Impact of circular measures to reduce urban CO_2 emissions: an analysis of four case studies through a production- and consumption-based emission accounting method

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Abstract

Cities are a major source of greenhouse gas emissions (GHGs), but they can play a significant role in climate change mitigation by adopting and implementing GHG emission reduction plans, policies and measures. Circular economy measures are recognized to contribute significantly to decarbonization. However, in the literature there is a lack of quantitative analyses on circular measures in cities and their impact on urban GHG emissions.

The paper aims to contribute to the literature on the relation between circular cities and climate change mitigation by focusing on circular interventions applicable in three high-impact sectors in cities: energy systems, mobility and built environment, in order to investigate their impacts in terms of emission reductions and contribution to decarbonization. The study covers four cities around the world accounting for more than 10 million of inhabitants and 2,000 km^2 of metropolitan area: Bogotá, Colombia; Genoa and Milan, Italy; Glasgow, UK. The methodology uses a Global Trade Analysis Project (GTAP) modelling approach to develop production and consumption-based emission baselines for the four cities and to assess impacts of selected circular measures in the three sectors on the baselines. According to the in-depth analysis of the four considered urban contexts, the majority of the emissions generated by activities carried out within the urban borders are emitted outside the borders in the form of emissions scope 3, thus demonstrating how today's cities are large consumers of goods produced outside their borders, requiring the use of a consumption-based approach for emissions inventory. The results on the modelling of the GHG reduction impact of circular measures show that there is a relevant emission reduction potential in Scope 1 and 2 emissions in cities and highlight the need to prioritize decarbonisation of electricity supply in order to ensure relevant emission reductions across the three sectors. The results also demonstrate the potential to reduce supply-chain Scope 3 emissions through urban measures.

Keywords

Circular cities, GHG emissions reduction, consumption-based approach, Energy, Mobility, Built environment

Introduction

Climate change is a top priority for countries and cities around the world. The damaging consequences of rising temperatures and the increased frequency of extreme weather events are impacting on social, economic and environmental systems. Cities are recognized as key contributors to climate change, as they account for 70% of global carbon emissions, 60% of resource use (UN-Habitat, 2019) and produce 50% of global waste (OECD, 2020). Cities, however, can be a significant element of the solution, largely achieved through climate protection and mitigation measures (Gallo et al., 2016). They are key places where GHG emission reduction actions can be implemented and relevant reductions can be achieved in different sectors, including built environment, mobility, public lighting, energy production (Croci et al., 2021). Given the increasing pressures and need to cut GHG emissions transforming our production and consumption models, cities can and need to adopt further measures and principles to decarbonize, including the circular economy (Bolger and Doyon, 2019). More and more cities today understand the importance of their role in the global process of decarbonization and leverage the principles of circularity in applying their strategies.

Circular economy represents a system-level approach that aims to maximise resource use and minimize waste, reappraising the entire economic model and encompassing the entire value chain. The implementation of a circular economy requires the transition to renewable energy sources and the use of renewable materials, as well as the implementation of principles like: design out waste and pollution across the value chain; keep products and materials in use to retain embodied energy; and regenerate natural systems to sequester carbon in soil and products (Ellen MacArthur Foundation, 2019b). The application of these principles in production and consumption models can contribute significantly to reduce GHG emissions (Ellen MacArthur Foundation, 2019b).

The benefits of applying a circular model become evident at the urban level where the city can be represented as a system of flows. Cities are the place where most goods and energy flows are consumed, as well as the place where most people live and work. The growing awareness of the link between a linear consumption model and the negative environmental impacts is leading many cities to apply the principles of the circular economy. City governments are increasingly looking at circularity to manage their cities more efficiently and sustainably, and many of them are already active on this topic, by developing city-wide circularity strategies or sectorial initiatives (C40, Climate-KIC, 2018). Incorporating the principles of circularity from the definition of policies to the management of the city allows policy makers to redefine the choice, use and procurement of goods and materials in pursuit of economic development “that supports prosperity, jobs, health and communities” (Ellen MacArthur Foundation, 2019).

The transition to a circular city needs to encompass all major urban sectors, including transportation, waste, food, public space management and energy, as well as foster the involvement of citizens and key stakeholders alike. It is an opportunity to develop integrated and complementary policies across different sectors, levels of governments and stakeholders (OECD, 2020). Fostering the spread of renewable energy and end-use electrification, reducing waste and the promotion of sharing and reuse of goods are among the distinctive elements of circular cities (Del Borghi et al., 2020; Gallo et al., 2017; Ellen MacArthur Foundation, 2017).

While in the literature there are several studies on circular city strategies, visions and targets, there is a lack of quantitative analyses on circular city measures and their impact on urban GHG emissions (Paiho et al. 2021). Some quantitative studies focus on specific sectors, and only a few of them widen their scope including several sectors and analysing their interactions (Paiho et al. 2021).

Christis et al. (2019) measure the material and carbon footprint of Brussels focusing on city residents’ consumption, and quantify the impact of circular strategies to climate change mitigation in three main sectors: food, housing and mobility.

Paiho et al. (2021) analyse a set of circular solutions in the transportation, energy and food sector for a district in the city of Espoo to quantify their energy and carbon emission impact; they also provide examples of circular business models and consider the relevant regulations that could support the implementation of such solutions.

While many cities worldwide have quantified their production-based GHG emissions and defined mitigation plans and policies to reduce them, only few cities have started to analyse or consider their consumption-based emissions (Sudmant et al., 2017). A production-based perspective - which considers only the emissions associated with production activities located in the city - is not enough to capture the benefits of circular measures which affect the whole supply chain of products and services, therefore a consumption-based approach to analyse urban emissions should be applied when assessing the GHG reduction impact of circular city measures.

This paper aims to contribute to the literature on the relation between circular cities and climate change mitigation by focusing on circular interventions applicable in three high-impact sectors in cities: energy systems, mobility and the built environment, in order to investigate their impacts in terms of emission reductions and contribution to decarbonization. Evaluations and results are carried out by using a model developed by C40 Cities (C40 Cities, 2018), in accordance with the consumption-based methodology described in the PAS 2070 (BSI, 2014), which employs an LCA approach, to assess impacts on consumption-based emissions of a set of interventions in cities (Strazza et al., 2015). Literature is showing increasing interest in consumption-based emissions (C40 Cities, 2018; Dahal et al., 2017; Sudmant et al., 2018) this is also confirmed by the development of standards such as the previously mentioned PAS 2070 (BSI, 2013). This is because city activities and consumption generate significant amounts of GHG emissions outside their administrative borders (Chen et al., 2016; Minx et al., 2013). Other accounting methods (i.e. territorial-based or production-based) have the limit that do not take in account upstream emissions that derive from goods production and services utilized by citizens.

The study considers cities around the world that are testing circular economy solutions, covering the following ones: Bogotá, the capital of Colombia, Genoa, leading Mediterranean port in Italy; Glasgow, a leading post-industrial city in UK and Milan, the most dynamic city for Italian economy. The four cities account together for more than 10 million of inhabitants and 2,000 km^2 of metropolitan area.

Firstly, the paper calculates and compares the production-based and consumption-based emission baselines for the four cities. After analyzing existing decarbonization policies and circular strategies of each city, a reference model (Arup et al., 2019) was used to help identify the most significant circular actions that could lead to a reduction in greenhouse gas (GHG) emissions associated with each city's consumption of goods and services. Following that, interventions were identified and the potential decarbonization impact on the municipal baseline emissions was calculated. Then, quantitative analyses of the defined circular interventions were performed for each city and sector with the aim of allowing cities to measure the global GHG emissions impact of their transition to a decarbonised and circular economy. In comparison to national and international research, it is proved that there is less research on GHG emissions from cities (Gouldson et al., 2015) but literature on production-based emissions of cities is growing (Kennedy et al. 2009, 2010; Glaeser, 2010; Lin et al., 2015; Minx et al., 2013; Feng et al., 2014). In this way, the paper aims to contribute to the literature on urban GHG emissions by providing an estimation of cities' consumption-based emissions, which are not often quantified and taken into account in studies on local mitigation policies (Sudmant et al., 2017). It also wants to contribute to the literature on circular city policies, offering an estimation of the decarbonization impacts of circular measures that could be applied and leveraged in several sectors.

The paper is structured in the following Chapters, after the introduction: 2) Methodology, describing the GHG emission accounting approach used in the paper to quantify the consumption-based emission baselines of the four cities, the main data sources and the process followed to identify and select the circular interventions to be modelled in the study; 3) Sectors and interventions, presenting in detail the selected circular interventions in the three sectors, the modelling approach and the main assumptions; 4) Results and discussion, presenting and commenting the consumption-based emission baselines of the four cities and the GHG emission reduction impacts of selected interventions in the three scopes, as well as the study main limitations; 5) The final Chapter summarizes the key results and identifies further lines of research.

Methodology

1.1 Cities' GHG emission accounting

As basis for their climate change mitigation strategies and actions, several cities worldwide have developed GHG inventories aiming to quantify emissions attributable to their territories. In lack of an official and common international standard or protocol on local and regional GHG accounting, different methodologies have been used at this purpose (Ibrahim et al., 2012). In some cases, methodologies initially developed for nations have been adapted and applied to the local level. There have been some initiatives to define GHG accounting protocols for cities which could be applied at international level, but up to now they have not succeeded to be widely diffused, for inherent complexities and lack of needed data (Erickson and Morgenstern, 2016).

A key issue in the elaboration of urban GHG emission inventories regards the definition of the spatial area to be considered and the activities that should be included or not in the inventory, namely which direct and indirect emissions should be included (Lombardi et al., 2017). Regarding the spatial definition, city boundaries can be defined using administrative, functional or morphological criteria (Seto et al., 2014).

To improve and rationalize the categorization of direct and indirect emissions in the context of GHG emissions accounting by local authorities, some organizations have adapted and applied at urban scale the concept of "scopes", which was initially used for GHG emission accounting in companies. According to WRI, C40 Cities, ICLEI (2021), Scope 1, Scope 2 and Scope 3 are defined as follows:

Scope 1: GHG emissions from sources located within the city boundary

Scope 2: GHG emissions occurring as a consequence of the use of grid-supplied electricity, heat, steam and/or cooling within the city boundary

Scope 3: All other GHG emissions that occur outside the city boundary as a result of activities taking place within the city boundary.

Scopes enable to categorize urban emissions based on the location where GHGs are physically emitted and are now used in several protocols for urban GHG inventories.

Three main methodological principles can be identified in local emissions accounting: a territorial approach, which accounts for emissions physically generated within city boundaries and jurisdiction; a production-based approach, which includes emissions from economic activities of households and businesses whose operations may extend beyond city limits (EEA, 2013); and a consumption-based approach, which assigns emissions to the consumption activity that has caused them, regardless of the location where emissions are physically emitted (Hermansson, 2014; Munksgaard and Pedersen, 2001; Peters and Hertwich, 2008). A consumption-based approach thus considers the upstream and embedded emissions of products and services consumed within a territory (Harris, 2019; EEA, 2013). A consumption-based approach is relevant to explore the impacts of interventions that affect the supply-chain of products and services and their associated GHG reductions in a circular economy perspective.

The technical methodology to develop this study is based on the modelling approach developed by C40, Arup and the University of Leeds (Arup et al., 2019). The technical modelling technique's purpose is to understand the global GHG impact of activities that occur within city borders by establishing a consumption-based emission baseline for a particular year. This approach was chosen to ensure that results reflect the emissions that occur as a result of the demand for goods and services driven by activities within city boundaries, as opposed to just emissions from sources within the city. Year 2017 is chosen as baseline year. To construct GHG emissions baselines for each city, the modelling framework developed by Arup/C40 Cities for the computation of 80 global city footprints as part of the "Consumption-based GHG emissions of C40 cities" study published in 2018 was used (C40, 2018). To estimate GHG consumption-based emissions, in according to the consumption-based methodology described in PAS 2070 (BSI, 2014), a hybrid modeling approach is followed, combining bottom-up and top-down accounting approaches: bottom up approach is used in order to create more complex systems higher up the informational ladder using data collection methods, simpler field-level systems are pieced together, becoming subsystems of the final design; top-down approach is a data collection method that entails developing a broad system of data collection and analysis before describing and developing its underlying subsystems (Arioli et al., 2020). In this paper, Scope 1 and 2 emissions are evaluated starting from bottom-up estimates while Scope 3 supply chain emissions are evaluated using a top-down approach based on an Environmentally Extended Input-Output Analysis (EEIO) (Yang et al. 2017). The EEIO analysis approach is used in order to identify financial flows connected with city consumption, and then uses these financial flows to estimate associated GHG emissions using sector-averaged emissions factors for each consumption category. This EEIO analysis was based on the Global Trade and Analysis Project's (GTAP) Multi-Region-Input-Output (MRIO) database (Aguiar et al., 2019) with city-specific data on economic activity and industry emissions used to scale national data to city emissions through the modelling platform. The GTAP model was last updated in 2014, and the city baselines were projected to the study's baseline year of 2017. This estimate was derived from the projection approach provided in Arup et al. (2019) which integrated reported city growth trends from 2014 to 2017 with IEA decarbonisation trends for key industrial emissions sources over the same time period.

This hybrid modelling method, which combines bottom-up and top down approaches, was chosen for the following reasons: i) it provides an estimation of Scope 1 and Scope 2 emissions which is consistent with previous studies on urban GHG emissions; ii) it allows to estimate Scope 3 emissions, showing the scale of GHG impacts related with cities' consumption patterns; iii) it allows to evaluate the circular interventions' impacts on all the three Scopes, including the consideration of products' supply chain, showing a more complete overview of their effect on GHG emissions.

A consumption-based perspective is chosen, as the study considers the Scope 1 and Scope 2 emissions associated with city-related energy consumption and Scope 3 emissions associated with citizens' consumption of goods and services.

1.2 Data sources

The study covers four cities around the world (Bogotá, Colombia; Genoa, Italy; Glasgow, UK and Milan, Italy). Table 1 reports an overview of key city figures and statistics. Sources are specified in the table. Due to the lack of statistics on the Gross Domestic Product (GDP) for the Municipality of Genoa, the value reported in Table 1 was retrieved from GDP data from the Liguria Region (to which Genoa belongs) and scaled using the population ratio. For Milan, the GDP value was retrieved from OECD statistics and is referred to the Metropolitan City of Milan, which is the wider metropolitan area comprising the Municipality of Milan and other 132 municipalities, corresponding to an overall population of about 3.2 million inhabitants and an area of 1,575 km^2. Given the role of Milan in the overall economy of its metropolitan area, this value is considered as representative for Milan's GDP.

Table 1 - Key figures for the cities (for year 2017)

Cities	**National population (no. of inhabitants)**	**City population (no. of inhabitants)**	**Metropolitan area (km^2)**	**GDP (MLN€)**	**Energy use (kWh)/capita**
Bogotà	44,164,417 (DANE, 2018)	7,412,566 (DANE, 2018)	1,580	70,980 (DANE, 2017)	3,707 (SDP, 2020)
Genoa	60,066,734 (ISTAT, 2017)	580,097 (ISTAT, 2017)	240	18,376	2,448

				(ISTAT, 2017)	(SECAP 2020-30, 2020)
Glasgow	5,424,800 (ONS, 2017)	621,020 (ONS, 2017)	175	26,115 (ONS, 2017)	4,309 (DBEIS, 2017)
Milan	60,066,734 (ISTAT, 2017)	1,363,683 (ISTAT, 2017)	182	174,898 (OECD, 2017)	4,948 (Piano Aria e Clima 2020)

Table 2 reports data and data sources used to calculate the city's 2017 consumption-based baseline. The data gathering process was the same in all three European cities where 2017 emissions statistics by end-use were easily and publicly available. In Bogotá, a previously built model (Arup et al., 2019) was used due to a lack of disaggregated emissions data for 2017. City population data are those reported in Table 1. Genova emissions were estimated from 2016 data using population variation ratio.

Table 2 – Data inputs for baseline calculation

Data point	Bogotà	Genova	Glasgow	Milan
Residential building emissions (Scope 1)	*	506,549 [tCO_2eq] (SECAP 2020-30, 2020)	540,596 [tCO_2eq] (DBEIS, 2017)	1,537,000 [tCO_2eq] (based on Piano Aria Clima 2020)[1]
Non-residential building emissions (Scope 1)	*	222,977 [tCO_2eq] (SECAP 2020-30, 2020)	278,873 [tCO_2eq] (DBEIS, 2017)	747,000 [tCO_2eq] (based on Piano Aria Clima 2020)
Residential building emissions (Scope 2) – electricity	*	291,126 [tCO_2eq] (SECAP 2020-30, 2020)	247,473 [tCO_2eq] (DBEIS, 2017)	481,000 [tCO_2eq] (based on Piano Aria Clima 2020)
Non-residential building emissions (Scope 2) – electricity	*	397,153 [tCO_2eq] (SECAP 2020-30, 2020)	357,044 [tCO_2eq] (DBEIS, 2017)	1,483,000 [tCO_2eq] (based on Piano Aria Clima 2020)
In boundary transport emissions	4,745,160 [tCO_2eq]	263,143 [tCO_2eq] (SECAP 2020-30, 2020)	815,652 [tCO_2eq] (DBEIS, 2017)	853,000 [tCO_2eq] (based on Piano Aria Clima 2020)
Baseline national grid intensity	0.191 [tCO_2eq/MWh]	0.308 [tCO_2eq/MWh] Piano Aria Clima 2020	0.352 [tCO_2eq/MWh] Greenhouse gas reporting: conversion factors 2017[2]	0.308 [tCO_2eq/MWh] Piano Aria Clima 2020

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[1] http://allegati.comune.milano.it/politicheambientali/AdozionePianoAriaClima/delibera79.pdf

[2] BEIS, "Energy and climate change: evidence and analysis," 2018. Available: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2017

* Due to a lack of disaggregated emissions data for 2017, the previously developed model of "The Future of Urban Consumption in a 1.5°C World" report was used.

1.3 Interventions selection approach

This research is part of a wider project performed by the authors together with other research groups focusing on the impacts of circular cities on decarbonization and beyond (ENEL 2021). The circular city vision encompasses several key urban sectors, as it aims to redefine energy and material flows. Given the need to prioritize, the study focuses on three of them: energy systems, mobility and the built environment.

After analyzing existing decarbonization policies and circular strategies of each city (considering Arup et al., 2019 for Bogotá and Glasgow, the Sustainable Energy and Climate Action Plan – SECAP 2020-30 for Genoa, the Air and Climate Plan - Piano Aria Clima 2020 for Milan), a preliminary list of interventions consistent with Valeche-Altinel C. et al (2021) and Ellen MacArthur Foundation (2020) was identified according to current best practices. The preliminary list was further refined based upon several criteria, including replicability in the four cities and in response to feedback from a wide range of stakeholders interviewed for the project. A mix of interventions already included in city plans, measures with increased ambition and completely new measures were considered and analysed in the modelling exercise. Energy system interventions aim to reduce the consumption of fossil fuels for energy production by exploiting local production through renewable sources, e.g., through photovoltaics (PV), and the reduction of consumption. Mobility interventions consider criteria such as the state of the existing transportation infrastructure and services, the opportunities arising from new technologies, and the current level of adoption of sustainable transportation modes, electric vehicles, and innovative technologies to improve vehicle manufacturing. Built environment interventions consider criteria such as improved use of existing buildings and spaces, energy efficiency interventions, electrification of building services, as well circular principles in new construction including more efficient use of materials, use of lower-carbon materials, and more efficient/modular/flexible design. The process to select the interventions and their modelling approach is described in detail for each sector in the following section.

Sectors and interventions

Energy systems sector focuses on production, distribution and supply of electricity to end customers to power operations within the city, emissions associated with the supply chain to build this infrastructure, and digitalization as an enabler of circularity. The sector analysis focuses on electricity consumption (Scope 2) emissions associated with the operation of cities, including buildings, infrastructure and electric vehicles. This is because shifting to renewable energy coupled with electrification is the strongest lever to achieve sustainable development. The study also considers supply chain emissions associated with the production and distribution of the electricity consumed in cities, and the manufacture (Scope 3) of products that generate, distribute and run-on electricity, such as lighting, highway signaling equipment and household appliances.

The mobility sector analysis looks at emissions from vehicle manufacture, fuel supply chain and electricity transmission and distribution (Scope 3), and direct emissions from the operation of vehicles (Scope 1). The indirect (Scope 2) emissions deriving from electricity consumption of electric vehicles were considered limited to the additional energy requirements that are implied by transport electrification; issues regarding the decarbonization of the energy grid were considered in the Energy Systems sector.

The built environment sector comprises direct emissions from the operation of buildings and infrastructure (Scope 1), emissions associated with energy efficiency interventions and building electrification (Scope 2), and supply chain emissions associated with the construction of buildings within each city (Scope 3). The built environment did not consider the source of energy supplied to buildings (for example renewable sources of energy for building operation) as this was covered in the Energy Systems sector.

The selected interventions are described in detail in the paragraphs below.

1.4 Energy systems interventions

Energy solutions considered in the study are novel and hard interventions aiming at drastically lowering the use of fossil fuels in energy production by exploiting local production via renewable sources (sun and wind) and reducing consumption.

Table 3 shows the final list of interventions selected for the study.

Table 3 – Selected circular interventions – Energy systems sector

Sector	Intervention	Description	Expected impact
Renewable Energy	Installation of PVs on the roofs of public and private buildings	This intervention aims to reduce the use of fossil fuels in the production of electricity, taking into consideration the different aspects of the cities due to their geographic location and the arrangement of the buildings in the environment.	Reduction of Scope 2 emissions caused by the lower use of fossil fuels and therefore reduction of Scope 3 emissions from the supply chain. Increase of Scope 3 is caused by the creation of new PVs.
	Buying energy from renewable plants outside the city limits	This intervention considers the possibility that the administration commits to buying energy from a specific renewable project over a long-term period e.g. by entering into a Power Purchase Agreement (PPA),	Reduction of Scope 2 emissions caused by the lower use of fossil fuels and therefore reduction of Scope 3 emissions from the supply chain. Increase of Scope 3 is caused

		and implies the construction of renewable plants able to satisfy the electricity needs of the municipality.	by the creation of new renewable power plants.
Digitalization of services - smart city	Smart metering	The real-time monitoring of various urban parameters (e.g. passenger flow, traffic patterns, parking space vacancies, etc.) to optimize operations and have a solid statistical base from which to define new interventions	Reduction of Scope 2 and Scope 3 emissions (reduction caused by the lower use of electricity and therefore reduction of Scope 3 emissions from the supply chain).

Further interventions related to service digitalization were also considered (e.g. connectivity, home automation) but they could not be evaluated for various reasons. Connectivity implies the development of a reliable digital infrastructure for all cities to enable them to benefit from remote services such as e-government, e-health, and remote working. Connectivity intervention, despite resulting in Scope 1 emissions reduction due to less mobility needs (Malmodin et al., 2015), could not be modelled since the reference literature assesses global impacts, and scaling the affects to an infinitely smaller size, such as the urban scale, is difficult.

Home automation is the implementation of domestic solutions that monitor and manage home appliances and aim at reducing the energy needs of any building, especially in terms of winter heating, summer cooling and lighting. According to the literature (Louis et al., 2015), home automation intervention has a good potential for reducing emissions scope 2, but due to its long payback time in terms of both electricity consumption and CO_2 emissions reduction, it was not modelled.

Table 4 outlines the process for modelling the impact of selected sustainable energy systems intervention against a city's consumption-based emissions.

Table 4 – Energy intervention application in the model description

Intervention	Modelling approach
Renewable Energy	
Installation of PVs on the roofs of public and private buildings	Apply a percentage reduction to the Scope 2 electricity emissions intensity to represent the reduction in use of electricity produced from non-renewable sources. Apply a percentage reduction to the electricity supply chain activities associated with the consumption of electricity in the city that is proportional to the reduction in total Scope 2 emissions within the city. Apply an increase in Scope 3 emissions directly to the overall value due to the construction, maintenance and disposal of PV panels.
Buying energy from renewable plants outside the city limits	Apply a percentage reduction to the Scope 2 electricity emissions intensity to represent the reduction in use of electricity produced from non-renewable sources. Apply a percentage reduction to the electricity supply chain activities associated with the consumption of electricity in the city that is proportional to the reduction in total Scope 2 emissions within the city.

	Apply an increase in Scope 3 emissions directly to the overall value due to the construction, maintenance and disposal of wind turbines.
Digitalization of services - smart city	
Smart metering	Apply a percentage reduction to the scope 2 emissions to represent the decrease in residential electricity consumption. Apply a percentage (equal to the 8% of the residential electricity consumption only) reduction to the electricity supply chain activities within the city. Apply a reduction in emissions Scope 3 due to the replacement of first-generation devices (common electricity meters) with those less impactful second-generation directly to the overall value.

The effectiveness of the installation of PVs, intervention acting on the improvement of the electric mix consumed in cities, strongly depends on two factors: the irradiation of the site under consideration, a city reached by better solar radiation will have a greater potential to exploit, and the ratio of the surface of the roofs available and suitable for installation of the PVs and the city's electricity consumption. In the present study, a ratio of 15% of the total area of the roofs of cities was considered to take into account the impossibility of installing PV panels on some roofs due to particular structural conformations, architectural constraints, roofs used as condominium terraces, unavailability of the owners, exposure of the northern slopes, shaded roofs. This parameter can be assessed in more detail by means of more accurate approaches that assess surfaces that meet the requirements described above (Qerimi et al., 2020; Jain, S. K., 2021). The emissions resulting from the installation of new PV panels have been accounted for using a bottom-up approach that incorporates the value, which varies by city depending on the amount of electricity production available from this source, into the model. An emission factor of 30,000 tCO_2eq/TWh is assumed to calculate the Scope 3 emissions value associated with the construction of new devices (Fthenakis et al., 2006).

To model the purchasing of renewable energy outside the city limits, as electricity generation sources changes due to the intervention, it has been hypothesised to replace the fossil component of the electric mix that feeds the public consumptions (public buildings, public lighting and electric public transport vehicles) and the residential ones with electricity from wind farms located close to the city borders. These consumption categories were chosen because, in order to boost all other sectors, public administrations must be at the forefront of the transition to clean energy use, and residential consumption was chosen because, according to statistics from the four cities, it represents the largest share of electricity usage within metropolitan boundaries. Onshore wind farms were planned in particular for the cities of Genoa, Milan, and Bogota, whereas an offshore wind farm was picked for the city of Glasgow due to the abundant wind potential (GWEC, 2021). The emissions resulting from the installation of new wind farms have been accounted for using a bottom-up approach that incorporates the value, which varies by city depending on the amount of electricity production available from this source, into the model. In order to calculate the Scope 3 emissions value associated with the construction of new wind farms an emission factor of 7,600 tCO_2eq/TWh is assumed for onshore wind turbines (Bonou et al., 2016) and 9,350 tCO_2eq/TWh for the offshore ones (Bonou et al., 2016).

The efficacy of smart metering, which entails installing meters in all the houses in the four cities, is primarily determined by the ratio of scope 2 emissions from the residential area to total Scope 2 emissions. As smart meters allow to reduce electricity consumption by about 8% (Bagnasco et al. 2015, Bagnasco et al. 2017, Carroll et al. 2014) in the residential sector, the higher this ratio, the greater the effectiveness of this intervention. The emissions resulting from the installation of new devices have been accounted for using a bottom-up approach that incorporates the value into the model. A scope 3 emissions reduction equal to 7 $kgCO_2eq$/device is obtained, according to Enel data (Enel, 2020), since smart devices substitute traditional ones.

Table 5 reports emission reduction obtained for each selected intervention in the energy sector, based on the results obtained in other places contained in the scientific literature.

Table 5 – Emission reductions – Energy Sector

	Bogotá		**Genoa**		**Glasgow**		**Milan**	
Interventions	Scope 1	Scope 2	Scope 1	Scope 2	Scope 1	Scope 2	Scope 1	Scope 2
Installation of PVs on the roofs of public and private buildings	-	-4.8%	-	-22.5%	-	-5.3%	-	-10.9%
Buying energy from renewable plants outside the city limits	-	-52.6%	-	-34.5%	-	-13.7%	-	-21.7%
Smart metering	-	-8%	-	-8%	-	-8%	-	-8%

1.5 Mobility interventions

All the four considered cities have already put in place a series of sustainable mobility policies and measures through their city plans, in order to improve the environmental performances mobility in their cities. These include for example the promotion of public transport, vehicle electrification, mobility sharing schemes, etc. However, these measures are seldom evaluated in terms of their impacts on Scope 3 emissions. In the study, it was decided to evaluate a combination of mobility measures already included in city plans, considering in some cases also a possible increase of their ambition, and measures not foreseen in city plans, in order to estimate when possible their impacts on the three emission Scopes.

Table 6 reports the final list of selected interventions for the mobility sector.

Table 6 – Selected circular interventions – Mobility sector

Sector	Intervention	Description	Expected impact
Transform mobility	Modal Shift	Reducing private vehicle use and replacing it with sustainable modes of transportation (public transit, active mobility, shared mobility and micro-mobility)	Reduce Scope 1 and Scope 3 emissions associated with fuel use.
	Vehicle sharing and pooling	Providing the same mobility services with fewer vehicles through "pay per use" solutions (e.g. car sharing). This would limit the number of cars on the road and the purchase of private vehicles, reducing emissions and improving air quality	Reduce Scope 3 emissions associated with the value chain to produce new vehicles.
Transport electrification	Switch to electric vehicles	Switching to electric bus fleets and developing or expanding subway and light rail systems. Encouraging the decarbonization of private mobility through supportive measures for electric mobility	Eliminate Scope 1 emissions from traditional vehicles. Increase in Scope 2 and 3 emissions due to electricity consumption, and in Scope 3 emissions due to the embodied emissions of new vehicles
Circular design	Vehicle manufacturing	Choice of materials, ease of repair/replacement of components, and durability, use of recycled and renewable materials (such as bio-based materials), the efficiency of disassembly and the recovery rates of components (especially batteries)	Reduce Scope 3 emissions associated with the production of vehicles.

Further interventions related to fleet renovation, circular approach in vehicle manufacturing and the adoption of flexible working schemes were considered, but they could not be evaluated due to data limitations and time constraints.

Fleet renovation refers to the substitution process of existing private/public vehicles with newer and more efficient ones, which may have an impact on reducing fuel use and related emissions. This intervention was not modelled due to the complex interaction of different factors (i.e. renewal rate due to vehicles' aging and wearing, availability of incentive schemes at different levels, EU legislation on new vehicles' CO_2 emission performances), for ongoing trends in purchasing bigger vehicles which might offset the fuel efficiency, and for the impact of newly purchased vehicles on Scope 3 emissions.

Circular approach in vehicle management and manufacturing includes a variety of measures which interact with each other, i.e. designing vehicles in a more efficient way and for durability (production side) and/or enhancing their maintenance and repair (consumer side), which could reduce Scope 3 emissions due to the embodied emissions of new vehicles. A further measure could involve the recovery, reuse and repurpose of materials and components of vehicles, which would reduce Scope 3 emissions associated with vehicle disposal and extraction/consumption of primary raw materials. Based on Arup et al. (2019), it was decided to focus on the possible reduction in materials consumption (in particular of steel and plastics) due to more efficient design of vehicles and model this intervention only.

Flexible working schemes refer to the possibility that employees perform remote working from their homes, therefore reduce mobility needs and optimizing commuting times. This intervention was not modelled as the COVID-pandemic is still unfolding and its impacts on mobility patterns are quite differentiated.

Table 7 describes the process for modelling the impact of selected mobility interventions against a city's consumption-based emissions.

Table 7 – Mobility intervention application in the model description

Intervention	Modelling approach
Transform Mobility	
Modal shift	Reduce the Scope 1 private transport emissions (personal mobility only) by the amount (taken from city plans or modelled) attributed to sustainable transport modes. Apply a percentage reduction to the Scope 3 emissions from the “Petroleum, coal products” GTAP sector equal to the Scope 1 percentage reduction (mobility baseline) due to modal shift. The percentage reduction in Scope 3 emissions of the “Petroleum, coal products” GTAP sector considers the supply chain emission savings due to reduction in fuel use both from modal shift measures and from transport electrification.
Vehicle sharing and pooling	Apply a percentage reduction to the Scope 3 emissions associated with vehicle manufacturing.
Transport electrification	

Switch to electric vehicles	Set tailpipe emissions to 0 for the share of traditional vehicles replaced with EVs. Increase the Scope 2 emissions for the electrified vehicles to account for their electricity requirements. Apply a percentage reduction to the Scope 3 emissions from the "Petroleum, coal products" GTAP sector equal to the Scope 1 percentage reduction (mobility baseline) due to transport electrification. Apply a percentage increase to the Scope 3 emissions from the "Electricity" GTAP sector equal to the Scope 2 percentage increase due to electrification. Where applicable, apply a percentage increase to the Scope 3 emissions to the batteries component of electric vehicles within the "Motor vehicles and components" GTAP sector.
Circular design	
Vehicle manufacturing	Apply a percentage reduction to the Scope 3 emissions associated with the material components (steel and plastics) of vehicle manufacturing.

Considering mobility interventions, the impact of modal shift measures on direct Scope 1 emissions was estimated as a reduction of CO_2 emissions due to the reduction of private car use. It also includes the effect of vehicle sharing and pooling, which affects individual mobility patterns. For the study cities, two alternative approaches have been followed. Where relevant city plans provided estimates of CO_2 reductions by 2030 due to measures falling within the Scope of modal shift, these values were used directly as the Scope 1 reduction. This was the case for Genoa and Milan, where the level of adoption is given by the GHG emission reduction estimates provided by the city plans (the SECAP and Air Climate Plan, respectively). These include measures both planned and already in phase of implementation that contribute to shifting to sustainable transport modes[3]. Alternatively, CO_2 emission reductions from this intervention were estimated based on the expected percentage reduction in demand for private transport resulting from the implementation of modal shift measures in the city, which was provided by city experts involved in this study. This approach was followed for Glasgow and Bogotá. A Scope 3 emission reduction was also considered related to lower fuel use from this intervention (together with transport electrification intervention), as reducing tailpipe emissions also implies a reduction of life-cycle emissions along the fuels supply chain (related to extraction, distribution, etc.).

Modal shift measures may also reduce purchases of new private vehicles. In fact, if efficient, affordable and sustainable mobility alternatives are provided, households may decide to buy fewer new cars and use other transport modes. Therefore, these measures could impact as well on Scope 3 emissions associated with the manufacturing of new private vehicles. In this study, the impact on

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[3] These targets are considered to be ambitious and are consistent with achieving at least a 40% and 45% GHG emissions reduction compared to 2005 levels, respectively.

Scope 3 emissions associated with lower household expenditure on privately owned vehicles is modelled together with the vehicle sharing and pooling intervention.

To evaluate the impact of transport electrification, all the three Scopes were considered in this study, considering the replacement of traditional vehicles with EVs (cars for private transport and buses for public transport) in Milan, Genoa and Glasgow, whereas for Bogotá only the implementation on public transport was modelled. The high decarbonisation potential from this intervention is underlined by Arup et al. (2019), highlighting the potential for electric vehicles to become zero emissions as electricity grids decarbonise.

The impact on Scope 1 emissions is estimated considering the reduction in tailpipe CO_2 emissions of traditional vehicles that are substituted with Electric Vehicles through this intervention. To this end, values are considered for each city regarding the expected penetration of electric vehicles in the fleet, average CO_2 emission factor of vehicles (gCO_2/km) and the annual average kilometres travelled by vehicle type.

The impact on indirect Scope 2 emissions due to electricity consumption by EVs is also modelled. To this end, values are considered for each city regarding national electricity emission factors (gCO_2/kWh), average consumption of electric vehicles (kWh/km), and the annual average kilometres travelled by vehicle type.

With respect to Scope 3 emissions, studies in the literature estimate that the embodied carbon associated with manufacturing EVs are between 15% and 68% higher than an equivalent ICE vehicle, depending on the size and range of the vehicle, according with Arup et al. (2019). World Economic Forum & McKinsey report (2021) estimate 1.5-2.0x higher material emissions for BEV compared to ICEV due to energy-intensive battery production. Therefore, an average uplift factor of 50% for vehicle manufacturing end-products from global supply chains was applied for Bogotá.

However, due to the new regulation and massive investments in the sector made by the EU, as outlined in the report, EVs manufactured in Europe in 2030 are assumed to be neutral in terms of Scope 3 CO_2 emissions. For this reason, no uplift of Scope 3 emissions due to EV manufacturing has been considered for the cities of Milan, Genoa and Glasgow. This assumption is reinforced by clear market trends. In fact, as EV demand ramps up, and new factories are built in Europe – which is transitioning to renewable energy sources for the manufacturing process -, their environmental impact will further decrease. Moreover, it is still difficult to correctly impute costs to electric vehicles as technologies are advancing and particularly reusage and recycling methods can extend battery lifecycles – while ICE technologies are nowadays mature and do not have a second-life potential. As batteries can be recycled, their environmental cost can be split over more years, specifically for a period that goes beyond the vehicle's lifecycle itself. In fact, batteries can normally be used in vehicles until they reach 80% of their initial capacity and a self-discharge rate of 5% over 24 hours (Engel, et al., 2019), but there are several potential applications after their first life, particularly in energy conservation for utilities, in deferring transmission and distribution investments and grid optimisation (ibid.). A recent study by Transport & Environment (2021) estimates that batteries for electric cars are already able to repay their "carbon debt" from production in "just over a year", based on average European electricity.

For what concerns vehicle sharing and pooling, its impact on Scope 1 emissions is considered in the "modal shift" intervention, as it interacts with other measures that promote modal shift.

The impact on Scope 3 emissions is mainly given by the fact that some households using shared vehicles will find it convenient to give up on their private car, and therefore reduce their expenditure on private vehicles. There is a vast literature on vehicle sharing trying to assess the impacts on mobility systems, in general, and car ownership more specifically; however, clear results do not emerge. Several studies highlight the number of cars that can be replaced by one shared vehicle among car-sharing members; however, it is less clear to what extent car sharing can spread across the wider population and reduce ownership within current non-members. Considering also the evidence that motorization rates have not significantly decreased even where sharing schemes are widespread, this study models a conservative 4% reduction in vehicle ownership due to the implementation of vehicle sharing and pooling and modal shift for all the four cities.

Finally, circular design in vehicle manufacturing was modelled considered mainly the possibility to reduce steel and plastic use for the production of new vehicles. According to Arup et al. (2019), experts in material efficiency in vehicle manufacturing have estimated that it is possible to reduce the amount of steel and plastic used in car manufacturing by 50%. Given the high degree of standardisation of vehicle manufacturing, this ambitious target is equally applied to all cities in order to achieve indirect Scope 3 emissions reductions.

Table 8 reports emission reduction obtained for each selected intervention in the mobility sector, based on the results obtained in other places contained in the scientific literature.

Table 8 - Emission reductions – Mobility Sector

	Bogotá			**Genoa**			**Glasgow**			**Milan**		
Interventions	Scope 1	Scope 2	Scope 3	Scope 1	Scope 2	Scope 3	Scope 1	Scope 2	Scope 3	Scope 1	Scope 2	Scope 3
Modal shift	-4.5%	-	*	-5.6%	0.0%	*	-8.4%	-	*	-8.5%	-	*

Vehicle sharing and pooling	Not modelled			**	-	-0.1%	**	-	-0.2%	**	-	-0.1%
Switch to electric vehicles	-21.8%	13.7%	-0.9%	-4.6%	3.9%	-0.5%	-5.5%	4.9%	-0.2%	-3.7%	0.5%	-0.4%
Vehicle manufacturing	-	-	-0.2%	-	-	-0.3%	-	-	-0.4%	-	-	-0.4%

*included in Scope 3 emission reduction from Vehicle Sharing and Pooling

** included in Scope 1 emission reductions from Modal Shift

1.6 Built environment interventions

Built environment interventions include solutions that have the potential to reduce direct emissions related to the operation of buildings and infrastructure (building operation interventions), with an impact mainly on Scope 1 and 2 emissions, and supply chain emissions associated with the construction of buildings (building construction interventions) targeting Scope 3 emissions.

Table 9 reports the final list of selected interventions for the built environment sector.

Table 9 – Selected circular interventions – Built environment sector

Sector	Intervention	Description	Expected impact
Building construction	Enhance building use and occupation	Reducing demand for new construction by using existing assets more efficiently. The intervention also considers the refurbishment, retrofitting and re- occupancy of vacant or disused buildings and the impact of extending and maximizing the lifetime of assets by designing spaces to be adaptable to accommodate changing uses.	Reduce Scope 3 emissions related to the consumption of all construction supply chain activities within the city
	Switching materials	Shift from high-carbon construction materials such as concrete and steel to lower-carbon, lightweight, and in some cases renewable materials such as timber or bamboo (sustainably sourced).	Reduce Scope 3 emissions related to the consumption of specific materials (steel and concrete) within the construction supply chain activities within the city
	Use materials efficiently	Reducing the quantity of materials used during construction through efficient, lightweight design, and reducing waste through off -site, modular construction processes.	Reduce Scope 3 emissions related to the consumption of specific materials (steel and concrete) within the construction supply chain activities within the city
	Recover, reuse, repurpose materials	Recovering materials at end-of-life for reuse in future construction projects with minimal processing.	Reduce Scope 3 emissions related to the consumption of specific materials (steel) within the construction supply chain activities within the city

Building operation	Reduce energy demand through retrofitting	Reducing the demand for energy for heating and cooling through building fabric improvements to minimize heat loss, increase natural lighting and ventilation, and control solar gains to reduce the need for cooling during summer	Reduce Scope 1 emissions from avoided gas consumption and Scope 2 emissions due to avoided electricity consumption because of retrofitting Reduce Scope 3 emissions (supply chain emissions) associated with the extraction, transmission and distribution of gas and electricity associated with demand in the city
	Implement low-carbon building services	Electrification of heating, cooling and ventilation in buildings (e.g. heat-pumps).	Reduce Scope 1 emissions from substitution of direct fuel consumption with electricity Increase Scope 2 emissions due to electrification. Scope 3 emissions variations (supply chain) due to reduction in fuel use/increase in electricity.

Table 10 outlines the process for modelling the impact of each intervention against a city's consumption-based emissions.

Table 10 – Built environment intervention application in the model description

Intervention	Modelling approach
Building construction interventions	
Enhance building utilization and occupation	Apply a percentage reduction to the consumption of all construction supply chain activities within the city
Switching materials	Apply a percentage reduction to the consumption of steel and concrete within the construction supply chain activities within the city
Use materials efficiently	Apply a percentage reduction to the consumption of steel and concrete within the construction supply chain activities within the city
Recover, reuse, and repurpose materials	Apply a percentage reduction to the consumption of steel within the construction supply chain activities within the city
Building operation interventions	
Reduce energy demand through retrofit activities	Apply a percentage reduction to the Scope 1 and 2 emissions from residential and non-residential buildings to represent and decrease in the consumption of gas and electricity. Apply a percentage reduction to the supply chain emissions associated with the extraction, transmission and distribution of gas and electricity (considered separately) associated with demand in the city. The percentage reduction was equivalent to the percentage change in emissions associated with total gas and electricity consumption, respectively.

Low-carbon building services	Apply a percentage reduction to the Scope 1 emissions residential buildings. Increase the Scope 2 emissions by applying the proportion of Scope 1 reduction emissions that would be replaced by the increased consumption of electricity from the use of heat pumps to produce the same heat output. Apply a percentage reduction to the supply chain emissions associated with the extraction, transmission and distribution of gas and electricity (considered separately) associated with demand in the city. The percentage reduction was equivalent to the percentage change in emissions associated with total gas and electricity consumption, respectively.

For the built environment sector, starting from building construction, the first intervention aims to enhance building utilization by repurposing underutilised office and retail spaces into residential spaces to meet increased housing demand without new construction. This could be enabled by the trends accelerated by the COVID-19 pandemic, namely the transition to increased remote working, e-commerce and automation, that are having an impact on demand for office and retail space. Furthermore, demand for new construction could be reduced also by extending the lifetime of assets designing spaces to be adaptable to changing uses and using durable materials (ENEL, ARUP, 2022). The intervention on switching materials considers a shift from high-carbon construction materials such as concrete and steel to e.g. timber (or bamboo) as a low-carbon alternative. This reduces the embodied carbon emissions associated with the extraction, production, and manufacturing of construction materials, provided that materials are sustainably sourced. In line with the approach taken in Arup et al. (2019), the intervention considers the proportion of residential and commercial buildings in which timber could replace traditional materials, the amount of steel and concrete in traditional buildings, the steel and concrete components that it would technically be feasible to replace, and the global timber stock, to assess the reduction in steel and concrete consumption that could be replaced in the construction of new buildings (ENEL, ARUP, 2022).

The intervention on efficient use of materials involves a reduction in the quantity of materials used during construction through more efficient, lightweight design, and the reduction in construction waste through off-site, modular construction processes. The intervention has been assessed in line with Arup et al. (2019), that considered on-site wastage reduction, decreased chosen loading, changes to building codes, higher design utilisation, and more efficient element geometry to assess the potential reduction in the use of steel sections, steel rebar and concrete during building construction.

A further intervention focuses on the recovery of materials at the end-of-life for reuse in future construction projects with minimal processing. The reuse of construction materials can be enhanced through using standardised, modular building components that can be directly transferred for use in new construction projects. This intervention was assessed in line with Arup et al. (2019), that considered the potential proportion of construction steel that could be reused with current methods of design and recovery, and the likely availability of reusable steel following the decommissioning of buildings (ENEL, ARUP, 2022).

Considering interventions on building operations, the first intervention foresees energy efficiency retrofitting which reduces operational energy demand in buildings. This intervention was modelled by setting an ambitious target of B in terms of Energy Performance Certificate for residential properties in the city[4]. To consider barriers to retrofit, an 80% success rate for residential buildings achieving this target has been applied. Barriers to energy retrofit can be of different nature and include technical, regulatory, cultural, economic and financial barriers (Mallaband et al., 2013; Bagaini et al., 2020). UK data was used for all the three European cities in the study to estimate for residential properties the average reduction in both gas and electricity demand obtainable by reaching the B rating. Due to lack of data on the impact of energy efficiency improvements on non-residential buildings, a 25% reduction in electricity and gas consumption from previous studies (Glasgow City Council, 2015) was applied for all non-residential buildings with an EPC rating lower than C. The embodied emissions associated with the materials used have not been considered in this intervention, because the impact depends heavily on the materials that are used and there are multiple viable options (ENEL, ARUP, 2022).

The last intervention on low carbon building services focuses on the electrification of heating in residential buildings, which is a key area both for UK and EU policies. This intervention focuses on the transition from gas boilers to electric heating through the installation of heat pumps. The difference in both efficiency and emissions factor between gas boilers and heat pumps supplied by grid electricity was considered. Given that heat pump installation is only feasible in energy efficient buildings where heat loss is minimised given the low temperatures that heat pumps produce relative to gas boilers, it is assumed that this intervention would be implemented following energy efficiency improvements through retrofit activities in residential buildings (ENEL, ARUP, 2022). An ambitious target for heat pump installation was set for each city, considering also other technical barriers (ibid). These include for example the availability of external space, the proximity of buildings in a heat network to minimise the cost of piping and associated groundwork, geological constraints for ground source heat pumps, and the accelerated corrosion of heat exchangers caused by air salinity in coastal locations (Scottish Government, 2020).

Table 11 reports emission reduction obtained for each selected intervention in the built environment sector, based on the results obtained in other places contained in the scientific literature.

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[4] The built environment intervention focusses on the reduction of energy demand, rather than changes to energy supply; for this reason the B rating was considered instead of A, which would require changes to energy supply and the introduction of renewable technologies (ENEL, ARUP, 2022).

Table 11 Emission reductions – Built environment Sector

	Bogotá			Genoa			Glasgow			Milan		
Interventions	Scope 1	Scope 2	Scope 3	Scope 1	Scope 2	Scope 3	Scope 1	Scope 2	Scope 3	Scope 1	Scope 2	Scope 3
Enhance building utilization and occupation	-	-	-0.4%	-	-	-1.4%	-	-	-1.1%	-	-	-1.4%
Switching materials	-	-	-0.4%	-	-	-0.1%	-	-	-0.2%	-	-	-0.2%
Use materials efficiently	-	-	-1.0%	-	-	-0.5%	-	-	-0.3%	-	-	-0.4%
Recover. reuse and repurpose materials	-	-	-0.1%	-	-	-0.1%	-	-	-0.0%	-	-	-0.1%
Reduce energy demand through retrofit activities	Not modelled			-10.8%	-11.9%	-0.4%	-12.3%	-16.3%	-0.8%	-25.4%	-21.5%	-0.8%
Low-carbon building services	Not modelled			-27.9%	28.2%	-0.6%	-14.4%	19.4%	-0.5%	-26.7%	18.3%	-0.5%

Results and Discussion

1.7 Baseline calculation

Table 12 shows the baselines (consumption-based) of the four cities generated using the approach and data described in Chapter 2.

Table 12 – Baseline 2017 for the four cities

	Baseline 2017	**Scope 1**	**Scope 2**	**Scope 3**	**2017 Baseline emissions per capita (tCO$_2$eq/capita)**
Bogotá (Colombia)	43,785,007	8,036,278	658,280	35,090,449	5.97
Genoa (Italy)	6,486,992	992,669	444,134	5,050,189	11.18
Glasgow (UK)	8,692,583	1,841,900	712,300	6,138,383	14.00
Milan (Italy)	19,145,970	3,137,000	2,068,011	13,940,959	14.04

Scope 3 emissions represent a high proportion of consumption-based emissions in the four cities, namely about 80% for Bogotá, 78% for Genoa, 71% for Glasgow, 73% for Milan.

Including Scope 3 in cities' emissions increases their GHG figure by more than two-folds for Milan and Glasgow, more than three-folds for Genoa and more than four-folds for Bogotá, compared to considering only Scope 1 and 2 emissions.

Baselines demonstrate that the cities under consideration are primarily consumers of goods: according to the literature, consumption-based emissions outnumber production-based emissions in many urban centers (Sudmant et al., 2018). To reduce the emissions generated by internal consumption in cities, it is clear that scope 3 emissions must also be considered in the planning process.

Following that, the interventions described in Chapter 3 were carried out on the city baselines to obtain new emission values for all cities as a result of the interventions.

The results obtained for the city of Milan are consistent with previous research: Harris et al. (2019) report that emissions evaluated using a consumption-based approach in the reference year 2007 were equal to 12.6 tCO_2eq/capita. The population of Milan has not changed significantly between 2007 and 2017 (ISTAT, 2022): the difference between the value calculated by Harris et al. (2019) and the value calculated in this study could be due to an increase in emissions generated by internal city consumption or a difference in the data used for calculation.

Because the same comparison cannot be made for the other cities, it was decided to compare the emission value evaluated with the consumption-based with certain results published in literature in order to frame in a larger spectrum as acquired for the four cities analyzed. The values of GHG emissions per capita obtained in this paper and those found in the literature are summarized in Table 13.

Table 13 – Comparison of different studies GHG per capita emissions

	Reference year	tCO_2eq/capita	Source
Barcelona (Spain)	2007	8	Harris et al. (2019)
Beijing (China)	2007	11.6	Mi et al. (2016)
Bogotà (Colombia)	2017	4.78	Investigated in this paper
Copenhagen (Denmark)	2007	15.5	Harris et al. (2019)
Genoa (Italy)	2017	11.18	Investigated in this paper
Glasgow (UK)	2017	14	Investigated in this paper
Istanbul (Turkey)	2007	5.2	Harris et al. (2019)
Lisbon (Portugal)	2007	7.1	Harris et al. (2019)
Litomerice (Czech Republic)	2007	9.5	Harris et al. (2019)
Malmo (Sweden)	2007	8	Harris et al. (2019)
Milan (Italy)	2017	14.04	Investigated in this paper
Rostock (Germany)	2007	9.6	Harris et al. (2019)
San Francisco (USA)	2013	44.1	Jones et al. (2017)
Shanghai (China)	2007	14.4	Mi et al. (2016)
Tangshan (China)	2012	36	Mi et al. (2019)
Turin (Italy)	2007	15.9	Harris et al. (2019)
Zagreb (Croatia)	2007	17.9	Harris et al. (2019)

As shown in Table 13, the emissions per capita range between 4.78 tCO_2eq/capita for Bogotá and 44.1 tCO_2eq/capita for San Francisco, while the average is 14.5 tCO_2eq/capita. The results obtained in this study for the four cities considered are close to average except for Bogotá: this may be due to different geographical and technological location of the Colombia’s capital city in comparison to the other three European cities. However, it was not possible to collect data relating to the same year of reference from the literature, which constitutes a limitation in comparison to what was obtained in this work: it is possible to conclude that the results obtained are consistent with the previous studies.

1.8 Intervention implementation in the model

This section describes how the selected circular interventions were applied to the municipal baseline models to assess the impact of each sector's activities. Although the actions within each sector were aggregated to analyse the total potential impact of all sector efforts, emission reductions for each sector were modelled independently. The impact of the application of these interventions was assessed with reference to a 2017 emissions baseline incorporating Scopes 1, 2 and 3.

Energy systems interventions

Results obtained from the modelling of the three interventions referring to energy sector are shown in Table 14. The contribution of each intervention for all the three scopes is shown together with a quantification of the effects from the combination of the three interventions. This value is lower than the algebraic sum of the effects of the single interventions as the combination of the three interventions in the same urban context does not lead to a proportional reduction of emissions and the effects of the interventions are not directly added due to problems of double counting of emissions reduction (Arup et al. 2019).

Table 14 – Overall emission variations – Energy Sector (expressed in tCO$_2$eq)

Intervention	**Impact of interventions**			**Overall variation**	**Sector variation**
	Scope 1	Scope 2	Scope 3		
Bogotá					
Installation of PVs on the roofs of public and private buildings	0	-31,913	+36,542	+4,629	-268,011
Buying energy from renewable plants outside the city limits	0	-346,034	-72,733	-273,302	
Smart metering	0	-37,785	-3,078	-40,863	
Genoa					
Installation of PVs on the roofs of public and private buildings	0	-96,726	-1,046	-97,771	-232,383

Buying energy from renewable plants outside the city limits	0	-148,261	-12,366	-160,626	
Smart metering	0	-19,769	-1,957	-21,726	
Glasgow					
Installation of PVs on the roofs of public and private buildings	0	-38,057	-1,067	-36,989	-151,064
Buying energy from renewable plants outside the city limits	0	-97,530	-4,779	-102,309	
Smart metering	0	-19,800	-1,549	-21,349	
Milan					
Installation of PVs on the roofs of public and private buildings	0	-215,027	+8,658	-206,368	-626,339
Buying energy from renewable plants outside the city limits	0	-425,720	-15,612	-441,332	
Smart metering	0	-38,480	-2,030	-40,510	

Table 14 shows that for all urban contexts the most effective action in terms of reducing emissions Scope 2 is buying energy from renewable plants outside the city limits, i.e. intervention no.2. The effectiveness of this intervention strongly depends on the values of electricity consumption by the sectors considered (public and residential): the higher the share of consumption in these two categories, the greater the amount of electricity replaced. Furthermore, the composition of the national electric mix is important: a country that is largely powered by electricity from fossil sources will benefit more from this intervention than a country that is entirely powered by renewable sources. These are the reasons why the city of Bogotá has seen the greatest success with this intervention, reducing Scope 2 emissions by half. This intervention is also effective in Genoa (33% reduction in Scope 2 emissions) and Milan (21% reduction in Scope 2 emissions). As for the city of Glasgow the impact of the intervention (reduction of 14% of emissions Scope 2) is however satisfactory even if not at the levels of other cities. Wind power was used as a source of electricity in this intervention, however other sources might be used to improve the impact of the intervention based on the geographical peculiarities of the location under consideration.

For intervention no.1, installation of PV, the city of Genoa had the best results, with a decrease in emissions Scope 2 of 22%, followed by the city of Milan, with a reduction of 10%. While the cities of Glasgow and Bogota achieve less satisfactory results by reducing Scope 2 emissions by 5%. The causes of reduced effectiveness in these two cities differ: in Glasgow, the problem is due to the low solar radiation that reaches the city due to its geographical location, whereas in Bogota, the main cause is due to the high-power consumption proportionate to the available surface area for PVs installation. To improve the efficacy of this intervention in Colombia's capital, consider constructing photovoltaic power plants in non-built areas of the city.
For intervention no.3, smart metering, the greatest effect is obtained in Bogota (6% reduction in scope 2 emissions) followed by Genoa (4%), Glasgow (3%) and Milan (2%). Bogota has the largest impact (6% reduction in scope 2 emissions), followed by Genoa (4%), Glasgow (3%), and Milan (2%). Of course, in order to model this intervention, a behavioural uniform shift caused by the installation of smart meters in all houses was assumed.

Figure 1 shows the entire variation in emissions (all three scopes) when the combined effects of the three interventions are taken into consideration. Figure 2 shows the impact of energy systems interventions for each Scope. In general, Scope 3 emissions increase due to the creation of new devices (wind farms, photovoltaic panels, and smart meters) and decrease due to the reduced use of fossil fuels, resulting in a reduction of emissions related with the fossil supply chain (extraction, transport, management, treatment, etc.). The combined effects of the three treatments allow for satisfactory outcomes in all the cities under consideration, resulting in significant reductions in Scope 2 emissions, such as in Bogota (57%) or Genoa (50%) and significant reductions in Milan (30%) and Glasgow (21%).

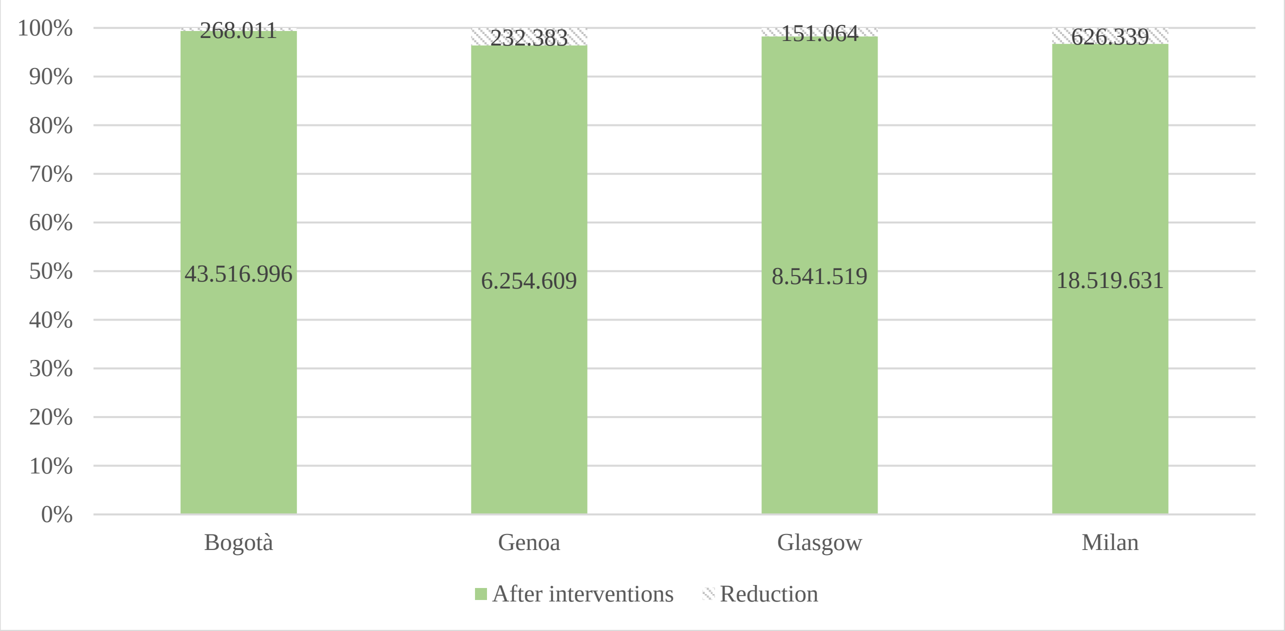

Figure 1 – Cumulative emissions reduction – Energy Sector (expressed in tCO$_2$eq)

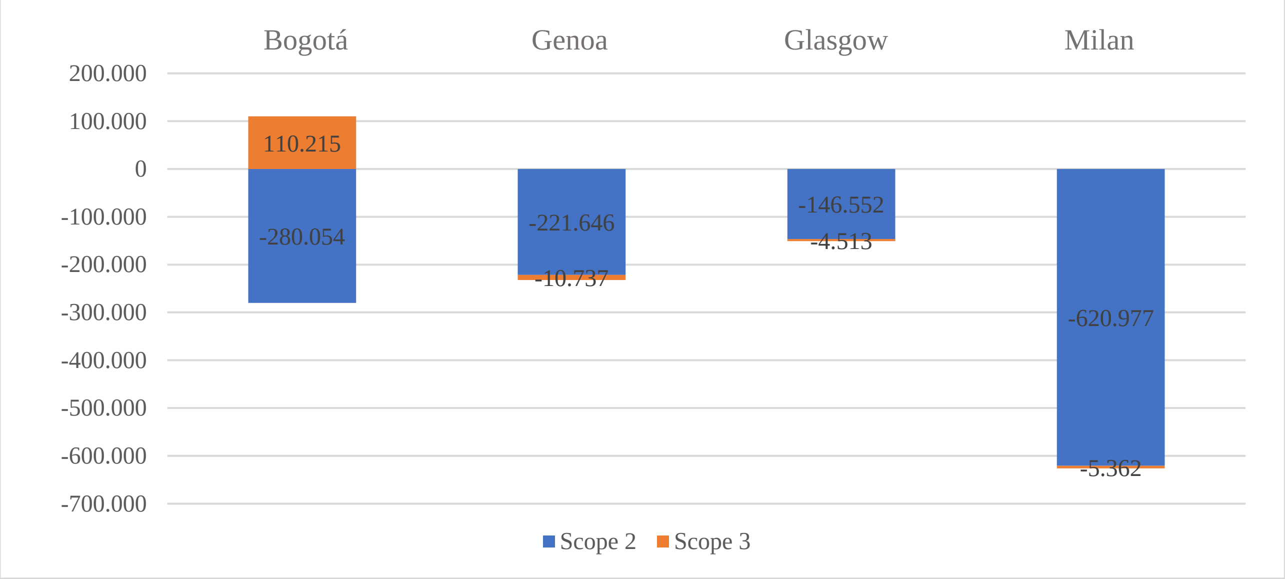

Figure 2 – Emissions reduction per scope – Energy Sector (expressed in tCO$_2$eq)

Mobility interventions

Results obtained from the modelling of the mobility interventions are shown in Table 15. The contribution of each intervention for all the three scopes is shown together with a quantification of the effects from the combination of the four interventions.

Table 15 – Overall emission variations – Mobility Sector (expressed in tCO$_2$eq)

Intervention	Impact of interventions	Overall variation	Sector variation

	Scope 1	Scope 2	Scope 3		
Bogotá					
Modal shift	-363,358	0	-69,509	-432,868	-2,481,537
Vehicle sharing and pooling	0	0	0	0	
Switch to electric vehicles	-1752,843	90,146	-325,847	-1,988,545	
Vehicle manufacturing	0	0	-60,123	-60,123	
Genoa					
Modal shift	-55,400	0	-31,740	- 87,140	-161,760
Vehicle sharing and pooling	0	0	-5,894	-5,894	
Switch to electric vehicles	-45,578	+17,152	-24,328	-52,755	
Vehicle manufacturing	0	0	+15,970	+15,970	
Glasgow					
Modal shift	-154,200	0	-21,093	-175,294	-287,776
Vehicle sharing and pooling			-10,261	-10,261	
Switch to electric vehicles	-102,064	+35,039	-10,995	-78,020	
Vehicle manufacturing	0	0	-24,202	-24,202	
Milan					
Modal shift	-265,700	0	-129,946	-395,645	-635,674
Vehicle sharing and pooling	0	0	-20,699	-20,699	
Switch to electric vehicles	-116,664	+10,988	-56,401	-162,077	
Vehicle manufacturing	0	0	-57,252	-57,252	

Table 15 shows that interventions on modal shift and transport electrification are relevant in reducing Scope 1 emissions. The amount of emission reductions due to modal shift depends on the variety and intensity of measures put in place to promote sustainable mobility in the cities, and therefore their impact, and the relevance of private vehicle use in passenger mobility. All the four cities have planned or implemented several policy measures to stimulate a shift from private polluting vehicles to sustainable and soft transport modes, including active mobility, micro-mobility, public transport and vehicle sharing and pooling. The modal shift intervention is expected to generate the most relevant reductions in Milan and Glasgow (-8.5% and -8.4 % in Scope 1 emissions respectively), but also has an important effect in Genoa and Bogotá (-5.6% and -4.5% in Scope 1). These results confirm that private mobility still has a relevant role in Scope 1 emissions of cities, and that integrated policies are needed to support the transition to low-carbon transport modes in order to obtain relevant reductions. The effects of Intervention 3 (vehicle electrification) on Scope 1 emissions depend on different factors, including the penetration of electric vehicles in the vehicle fleet, the emission intensity of vehicles circulating in the city that are replaced by electric vehicles, the composition of the public transport vehicle fleet, as well as the average distances covered by vehicles in the four cities. The impact of this intervention in Bogotá, which is modelled only considering the public transport sector, is particularly high because of the large number of buses considered in the electrification process, as well as the high emissions factor of circulating buses. For Bogotá, a -21.8% emission reduction is expected from this intervention. For the other cities, where circulating vehicles are to a certain extent less emission intensive and the circulating fleets are smaller, the expected impact is estimated to be less strong, around -4.6% in Genoa, -5.5 in Glasgow, -3.7% in Milan. Intervention n.3 on vehicle electrification also implies an increase of Scope 2 emissions due to electricity consumed by electric vehicles. In the study, the decarbonisation of electricity supply was accounted for exclusively in the "Energy systems" sector, in order to avoid double-counting of emission reductions between sectors. For this reason, mobility interventions estimate the impact of electrification on Scope 2 emissions by assuming the same national emission factor for electricity of the baseline, with no decarbonisation interventions. An exception for this is Milan, where electricity purchased for public transport is already 100% renewable. For this reason, the increase of this intervention on Scope 2 emissions for Milan is limited compared to the other cities. This result reaffirms the importance of coupling electrification with decarbonisation of electricity supply, in order to obtain more relevant emission reductions.

Intervention n. 2, vehicle sharing and pooling, was modelled only for Genoa, Glasgow and Milan, as the intervention seemed to be not applicable in Bogotá that is characterized by low car ownership rates. The impact of vehicle sharing on Scope 1 emissions is already accounted for under Intervention 1, as vehicle sharing can contribute to modal shift and sharing systems can be deeply integrated with other sustainable mobility modes available in a city. The effect of vehicle sharing on Scope 3 emissions for the three cities is limited (-0.1% Genoa; -0.2% Glasgow; -0.1% Milan). This suggests that a small decrease in car ownership entails limited benefits in terms of Scope 3 emission reductions, and that further measures and incentives to decrease car ownership rate should be put in place.

It should also be highlighted that the figure of Scope 3 emissions reported for the cities include emissions embodied in all sectors of consumption in a city, considering also sectors which are out of the scope of this analysis. Therefore, the relevance of mobility interventions' impacts on the overall city's Scope 3 emission figure is limited. The same is true also for the last intervention on vehicle manufacturing, which shows a limited effect on Scope 3 emissions across the four cities (-0.2% for Bogota; -0.3% for Genoa; -0.4% for Glasgow; -0.4% for Milan).

If we consider the impact of all mobility interventions on Scope 3 emissions embodied only in the sector "motor vehicles and parts", the impact is more visible: -10% for Bogotá, -13% for Genoa, -12% for Glasgow, -14% for Milan.

Figure 3 shows the entire variation in emissions (all three scopes) when the combined effects of the four interventions are taken into consideration. Figure 4 disentangles the impact of mobility interventions for each Scope. In general, Scope 1 emissions are reduced by interventions that shift mobility behaviours from private cars to other less emitting modes (including e-vehicles); Scope 2 emissions increase because of electricity consumption by e-vehicles; and Scope 3 emissions decrease because sustainable mobility measures can contribute to reduce private car ownership rates and because reducing fuel consumption also entails less fossil-fuel supply chain emissions.

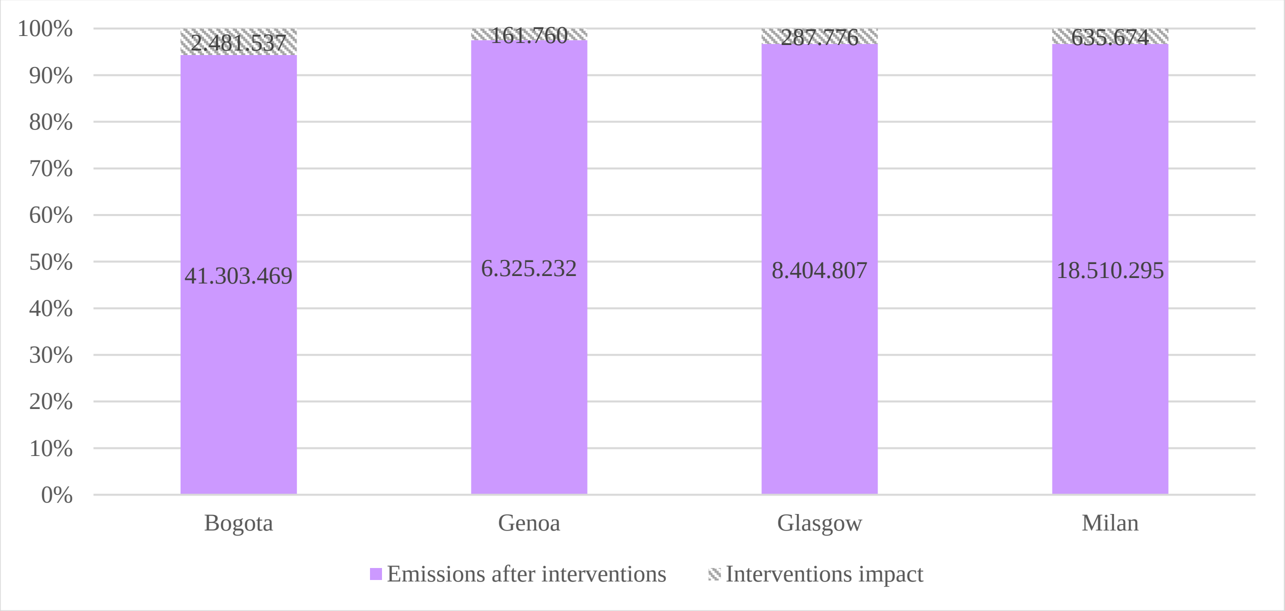

Figure 3 – Cumulative emissions reduction – Mobility Sector (expressed in tCO_2eq)

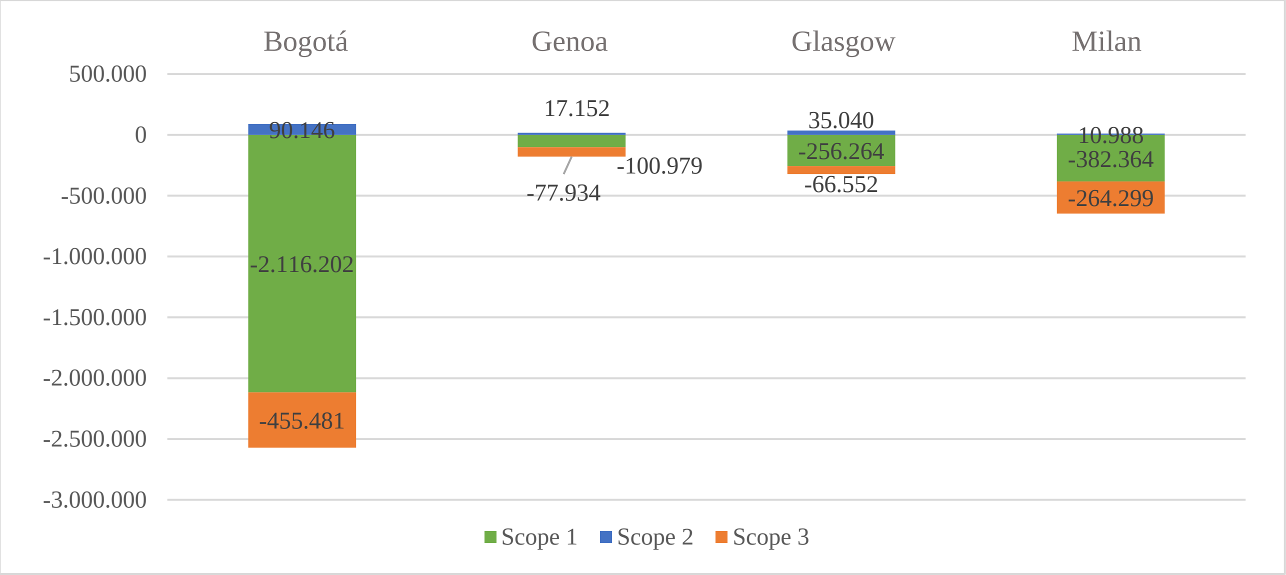

Figure 4 – Emissions reduction per scope – Mobility Sector (expressed in tCO$_2$eq)

Built environment interventions

Results obtained from the modelling of the built environment interventions are shown in Table 16. The contribution of each intervention for all the three scopes is shown together with a quantification of the effects from the combination of the six interventions. This value is lower than the algebraic sum of the effects of the single interventions as the combination of the interventions in the same urban context does not lead to a proportional reduction of emissions and the effects of the interventions are not directly added due to problems of double counting of emissions reduction (Arup et al. 2019).

Table 16 – Overall emission variations – Built environment Sector (expressed in tCO$_2$eq)

Intervention	**Impact of interventions**			**Overall variation**	**Sector variation**
	Scope 1	Scope 2	Scope 3		
Bogotá					
Enhance building utilization and occupation	-	-	-152,149	-152,149	-612,161
Switching materials	-	-	-130,282	-130,282	
Use materials efficiently	-	-	-359,003	-359,003	
Recover, reuse and repurpose materials	-	-	-43,720	-43,720	
Reduce energy demand through retrofit activities					

	Not modelled				
Low-carbon building services	Not modelled				
Genoa					
Enhance building utilization and occupation	-	-	-69,409	-69,409	-429,224
Switching materials	-	-	-5,733	-5,733	
Use materials efficiently	-	-	-25,528	-25,528	
Recover, reuse and repurpose materials	-	-	-3,937	-3,937	
Reduce energy demand through retrofit activities	-107,097	-53,403	-21,718	-182,219	
Low-carbon building services	-276,576	+124,889	-27,649	-179,336	
Glasgow					
Enhance building utilization and occupation	-	-	-67,668	-67,668	-587,663
Switching materials	-	-	-10,523	-10,523	
Use materials efficiently	-	-	-20,349	-20,349	
Recover, reuse and repurpose materials	-	-	-1,585	-1,585	
Reduce energy demand through retrofit activities	-226,900	-115,872	-46,753	-389,525	

Low-carbon building services	-264,894	+137,745	-31,467	-158,616	
Milan					
Enhance building utilization and occupation	-	-	-200,036	-200,036	-1,920,413
Switching materials	-	-	-20,981	-20,981	
Use materials efficiently	-	-	-52,719	-52,719	
Recover, reuse and repurpose materials	-	-	-9,179	-9,179	
Reduce energy demand through retrofit activities	-796,232	-443,961	-118,030	-1,358,223	
Low-carbon building services	-839,202	+378,945	-71,209	-531,466	

Considering interventions on the building construction, which affect only Scope 3 emissions, the one with more impact for the three European cities is enhancing building utilization and occupation (-1.4% for Genoa and Milan, -1.1% for Glasgow). This could be to the availability of vacant buildings in the three cities and the wider potential for better utilisation, compared to Bogotá. In the Colombian city in fact the situation is rather a lack of affordable and suitable housing across the city, particularly in the low-income sector. According to the latest census, 14.1% of households suffer from overcrowding and live in poor quality housing. There has been a disconnect between the types of buildings being constructed and the needs of citizens (e.g. public housing) (ENEL, ARUP, 2022). The overall demand for new construction in Bogotá can be reduced by focusing real estate development on meeting citizen needs, though this potential is lower than for the other study cities. For Bogotá, the most relevant intervention seems to be the efficient use of materials, which bring a reduction of Scope 3 emissions of -1%.

Overall, interventions on the building construction seem to have a limited impact on overall cities' Scope 3 emissions. As recalled above, the figure of Scope 3 emissions reported for the cities include emissions embodied in all sectors of consumption in a city, considering also sectors which are out of the scope of this analysis. If we consider the impact of all built environment interventions on Scope

3 emissions embodied only in global construction supply chain, the impact is more visible: -20% for Bogotá, -21% for Genoa, -27% for Glasgow, -26% for Milan.

Interventions regarding building operations show a relevant impact on Scope 1 and 2 emissions. In particular, retrofit activities seem to have the widest impact in terms of Scope 1 emissions reduction: the best results are obtained for Milan (-25.4%), followed by Glasgow (-12.3%) and Genoa (-10.8%). Regarding Scope 2 emissions reduction, interesting results are obtained for Milan (-21.5%), Glasgow (-16.3%) and Genoa (-11.9%). A significant share of the built stock in Italian cities has low energy performances, as more than 65% of the overall built stock is older than 45 years when the first law on energy saving was adopted, therefore the potential for energy efficiency improvement is relevant (ENEA, 2021). Also Glasgow is characterized by relevant opportunities in terms of energy efficiency retrofit, as its built stock is aging and in many cases degraded, with over 40% of dwellings built before 1945 (ENEL, ARUP, 2022).

Electrification in in the building sector has the most relevant effect on Scope 1 emissions in Genoa (-27.9%) and Milan (-26.7%), followed by Glasgow (-14.4%), but also brings an uplift of Scope 2 emissions due to the increased use of electricity. This result highlights the need to decarbonize the electricity supply to improve emission reductions from this intervention. Overall, building electrification and the uptake of heat pumps is an important step for decarbonising buildings, particularly in Milan and Glasgow. For Bogotá, building operation interventions were not modelled, due to the city’s minimal use of energy for indoor heating and cooling.

Figure 5 shows the entire variation in emissions (all three scopes) when the combined effects of the six interventions are taken into consideration. Figure 6 disentangles the impact of built environment interventions for each Scope.

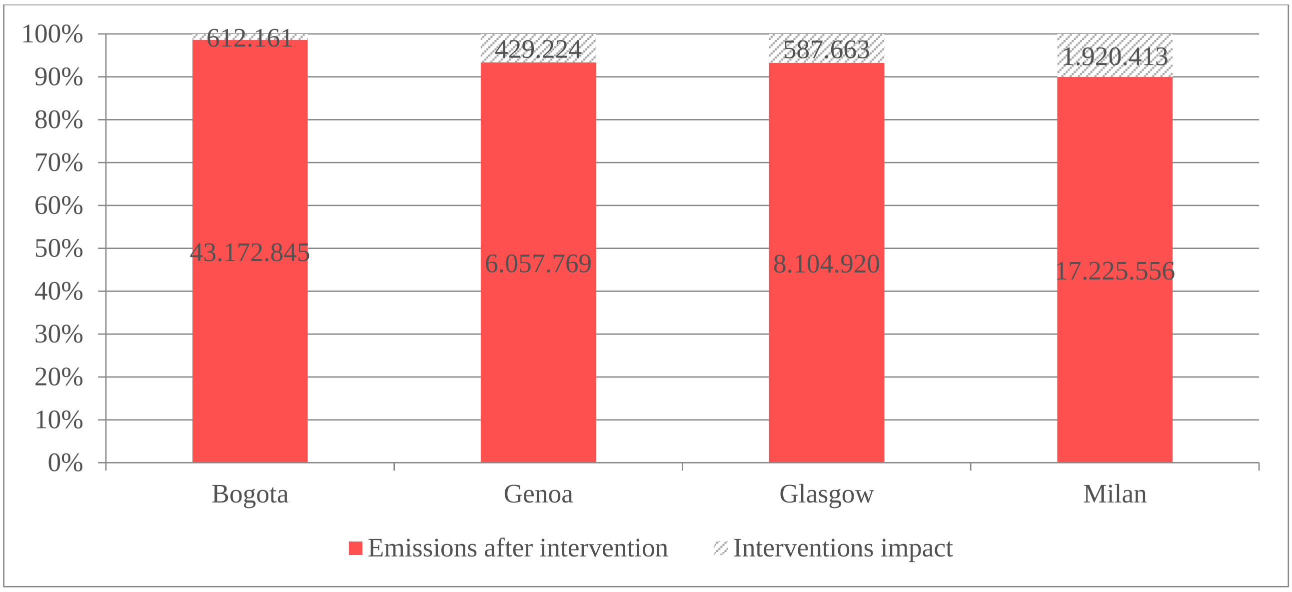

Figure 5 – Cumulative emissions reduction – Built Environment Sector (expressed in tCO_2eq)

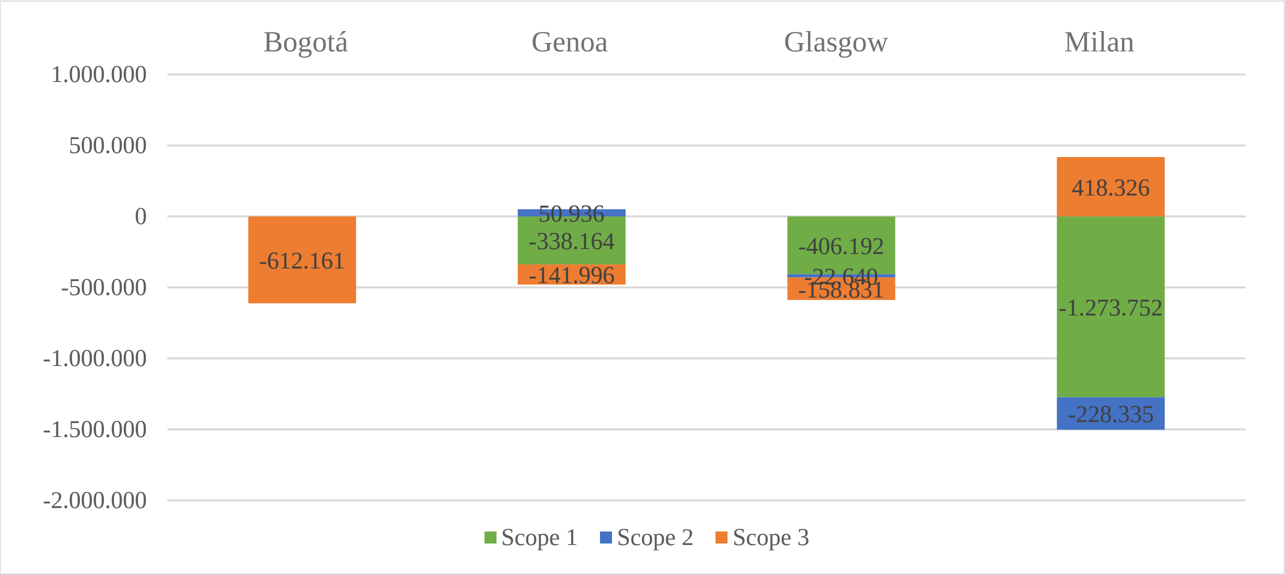

Figure 6 – Emissions reduction per scope – Built environment Sector (expressed in tCO_2eq)

1.9 Study assumption and limitation

This study presents a high-level assessment of the scale of the opportunity presented by the three sectors for the four cities. Several assumptions were required in the modelling technique to allow for the evaluation of the broad patterns highlighted in our research, and these assumptions came with a few limitations. Further details can be found in Arup et al. (2019). The model is based on GTAP's supply chain structure for 2014, the most recent year for which data for the GTAP model is available. Circular interventions that are tested on this static model of a largely linear economy would miss the full impact of a move to a more circular economy, which will entail system restructuring. The emissions intensities determined from input-output analysis for sectors are based on the premise that each economic unit of output in a sector has the same environmental impact across the sector, which is known as homogeneity. For example, in one sector, it is assumed that the environmental impact for every dollar spent is uniform, when in reality, there will be variation within the sector because different activities have distinct environmental effects. As a result, the emissions intensity reflects the sector's average environmental impact and cannot simply accommodate for changing modes of transportation. Interventions in each of the three sectors were investigated independently, and modelling did not account for a scenario in which a city engages in both at the same time. Because they all start from the identical baselines for each city, combining the results for the three sectors as mentioned in this study would result in double counting. Changes in grid intensity in energy systems, for example, would have an effect on electrification interventions in transportation and the built environment, and this interdependence was not accounted for in the modelling.

When behavioural changes and spending reductions are represented as mitigations, there is the possibility of rebound effects – the expenditure is not reduced, but rather redirected to other activities with a higher or lower emissions intensity. Rebound effects frequently reduce the predicted benefit derived from a switching expenditure-related activity; however, rebound effects were not included in this study.

Conclusions

Given the urgency to address the climate crisis and the role of cities in the global economy as centers of economic activity and nodes of consumption, it is necessary to better understand the contribution of cities' consumption patterns to global GHG emissions, as well as to identify the key sectors and the measures that can most effectively target and reduce urban emissions. Circular measures can provide a contribution to decarbonization and their implementation at the urban level requires quantitative investigation and assessment.

Consistently with these research needs, the study developed consumption-based emission baseline for four cities worldwide, and assessed the potential contribution to decarbonization of a set of circular interventions applicable in three high-impact sectors in cities: energy systems, mobility and the built environment. According to the results of the cities' emission baselines, the majority of the emissions generated by activities carried out within the urban borders are emitted outside the borders in the form of Scope 3 emissions. This result is consistent with previous studies (Christis et al., 2019; Harris et al., 2019; Athanassiadis et al., 2018; Sudmant et al., 2018) and demonstrates how today's cities are large consumers of goods produced outside their borders, especially in the global north, requiring the use of a consumption-based approach for emissions inventory.

Interventions are quantified in the model, exploring how policies can impact consumption – reducing demand or switching demand to low-carbon alternatives – and emissions intensity – producing the same resources at a lower level of emissions. Results on energy systems interventions demonstrate how important it is to act both for the improvement of the electricity mix by increasing the share of energy from renewable sources (a process that can be carried out at the national or local level) and for the optimization and consequent reduction of electricity consumption. Renewable energy sources are no longer inconvenient from an economic standpoint, but rather competitors on par with fossil fuels (IRENA, 2021): previously prohibitively expensive technologies, such as photovoltaics, are now affordable to the average citizen, allowing for widespread adoption of these technologies. The key to a more sustainable and resilient society is the uniform distribution of energy sources, as well as the development of large renewable electricity production plants. The results of scope 2 emission reduction are remarkable, demonstrating how an improvement in the electrical mix used in urban areas, combined with efficiency improvements and consumption reduction, leads to drastic reductions in GHG emissions.

Results on mobility interventions confirm that private mobility still has a relevant role in Scope 1 emissions of cities, and that integrated policies are needed to support the transition to low-carbon transport modes in order to obtain relevant reductions. Results on Scope 2 emissions highlight the need to combine electrification measures with supply of low-carbon electricity. Results on Scope 3 emissions show a more limited decarbonisation potential from modelled interventions.

Results of built environment interventions targeting operations show a relevant impact on Scope 1 and 2 emissions for the three European cities, as there is a wide potential to make the built stock more energy efficient and renovate existing buildings both in the residential and non-residential sectors, and to adopt efficient low carbon technologies like heat pumps. Given the relevant use of electricity, the need for a deeper decarbonisation in electricity supply is visible also in this sector.

Considering the impact of interventions that target new construction, the results highlight the importance of better use and manage existing vacant and unused buildings in order to improve their occupation rate and avoid new constructions, also in light of new trends emerged from the pandemic which are bringing up new and more flexible living and working models. The three European cities in particular have a considerable share of assets which are underutilised and need to be monitored in order to define alternative uses. On the other side, measures that target the typologies of materials used in construction, the possibility of reuse, recover and repurpose materials and more efficient design can have a relevant impact on Scope 3 emissions embodied in the global construction supply chain.

The adopted approach shows the aggregate impact of the modelled circular interventions on the cities' consumption-based emission baselines, and it disentangles it according to the three emission Scopes, providing insights for policy-elaboration and policy-making. In fact, city governments have different powers and policy levers in these sectors and to act on different scopes of emissions. In the energy sector, city governments can invest in local renewable energy production in their municipal properties, or establish Power Purchasing Agreements, or leverage policy instruments (such as building regulations or incentives) that promote the incorporation of renewable energy plants in private buildings. Moreover, they can push towards more efficient energy consumption systems using new smart technologies like smart electricity meters in order to shift citizens' lifestyles towards more sustainable models. In the mobility sector, city governments have several competences and policy instruments that they can leverage to promote and incentivize sustainable mobility, supporting low-carbon mobility behaviours and decreasing private car-use (e.g. through the creation of low or zero-emission zones; by activating vehicle-sharing schemes; by expanding local public transport networks and bicycle networks). In coming years, due to strong engagement with car manufacturers along the value chain – from raw materials to manufacturing to closing the loop at the end-of-life – there will likely be a significant improvement in terms of circularity and therefore a reduction in materials consumption. In the built environment sector, city governments have at their disposal several policy and planning levers, and they may adopt new policy instruments and procurement policies to reduce construction supply-chain emissions. City governments need to adopt a life-cycle perspective and consider the overall impact of buildings across their life-stages when they develop their urban development programs or renovation programmes, as well as their procurement decisions. In this way they will have a clearer picture of construction strategies' implications for climate change. Overall, these results can be useful for policy makers to inform the development of their decarbonization strategies.

Future research could expand the number of interventions and the sectors considered in the analysis, including other high-impact sectors like food which are very relevant in cities' consumption-based emissions. Further research could also incorporate socio-economic and cultural elements to assess the feasibility of circular interventions according to local habits and the citizens' climate protection awareness or propensity to circular practices.

The results of this study highlight the need for cities to consider their consumption-based emissions in their decarbonization strategies, in order to devise a relevant contribution to climate protection policies. While there is still a relevant emission reduction potential in Scope 1 and 2 emissions in cities, which can be targeted through a series of policy instruments, Scope 3 emissions need to be considered as well as cities emerge as relevant consumption-nodes, which requires a shift in the consumption and lifestyles of citizens towards more sustainable models.

Even if city governments cannot directly act on the supply-chains of products consumed in their city, they can engage with a variety of actors and stakeholders at the local, national, European and international level to promote the incorporation of circular principles across various sectors and advocate for a global transition of production chains to more sustainable models.

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