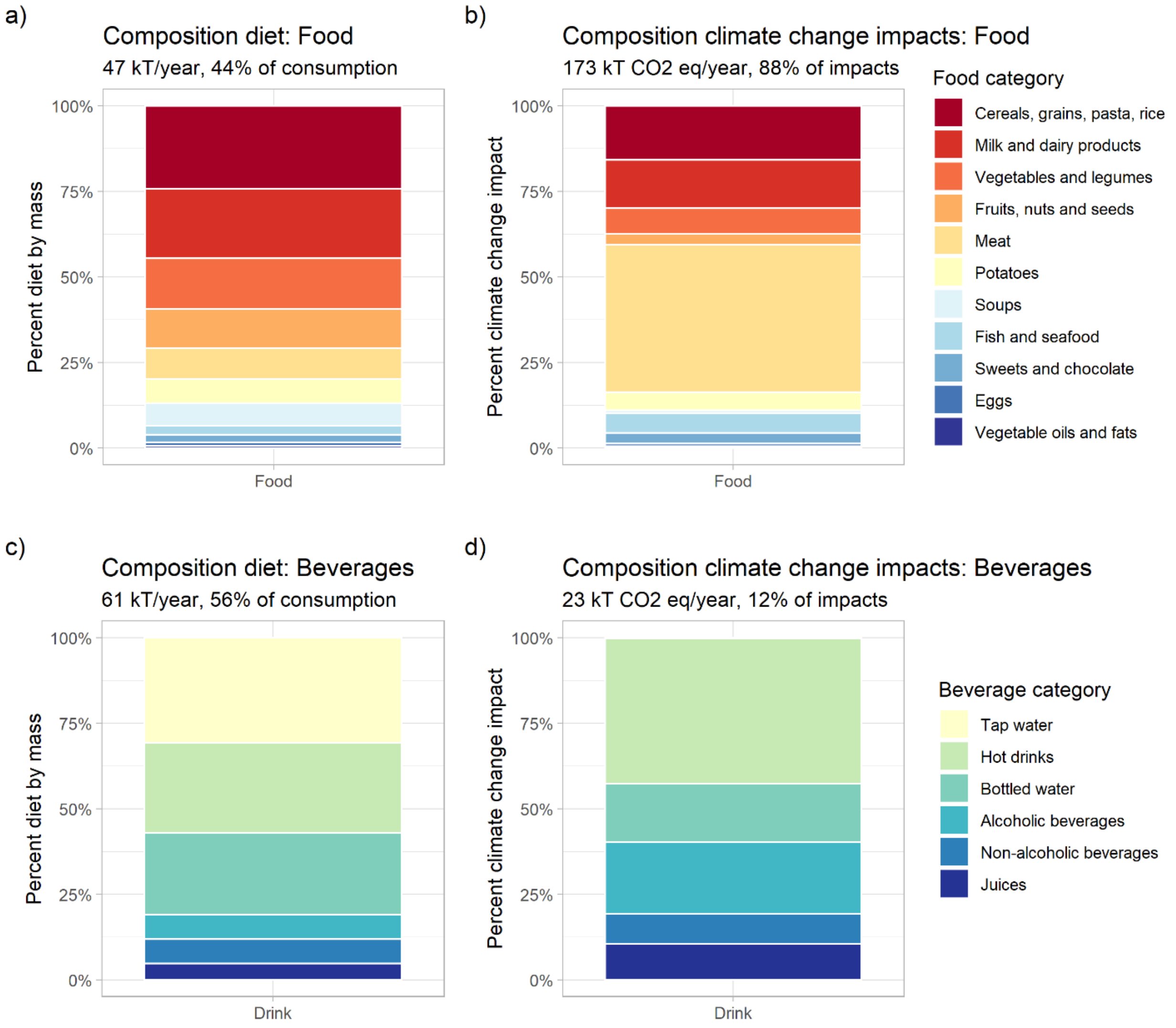

Figure 2: a) solid food consumption distribution, b) GWP solid food contributions, c) beverage consumption distribution and d) GWP beverage contributions

4.2.2 Environmental impacts from buildings

Buildings environmental impacts were calculated with the software Pleiades using LCA methodology. The estimated building lifetime was 100 years. Results showed that the building sector emitted 159 kt CO_2 eq per year, or 1,4 t CO_2 eq/cap/a, 70% and 30% of this impact comes from dwellings heated with respectively natural gas and electricity.. This result is consistent with the energy and climate diagnostic, commissioned by the city of Montreuil in 2011, which found that the residential sector emitted 157 kt CO_2 eq in 2011. As expected, old buildings emitted more GHG, in particular buildings before 1945 which emitted 51 kg CO_2 eq/m²/a against 21 to 26 kg CO_2 eq /m²/year for buildings after 1945. Furthermore, the use stage was the major contributor of GHG, 82% in average at the city scale.

GHG emissions of the city by area were 39,5 kg CO_2 eq./m²/a. This result can be compared with other studies referenced in the critical review (Lotteau et al., 2015). This study reviewed 21 case studies, and summarized the CO_2 emissions per m² of surface area and per year for residential buildings, and found that case studies emitted between 11 and 124 kg of CO_2 eq/m²/a.

4.2.3 Environmental impacts from transport

The total GHG emissions for daily mobility were estimated to 98 kt CO_2 eq per year for Montreuil when considering personal cars only. Per individual, it represents 0.902 t CO_2 eq/cap/a, which was in line with others similar study assessing urban mobility with LCA. This output does not include public transports impacts, but mobility LCAs highlight a low contribution of these modes in urban areas (below 10%) (Anderson et al., 2015; François et al., 2021; Le Féon, 2014). Compared to studies assessing more rural territories or more car dependent societies, our results were low because of the favorable condition for public transport, walking, or cycling with shorter distances traveled (Bastos et al., 2016; Saner et al., 2013; Stephan et al., 2013). 57% of total GHG emissions were related to direct exhaust emissions, 14% to fuel production, 26% to vehicle manufacturing and 3% to road infrastructure. For the other environmental impacts the contribution can be found in Supplementary data (Vehicle_impacts.docx).

Within Montreuil, small spatial variability emerged from our calculations: the North East part was 14% more emitting than the rest of the city, with respectively 973 and 853 kg CO_2 eq/cap/a. This part of the city is less accessible by public transport with more individual housing.

4.3 Levers for change

4.3.1 Presentation and motive

A city has limited margins of action to support the reduction of its inhabitants' carbon emissions. While the city has political competences, it is only one link in a long chain of decisions from individuals to international organizations. Moreover, its restricted budget does not enable it to offer large subsidies to incentivize GHG reductions. Finally, many carbon emissions related to the practices of the residents are generated outside the geopolitical boundary and area of jurisdiction of the city. . The measures tested (Table 3) mainly concerned the lifestyles of the residents: (i) food practices with a decrease in waste and meat consumption, (ii) for buildings, an ambitious thermal renovation of a large part of the housing stock, and (iii) no trip of less than three kilometers would be made by car and a certain part of the car fleet would be renewed according to the forecasts of the climate plan for 2022. For daily mobility, a final municipal measure of limiting speeds to 15km/h instead of 50km/h was modeled.

The majority of these measures primarily concerned the behavior of residents, and most are recognized as having a significant impact on the CO_2 balance on an individual scale (Gardner and Stern, 2008; Hoolohan et al., 2013). They were also chosen after discussion with the city's technical department as being suitable for public policy measures. Indeed, awareness-raising incentives, subsidies, or targeted taxes can orient certain practices or facilitate the renovation of housing. The constraints of our tools and models were also considered in the choice of possible measures.

Sector	Action scope	Scope	Name in figure 3
Mobility	Renewal of the car fleet: 10% electric, 15% hybrid, 75% recent thermal (since 2011)	All residents' vehicles	Motorization renewal
Mobility	Car speed limit of 15km/h	All streets of the city	Speed limit 15 km/h
Mobility	Trips of less than 3 km by car made with an alternative mode.	All resident trips	No car below 3 km
Food	Reduction by half of the waste of each food category (final waste rates of 1-5%, except water which was 0%)	All foods consumed by residents	Food waste
Food	Reduction of 20% of red meat consumption, replaced by vegetable proteins and eggs	Meat, eggs, and vegetables consumed by residents	Replacement of red meat
Building	Replacement of windows installation of double glazing	All housing stock built before 1990	Replacement of windows
Building	Replacement of standard gas boilers with condensing gas boilers (PCI = 0.95)	All housing stock built before 1990	Renewal of gas boilers
Building	Insulation of facades	All housing stock built before 1990	Isolation of facades

Table 3: List of all levers for change considered in the scenarios

4.3.2 Reductions in impacts

Figure 3 shows the reduction in GHG emissions from each of the measures implemented successively for each sector. For the daily mobility of residents, the current total emissions were 98 kt CO_2 eq per year and were reduced by 12% from the restriction on motorized trips of less than 3km, then by 6% by reducing the speed limit to 15km/h throughout the city, and then by 5% by renewing the car fleet. Finally, combining all the measures, we obtained a 23% reduction compared to the initial baseline of the transport sector. For the residential building sector, window renovation saved 10% of GHG emissions, the addition of boilers replacement saved another 11%, and the most complete renovation which isolated the facades of the buildings reduced emissions by 14%, to finally reach a gain of 35% on the residential buildings sector. For food, the replacement of a part of red meat by protein with a lower carbon impact allowed a reduction of 7% of food sector GHG emissions. Additionally, food waste reduction measures saved 3% of GHG emissions.

Figure 4 summarizes the gains from applying all measures for the 3 sectors compared to the baseline situation. Montreuil's carbon footprint of 453 kt CO_2 eq was thus reduced by 23% to 348 kt CO_2 eq. As expected, the sector whose emissions were mostly part produced locally—the building sector—succeeded in reducing its emissions the most. In contrast, emissions from the food sector were mainly produced by agriculture, thus outside Montreuil's geographical boundaries, and the scope of direct influence of elected officials, and only slightly reduced emissions. Measures on agricultural practices will therefore be necessary to improve climate change mitigation strategies.

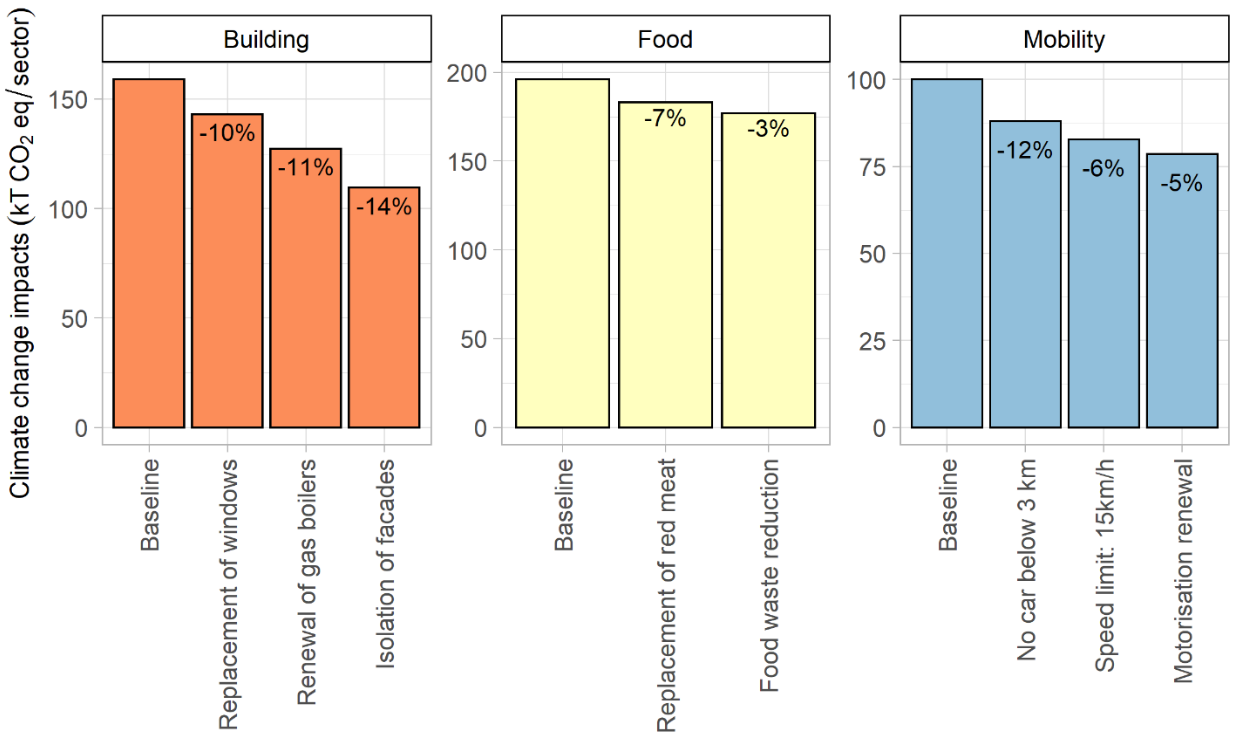

Figure 3: Gains resulting from the implementation of each measure per sector on the GHG emissions in kt of CO_2 eq

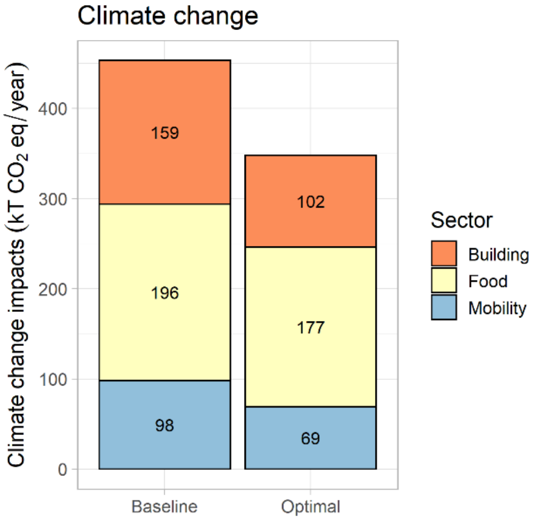

Figure 4: Final GHG reduction per sector of 23%.

Figure 5 shows the GHG emission reductions in different neighborhoods (i.e. IRIS sections) of the municipality and the final distributions of emissions by sector. This territorial representation highlights the disparity of gains between Montreuil's neighborhoods from -15% to -28%. It also displays the disparity of GHG emissions per resident between sectors and between districts. Thus, between IRIS, in each sector, important standard deviations were observed: the mean and standard deviation were 1.7±0.7 kt CO_2 eq/a for mobility, 6.2±2.4 kt CO_2 eq/a for food, and 2.3±0.8 kt CO_2 eq/a for buildings. These disparities were of multiple origins. The main factor for food and mobility was the socio-demographic structure of the population, which differs considerably between districts and influences diet and mobility behavior. For daily mobility, accessibility to jobs and public transport networks also varied widely from one area to another, providing another explanation for the heterogeneities in behavior. For buildings, the structure of the stock, the age, the rate of single-family homes or the construction systems varied significantly between neighborhoods.

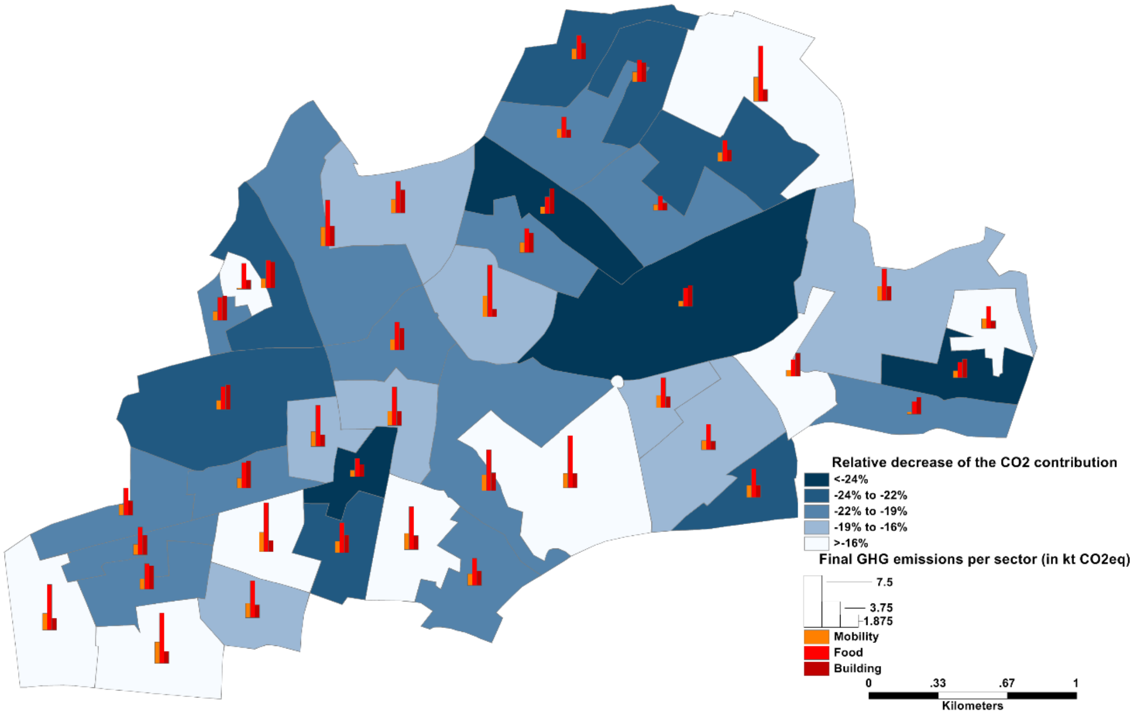

Figure 5: Montreuil map of GHG emission gains by IRIS and distribution of contributions by sector

Finally, the LCA results of other environmental indicators were calculated for the baseline scenario and a scenario including selected decarbonization measures. 12 environmental indicators were calculated (presented in the supplementary material), and 3 are presented in Figure 6: bulk waste, land-use and primary energy. For these indicators, the gains were lower than those of GHG emissions (-23%): -13% for waste, -12% for land use and -21% primary energy consumption. Food represented nearly all of the land used. Reducing meat consumption by 20% would only reduce land use by 12% as the animal proteins consumed were substituted by other proteins in our scenario. The energy gains were logically the most important for the building sector, which targets a reduction in heating consumption. The electrification of the vehicle fleet does not change significantly waste production, and neither the energy use. A reduction of food waste by half led to a reduction of only 8% of the total waste produced by the food sector.

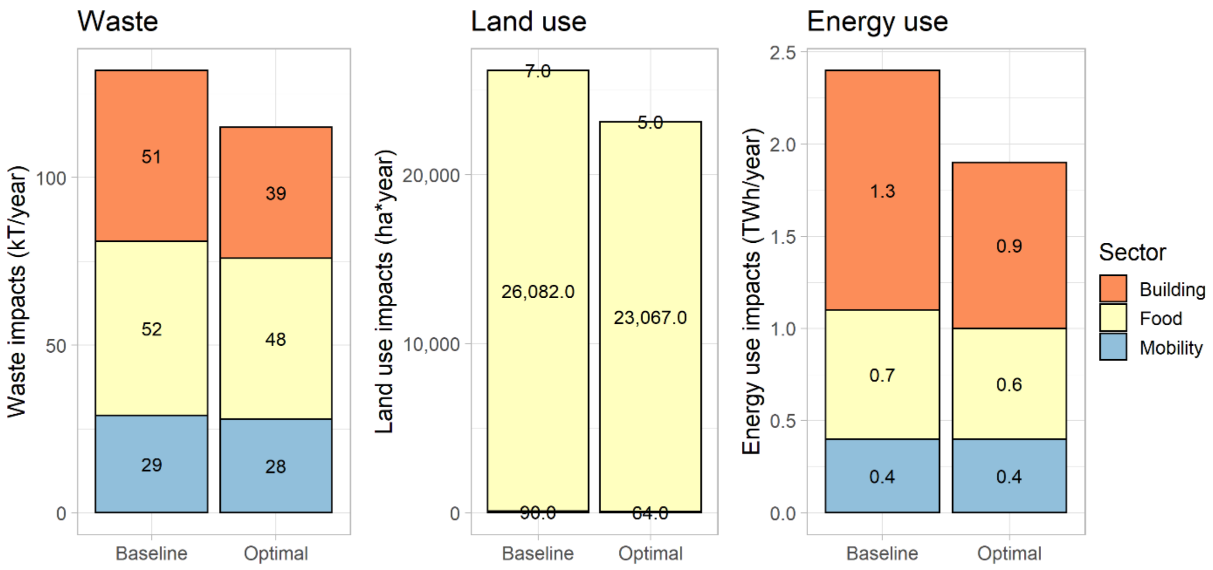

Figure 6: Additional LCA indicators (waste, energy consumed and land use mobilized) by scenario and by sector

5 Discussion

GHG emissions per capita can be compared to studies from other cities. We found climate change impacts of 1.8 t CO_2 eq/cap/a for food, 1.4 t CO_2 eq/cap/a for buildings, and 0.9 t CO_2 eq/cap/a for transport. The total impact was 4.1 t CO_2 eq/cap/a for these three sectors estimated to be the most impactful for a city (Goldstein et al. 2017). The French environmental agency (ADEME) calculated an average carbon footprint of 10.1 t CO_2 eq/cap/a in France (Barbier et al., 2019) and the French high council for the climate gave a higher value of 11.5 t CO_2 eq/cap/a for 2018 (HCC, 2020). Other studies taking a more comprehensive approach also found larger total impacts per person per year, ranging from 11-18 t CO_2 eq/cap/a, in cities including Hong Kong; London, England; Toronto, Canada; Cape Town, South Africa; Beijing, China; and Suzhou, China (Goldstein et al., 2013; Wang et al., 2014). Froemelt et al. (2018) studied a rural municipality with an LCA of 8 consumption sectors, and found a carbon footprint of 9.9 t CO_2 eq/cap/a, with 2.3 t, 1.2 t and 1.7 t CO_2 eq/cap/a for respectively the mobility, building energy and food sectors. Saner et al. (2016, 2013) implemented building, mobility and food LCA at a municipal level based on a micro-simulation methodology for a rural municipality, and found a mean carbon footprint of 5.4 t CO_2 eq/cap/a, with 2.4 t, 1.9 t and 1.1 t of CO_2 eq/cap/a for respectively the mobility, building and food sectors. Based on the Urban Metabolism approach, González-García et al. (2021) estimated the annual carbon footprint for Madrid, Spain, with 7.5 t CO_2 eq /cap/a, and 1.4 t, 2.6 t and 1.9 t related to respectively mobility, building energy and food. The impacts found in our study may be lower than others because we excluded processes like consumption of goods and airplane travel, and because the electricity grid of France is composed of mostly nuclear energy, which has low carbon emissions.

The scope of our study inherently limited our results and the levers of change we evaluated. Our simplified scope of the three sectors excluded important sectors such as consumption of household goods (clothes, appliances, furniture...), which can contribute about 1.5 t CO_2 eq /cap/a in Europe (Castellani et al., 2021). Within sectors, transportation was limited to daily travel by car, excluding public transports, as well as exceptional and long-distance trips, the latter of which have been estimated to be more impactful than daily travel in Paris (Longuar et al., 2010). Buildings were limited to residences, excluding the tertiary sector which represented 33 % of energy consumption of the building sector in 2020 in Europe (European Commission, 2020). Publicly sourced food, such as school and cafeteria meals, was not specified, which limited our ability to assess the specific opportunities of public procurement to reduce impacts, which is a main strategy of cities to reduce impacts (Molin et al., 2021). Finally, the city-scale approach limited the possible levers for change, because strong and transformative initiatives towards reducing climate change impacts come from the national scale, and affect processes beyond the control of the city.

To assess the environmental performance of a city and its potential decarbonization strategies, we built a specific consumption-based approach coupled with LCA framework and data. In this study, consumption patterns for food, building and mobility were determined at disaggregated levels based on detailed and spatialized information on population, activities, buildings and transports networks. In that respect, our methodology stands between "macro" level studies, which represent territorial consumption based on Input-Output tables and downscaling procedure (Dias et al., 2014; Goldstein et al., 2017; González-García et al., 2021), and agent-based modeling studies, which represent individually each inhabitant through microeconomic decision models (Froemelt et al., 2020; Saner et al., 2016).

Our process-based LCA approach provided details to analyze technologies and products contributions (i.e. red meat, car exhaust …) but also to investigate various strategies that modify technology use (i.e. electrical vehicles, new heaters …). In most studies, the data collection and the construction of inventories to handle building, mobility and food sectors is a long process and may include cut-offs to simplify models (Dias et al. 2018, Dong et al. 2016). In our case, we used existing models and databases, such as Pleiades for building energy simulation (Peuportier et al., 2013), MODUS and ModEm-ACV, for mobility and car fleets (François, 2022), and AgriBalyse, for food production and transformation (Asselin-Balençon et al., 2020). Still, the quality of foreground and background LCA data is important, especially because nutrition, mobility and energy use for housing are the three main contributing consumption sectors (Goldstein et al., 2017). In the building sector, the archetype approach allowed for the assessment of city at the expense of simplified building modeling. This could be important because buildings are sensitive to many design variables (material, exposure, …), and it is difficult to conserve a full description of buildings at city scale (Reinhart et Davila, 2016). In transport, the local traffic condition is a relevant factor that impacts environmental performance, and the representativeness and quality of background LCA data remain an issue in transport and required additional work (Frischknecht et al., 2018). In the food sector the main difficulty was the vast range of food products that only few databases can represent consistently (Asselin-Balençon et al., 2020; van Paassen et al., 2019). Relying on general databases prevented us from considering specificities of the local food system that may largely affect environmental performance, such as agricultural practices, production location and food waste treatment (Gheewala et al., 2020; Nemecek et al., 2016).

One important limitation of our methodology was related to its forward-looking aspect, especially its capability to support decarbonization policies. In fact, our territorial consumption assessment method stays descriptive and static, with a set of scenarios based on an "all other things being equal" hypothesis. With this hypothesis, important rebound effects may be omitted, with some time and financial redistribution mechanisms (Girod et al., 2011). Because of their microeconomic and individual equations, some agent-based models can develop dynamic and forecasting approaches to analyze decarbonization policies (Froemelt et al., 2020). The development of such models remains complex with large amounts of data required to extrapolate and calibrate equations, and depending on data sources, results may be less context-specific than our method, due to the generic formulation of consumption mechanisms.

6 Conclusion

This research proposed an original method coupled to a demonstration with a case study for assessing the three main sectors of greenhouse gas emissions at the city level: mobility, buildings, and food. Based on data and models available at the city scale, our method demonstrated a life cycle assessment and allowed to test a number of climate change mitigation scenarios at the individual scale or on a zone of the study area. In addition to providing multicriteria assessment on local consumption, the present method offers a large panel of analyses and interpretations, such process contribution, mapping, and evaluating impact reductions from prospective climate change mitigation measures. The method was demonstrated on a city of 110,000 inhabitants as a part of a large urban metropolitan area. The method can easily be replicated at the scale of the entire region or other cities, if the necessary data are available. However, the use of local commuting patterns and the diversity of residential building types make this method unfeasible at the national level.

The decarbonization plans at the different territorial scales suggest many action levers for all the sectors. However, there is no method or tool to verify whether the proposed actions are sufficient to achieve the targets announced. Our multi-sectoral method provides this response for public decision making. The relative reduction of 23% of GHG emissions with ambitious levers highlights the gap that remains to be filled to achieve a 55% reduction in GHG emissions by 2030. It is clear that the measures proposed in the strategic documents are still largely insufficient.

Our results put into question the potential magnitude of the proposed decarbonization measures, which aim for collective gains as a sum of individual gains from changes in citizens' behavior (Steg and Vlek, 2009; Wynes and Nicholas, 2017). We showed that awareness measures and subsidies for building renovation or vehicle replacement or behavioral nudges are insufficient to reach ambitious climate change reductions. The environmental transition must also be carried out at all levels of society and of the production system. A key element for large-scale, ambitious transitions is the articulation of measures between scales of decision-making, where the city is only one level in a complicated system.

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9 Annex

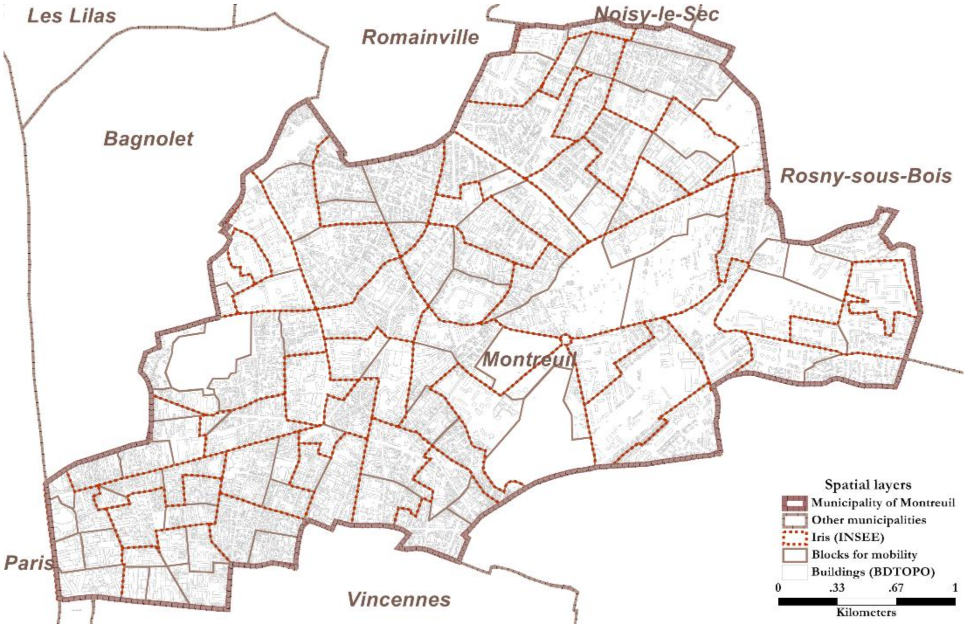

Figure 7: The city of Montreuil, the different territorial divisions and build geographical prints