**ASSESSING THE IMPACTS OF CITIZEN-LED POLICIES ON EMISSIONS, AIR QUALITY AND HEALTH**

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## Abstract

Air pollution is a global challenge, and especially urban areas are particularly affected by acute episodes. Traditional approaches used to mitigate air pollution primarily consider the technical aspects of the problem but not the role of citizen behaviour and day-to-day practices. ClairCity, a Horizon 2020 funded project, created an impact assessment framework considering the role of citizen behaviour to create future scenarios, aiming to improve urban environments and the wellbeing and health of its inhabitants. This framework was applied to six pilot cases: Bristol, Amsterdam, Ljubljana, Sosnowiec, Aveiro Region and Liguria Region, considering three-time horizons: 2025, 2035 and 2050. The scenarios approach includes the Business As Usual (BAU) scenario and a Final Unified Policy Scenarios (FUPS) established by citizens, decision-makers, local planners and stakeholders based on data collected through a citizen and stakeholder co-creation process. Therefore, this paper aims to present the ClairCity outcomes, analysing the quantified impacts of selected measures in terms of emissions, air quality, population exposure, and health.

Each case study has established a particular set of measures with different levels of ambition, therefore different levels of success were achieved towards the control and mitigation of their specific air pollution problems. The transport sector was the most addressed by the measures showing substantial improvements for NO2, already with the BAU scenarios, and overall, even better results when applying the citizen-led FUPS scenarios. In some cases, due to a lack of ambition for the residential and commercial sector, the results were not sufficient to fulfil the WHO guidelines.

Overall, it was found in all cities that the co-created scenarios would lead to environmental improvements in terms of air quality and citizens’ health compared to the baseline year of 2015. However, in some cases, the health impacts were lower than air quality due to the implementation of the measures not affecting the most densely populated areas. Benefits from the FUPS comparing to the BAU scenario were found to be highest in Amsterdam and Bristol, with further NO2 and PM10 emission reductions around 10% to 16% by 2025 and 19% to 28% by 2050, compared to BAU.

**Keywords:** Citizen engagement, impact assessment, urban emissions, air pollution reduction, health benefits, European cities

## Introduction

Air quality remains poor in various areas, and many European cities are still affected by severe air pollution episodes, despite notable reductions in emissions and ambient concentrations over recent decades. Urban areas are of particular concern due to higher population densities with 8 % and 77% (EEA, 2020), in 2018, of the EU-28 urban population exposed to PM2.5 concentrations that exceed the EU Limit Value established by the EU Directive 2008/50/EC (EU, 2008) and the stricter PM2.5 limits established by the WHO Air Quality Guidelines (WHO, 2006), respectively. In fact, air pollution represents one of the biggest environmental risks to health, responsible for around 400,000 premature deaths per year in the EEA-39 (excluding Turkey) as a result of exposure to PM2.5 (EEA, 2020; WHO, 2018).

In cities, the main problems are associated to NO2, PM10, and PM2.5 pollutants, mainly related to transport and residential combustion sectors (EEA, 2020). Thunis et al. (2018) showed that cities could have an essential role by taking actions to resolve air pollution problems. A lot of research has been done to assess the impact of traffic management control strategies in urban areas (York Bigazzi and Rouleau, 2017) and even on background concentrations (Pisoni et al., 2019). Road transport technological measures show an expected reduction of emissions below 20%, for some measures, while low emission zones and pricings are expected to be more effective, reaching up to 50% of reductions (York Bigazzi and Rouleau (2017)). These measures were expected to lead from 10% up to 25% of air quality improvements. Matthias et al. (2020) concluded by applying traffic measures that in the future, NOx emissions from transport are expected to be highly reduced, while PM emissions show less reduction due to non-exhaust particle emission, i.e., brake, tire, and street wear.

To tackle PM emissions in urban areas, it is essential to consider the residential heating sector, especially due to the increased practice of household biomass burning as it is a cheaper alternative to the primary energy sources (e.g., oil and natural gas) and as the emergence of solid fuel-burning for recreational or atheistic purposes. Domestic wood combustion is a major source of ambient PM, mainly during winter, accounting for 20–30% of local heating-season ambient PM2.5 levels, varying by location (WHO, 2015), but not always perceived as a problem by citizens (Slingerland et al., 2020). As shown by Vicente and Alves (2018), several technological improvements can be made to reduce residential biomass combustion PM emissions. However, some of these technologies are not well-developed for domestic scale applications, would increase costs and maintenance and may even raise safety issues. Therefore, national governments and regional authorities should support voluntary woodstove and fireplace replacement/retrofit programs to motivate households to replace older technologies with safer, more efficient, cleaner-burning technologies. Even with the recent standardisation framework of requirements for domestic heating systems set by the European Committee (Council Directive 2009/125/EC, 2009), the citizen behaviour change is necessary to face this problem (Vicente and Alves, 2018).

Understanding how populations live and the societal factors that influence daily behaviours is the key to reduce emissions and improve air quality (Fogg-Rogers et al., 2020) and therefore comprehend the reasons for high levels of air pollution in cities is crucial for decision-making on urban air quality management (EEA, 2018). Initiatives targeting public awareness and behavioural changes have led to growing support and demand for measures to improve air quality (EEA, 2019). The ClairCity project, funded under EU Horizon 2020, aimed to put citizens’ behaviour and activities at the core of policymaking in six European countries (ClairCity, 2020). The six pilot case study areas examined are Bristol (United Kingdom), Amsterdam (Netherlands), Ljubljana (Slovenia), Sosnowiec (Poland), Aveiro Region (Portugal) and Liguria Region (Italy). The ClairCity co-designed framework led to a creation of a policy package for each case study, consisting of a set of policies designed by citizens, decision-makers, local planners and stakeholders based on data collected through multi-stakeholder collaboration processes.

This paper tries to bring 'citizen-inclusive policy making' as an important focus point for future air quality policy plans development to improve air quality and reach expected objectives. The main objective of this paper is to quantify, understand and compare the impacts from citizen-led policy package, which account for behavioural changes for the short and long term. The analysis focuses on emissions, air quality, population exposure, and health for the six case studies. The paper is structured into four main sections: Section 2 describes the methodology behind the BAU and FUPS scenarios, the methods and tools adapted for the emission estimation, air quality modelling assessment, population exposure and health impact assessment. Section 3 shows the results and discussion by applying both scenarios analysing reductions achieved in terms of emission, air quality and population exposure, but also the improvements in terms of health impacts. The main conclusions are presented in section 4.

## Methodology

This section presents a summary of the engagement processes (section 2.1), then describes how the measures were obtained to build the scenarios (section 2.2), and how they were interpreted to quantify the variability in terms of emission (section 2.3), the impacts on air quality (section 2.4) and the respective impacts on population exposure and health (section 2.5). The results from the quantification framework will be further presented and discussed in section 3. A schematic representation of the ClairCity methodology flow is presented in Figure S1 of the supplementary material, showing the connection between the engagement process and the scenario co-creation. This work is focused on the impact assessment step.

### 2.1 Engagement processes

The engagement and co-creation process in ClairCity were performed in three key phases with several activities which work towards achieving a final policy package, as schematically represented in Figure 1. More details can be found in Artola and Slingerland (2019). This process has been adapted and applied across all six case study areas and consists of:

1. Establishing the baseline situation for each city;
2. Citizen and Stakeholder Engagement & Co-creation of Scenarios;
3. Quantified Policy Package, Evaluation and Mutual Learning, Policy Recommendations;

In Phase 1, data on city characteristics, demographics, air quality and climate change situation, as well as historical and current policy and citizen engagement landscape, were collected to quantify the baseline air pollutants emissions and concentrations, public health impacts, and current policies. Phase 2 focused on engaging citizens and key stakeholders in order to: understand citizens' current behaviours, practices, and activities; enabling citizens and stakeholders to co-create and provide information about desired future behaviours and future policies; and raising awareness of the environmental challenges and their solutions. For this purpose, in addition to the Skylines Game and the GreenAnt App, 2-round Delphi surveys and a Delphi workshop were carried out with citizens to get their views and opinions on their city/region needs, challenges and barriers. The engagement process was crucial for the project goals. The results from these activities were surmised towards achieving consensus and processed into qualitative ‘citizen scenarios’. These were subsequently discussed in workshops with stakeholders – Mutual Learning Workshops and Stakeholders Dialogue Workshops (SDW), and with policymakers - Policy Workshops (PW), regarding opportunities, barriers and limitations to their implementation, as well as their prioritisation and planning. The SDW originated scenarios with different levels of ambition, which were later quantified and presented as an input for the PW to help participants choose between the level of ambition of each measure and to be further integrated into phase 3. The impact assessment between different stages, as shown in figure S1 of the supplementary material, is an essential step in the framework. This allows to provide quantified guidelines to assist the debate but also identify possible limitations which improve the quality of further debates and results.

Phase 3 gathered the evidence and lessons learned from Phase 1 and Phase 2 to reach a quantification of the FUPS in each city. The inclusion of citizens and stakeholders’ suggestions into decision making was evaluated using cutting-edge modelling to understand the impacts on emissions, air quality and health, compared to a policy baseline scenario, as described in the following section 2.2. Then, this assessment returned to policymakers, citizens and influential organisations in each city and region. The policy and political feasibility of the scenarios were discussed together with policymakers in the PW to draw a consensual package of measures – Policy Package –that defined the FUPS for each city/region.



Figure 1-Schematic representation of the engagement process to obtain the Final Unified Policy Scenario (FUPS) for each city/region.

### 2.2 Scenarios development

The scenarios developed in the scope of the ClairCity project were co-designed following a framework that can be separated into two different groups: (1) the Business-As-Usual (BAU) scenarios, which aims to capture the continuation of city policy assuming no additional measures are taken, reflecting the normal trend without any behavioural changes, or any policy, neither interventions beyond the measures already established; and (2) the Final Unified Policy Scenarios (FUPS), which translates the vision and expectations of local citizens, stakeholders and policymakers based on data collected through ClairCity engagement processes. The data collected through the engagement process from the ClairCity framework estimated the impact of future scenarios considering 3-time horizons: 2025, 2035 and 2050, and was used to support and inform the development of city policy packages. The scenarios were compared, considering the impact on the baseline year (2015).

As previously mentioned, BAU scenarios take into consideration national and city-level measures already defined. Overall, for the six case studies, the scenarios were designed using the projections of greenhouse gas emissions and energy demand from the 7th national communication to United Nations Framework Convention on Climate Change (UNFCCC); from the national measures projections in the frame of the National Emission Ceiling Directive (NECD); and when applicable, other specific case study related measures, as for example, the ban of coal power plants by the Dutch government in 2018, or the permanent shutdown of the Genoa coal thermal power plant in 2016 (Rodrigues et al., 2020).

The final policies included in the FUPS for each case study are presented in Table S1 of the supplementary material.

Overall, for the developed FUPS (see section 2.1), there was no set of measures to fit all cases equally since each city/region has different priority measures and views on how far they can go implementing those measures. A common ground found across all cities is the focus on the transport sector, whether these are public transport policies, policies targeting private vehicles or policies to foster active travel. All the cities proposed ambitious policies to discourage car use. Regarding the energy sector, Bristol, Amsterdam, Sosnowiec and the Liguria Region were quite ambitious, while Ljubljana and Aveiro were less so. When assigning ambition levels for each policy, generally, the reasons for opting for a low ambition level were the cost of implementation of the measures and an unrealistic timeframe proposed in the high ambition level (Artola and Slingerland, 2019). For example, cleaner public transport was given low ambition in all cases.

Bristol is the only city with an equality policy, namely "spread economic opportunities across the city". Most energy policies are found in Amsterdam, while in Ljubljana deliberately no energy policies were generated, which reflects the dominance of transport policies in the public debate. Sosnowiec was the only case which proposed two measures that can be considered adaptation measures to air pollution, namely: "Free public transport on days with a high level of air pollution by 2020", and "Ban diesel cars from the city centre on days with poor levels of air pollution by 2050”. Liguria region considered high priority shifting private vehicles to electric, and it is partly being facilitated through financial incentives. Active travel policies mostly regard cycling, with only Aveiro proposing a specific measure to foster walking. Four out of the six case studies (Bristol, Amsterdam, Ljubljana and Liguria) discussed measures around “environmental zones”. Furthermore, the set of policy measures of Sosnowiec and Aveiro included industry (technological) measures, which do not require behaviour change of citizens.

### 2.3 Emissions estimation

The ClairCity impact assessment framework included the development of an emission inventory considering the most relevant emission sectors in urban areas, such as the road transport sector, the residential, commercial and institutional sector (IRCI), and the industrial sector. Additionally, the shipping sector was quantified for the baseline for Amsterdam and the Liguria Region. The BAU scenarios for the shipping sector were only quantified for the Liguria Region, where the International Maritime Organization Tier 2 and cold ironing implementation measures account for reductions of NOx emissions of 15.5% in 2025 and 24.1% in 2050.

The methodology for the scenarios’ emissions quantification process for each sector will be described next. The baseline framework also follows the quantification methodology for all case studies described in Rodrigues et al. (2020).

#### 2.3.1 Transport

The transport sector was the most addressed sector by measures of the FUPS, therefore the scenarios accounted for several variations in terms of the vehicle fleet composition and modal choice changes for the future.

A mode choice model (Purwanto et al., 2017) was used to predict the modal shift (and the mileage change) caused by various policy decisions or scenario targets. The model predicts the percentage chances of a traveller choosing a given transport mode, based on a given socioeconomic background (income, car ownership, age, gender, etc.), who travels for a given reason (work, education, shopping, etc.), between two points. It then forecasts transport demand and vehicle fleet size, calculating change not only in the percentage of trips over various modes but also the change in total mileage per mode. Predicting how mode choices would be influenced by different assumptions made for each measure/scenario allows estimating energy and emission values, which are related to the vehicle kilometres.

While the FUPS scenarios account for all the behavioural change idealised by citizens and stakeholders, BAU scenarios assumed no change in the modal split, accounting only for the predicted fleet evolution as stated by McKinsey & Company (2012). For each scenario, the final emissions were then estimated based on the new modal splits and the resulting mileage changes for the various years. So, the emissions were calculated by following the common COPERT V methodology (https://www.emisia.com) by applying the EU standard vehicle emission factors to the new traffic volumes.

Although different approaches and assumptions had to be made for each case study, all the cities proposed one or multiple measures focusing on four main groups: restrictions of private vehicles, an improvement in terms of public transportation, improvements to promote active travel, and encouragement for electric vehicles (EV).

The restrictions of private vehicles account for several aspects regarding private transportation. In a lot of cities, the restriction pointed to a ban on most polluting vehicles which resulted in policies ranging from banning the most polluting vehicles (old Euro standard diesel) in low emission zones to completely banning cars with an internal combustion engine. These kinds of measures were all modelled by changing the survival rates and the growth rates in the fleet models. For example, if a city decides to introduce a stepwise ban on diesel cars, so that, e.g., by 2030 only Euro 6 diesel cars are allowed on the roads, then this is modelled by making sure that all Euro 5 or worse diesel vehicles were scrapped out of the fleet by the end of 2029 (for example scrapping all Euro 3 by the end of 2025 and Euro 4 by the end of 2027 as a lead up to put smaller pressure on the new sales that still need to fill the suddenly larger demand-gap). Such scrapping schemes are very easy to model by setting the survival rates for all to be fully scrapped vintages to 0.

Cheaper and more efficient public transportation was seen as a common goal between all cities/regions. The idea behind these measures is to induce a modal shift by reducing the use of private vehicles and enhancing the use of public transportation. The improvement of the overall network organisation, as a result of higher frequencies and more fluid routes (e.g., with the introduction of more bus lanes), leads to a strong decrease in waiting and travel times. Furthermore, overcoming the identified problems with the public transportation network is evident to be a suitable alternative to private vehicles, and so, it will lead to a bigger modal shift in the future. Combining a reduction of private vehicles, the improvement of the network and a greener public fleet shows a significant impact on emission reduction.

To promote active travel, the measures focused mainly on bike lanes and pedestrian routes. The construction of bike lanes or pedestrian routes was seen as an incentive for active travel since it improves the safety of the users, a highly valuable factor in decision making. The attractiveness of better infrastructures in the future, combined with the willingness by the citizens to change, leads to assumptions for the growth of walking/bike trips share. The identified levels of ambition from the citizens for active travel were significantly different between case studies, therefore the growth assumptions by measure for each scenario was heavily influenced by this factor.

The encouragement of electric vehicles covered different aspects, e.g., financial incentives, replacement of fleets, charging facilities, and others. For example, in the Liguria Region, one measure consisted of replacing 50% of vehicles circulating in urban areas with electric automobiles and motorcycles (including sharing) by 2050 and installing an adequate number of recharging stations. The assumption focused on updating the EV sales share progressively to achieve the 50% fleet share by 2050. Overall, the assumption for the scenarios focuses on a fleet evolution, from incentives (as subsidies, advertisement, environmental considerations) that will boost the uptake of vehicles with electric and hybrid powertrains.

#### 2.3.2 Industrial, Residential, Commercial & Institutional (IRCI)

The IRCI emissions were estimated for the future years for every single territorial unit LSOA (Bristol), buurt (Amsterdam), naselje (Ljubljana), gminas (Sosnowiec), freguesia (Aveiro region), and census section (Liguria region)) for a specific activity starting from the emissions from the baseline year. These estimations use specific projections factors (drivers) of activity level due to activity measures and specific drivers for emission factors related to emission control measures and, if any, additional emissions are foreseen for a selected new activity. Drivers for activity levels and emission factors can be related to multiple activities. For example, the demographic driver can be used to forecast emissions for the residential sector related to fuel consumption.

Regarding policy measures for the IRCI sector, Bristol and Amsterdam were the most ambitious case studies. For Bristol, the measures focused on increasing the production and usage of renewable energy, raise awareness between property developers regarding air pollution and climate change, improve the energy efficiency of housing, and further measures were designed based on the Bristol strategy for carbon neutrality by 2050. For Amsterdam, the measures aimed at gas-free policies by 2040, with no fossil fuel for 100% of buildings and residual use of gas allocated to biogas (45%) and green gas (55%). While Sosnowiec aimed for a partial ban of coal on the Residential and Commercial sector. Ljubljana, Liguria Region and Aveiro Region didn’t include measures concerning the residential and commercial sector to go further than established by the BAU scenarios.

The planned strategies by the governments accounted for in the BAU scenarios had big impacts on the industrial sources in different case studies. For example, in Amsterdam due to the coal ban, the production of electricity with coal as fuel is prohibited from 2030 onwards. Therefore, the two oldest power plants will stop electricity production by the end of 2024 through coal. In consequence, the BAU scenario accounts for the closure of a power plant by 2025. In Liguria Region, the BAU scenario accounts for the shutdown of the Genoa Power Plant in 2016 (Rodrigues et al., 2020).

The cities/region to present FUPS scenarios to go further than the BAU scenarios for the industrial sector were Sosnowiec and the Aveiro Region. The Aveiro region presented measures to reduce PM industrial emissions by 15% in 2025, and Sosnowiec defined a measure to reduce industrial emissions by 25% in 2025. One important assumption considered is without any policy to limit or to prohibit the most polluting fuels, no change was foreseen in the share of use of the different fuels.

### 2.4 Air quality modelling assessment

To assess the impact of the scenarios on air quality, a hybrid method composed by a numerical approach – using the URBAIR – URBan AIR model (Borrego et al., 2016; Dias et al., 2018) and a weighting approach, was applied.

First, the air quality simulations were performed for the entire year of 2015 on an hourly basis considering the meteorological conditions for each hour and emission variability, following the quantification methodology described further in Rodrigues et al. (2020) and Rafael et al. (2021). The URBAIR is a second-generation Gaussian model that has been widely applied to assess air quality at urban scale (Borrego et al., 2016; Dias et al., 2018). The assessment of air quality was focused on NO2, PM10 and PM2.5 concentrations. The different emission sectors – transport, IRCI, industrial, and shipping (for Amsterdam and the Liguria Region) - were simulated separately in order to have their individual contribution (source-apportionment approach). The air quality simulations were performed for the computational domain over the urban area of each city/ region with a horizontal resolution of 200 m x 200 m, except for the Aveiro Region, which was run with a horizontal resolution of 400 m x 400 m. The computational domains of each city/ region differ in Bristol, Ljubljana, and Sosnowiec domains dimensions are 20 km x 20 km, Amsterdam domain is 25 km x 20 km, Liguria domain is 25 km x 15 km, and Aveiro domain is 40 km x 55 km.

Second, the annual percentual reductions of each emission sector were applied to the annual air quality outputs per sector for each scenario and time-horizon for the six cities/regions.

It should be noted that this hybrid method can be adopted since the focus of the study are annual metrics. As showed by Thunis et al. (2015), linear simplifications could have different impacts depending on the time scales considered. In particular, when focusing on long-term averages (annual averages), can exhibit very low level of non-linearities depending on the pollutant and location, and so, the secondary formation through chemical reactions can be neglected when the annual mean concentrations are calculated. This simplification guarantees both spatial and temporal distribution of air pollutants concentrations, proving to be less time demanding and requires less computational resources. Despite that, this hybrid method has uncertainties associated, which will be discussed further in section 3.5.

For each case study, air quality spatial and temporal maps were produced, and different analyses were conducted considering the EU regulated limit values for these specific pollutants and the stricter but voluntary WHO guidelines that are established for PM10 and PM2.5.

### 2.5 Population exposure and health impact assessment

The population potentially exposed to NO2, PM10 and PM2.5 concentrations above the EU legal limit values (EU, 2008) and the WHO guidelines (WHO, 2006) was estimated for all the case studies. The population exposure was estimated considering an annual average of air quality concentrations and population data (CBS, 2015; INE, 2011; Istat, 2011; ONS, 2015; Statistics Poland, 2011; SURS, 2011) distributed by each computational grid cell.

To estimate the health benefits related to each of the individual air pollution reduction scenarios, the following health impact indicators were calculated individually for PM2.5, PM10 and NO2 concentrations:

1. Reduction in mortality is expressed as the reduction in premature deaths.
2. Reduction in years of life lost (YLL).

These mortality health outcomes were estimated based on the methodology described in Soares et al. (2019). To calculate premature deaths and YLL, population density and demographic data per country, age, and sex was combined with gridded concentrations provided by the air quality estimations from section 2.3 and concentration-response functions. The concentration-response functions follow the recommendations from the HRAPIE project (WHO, 2013): for PM2.5, all-cause (natural) mortality is considered in ages above 30, for all concentration levels, assuming an increase in the risk of mortality of 6.2% for a 10 µg.m-3 increase of PM2.5; for PM10, all-cause (natural) mortality is considered in ages above 30, for all concentration levels, assuming an increase in the risk of mortality of 4.0% for a 10 µg.m-3 increase of PM10; and for NO2, all-cause (natural) mortality is considered in ages above 30, for concentrations above 20 µg.m-3, assuming an increase in the risk of mortality of 5.5% for a 10 µg.m-3 increase of NO2.

## Results and discussion

This section discusses the potential impacts of implementing the measures comparing to the baseline year in terms of emissions (section 3.1), air quality (section 3.2), population exposure (section 3.3), and health impacts (section 3.4).

### 3.1 Emissions

Figure 2 shows the emission reductions for the transport, residential and commercial sector, for NOx and PM, compared to the baseline for both BAU and FUPS scenarios for all the cities/regions.

|  |
| --- |
| **Bristol** |
|  |  |
| **Amsterdam** |
|  |  |
| **Ljubljana** |
|  |  |
| **Sosnowiec** |
|  |  |
| **Aveiro Region** |
|  |  |
| **Liguria Region** |
|  |  |

Figure 2- Scenario emissions for NOx and PM as a percentage of the baseline emissions after applying the emission reduction measures

For Bristol, the FUPS scenario is successful in further decreasing the emissions from transport beyond the reductions already in the BAU. Transport NOx emissions are reduced to about 10% in 2035 compared to 2015 in the FUPS scenario, while the BAU emissions in that year are still 19% of the 2015 emissions. For the FUPS scenario, transport emissions are reduced to 5% for NOx and 3% for PM in 2050 compared to 2015. A side-effect of the FUPS scenario is that it increases the importance of emissions from other sources that are not affected by the policy measures. For example, while PM emissions of residential sources overall are decreasing, their slower emission reduction pace compared to transport is making residential sources the dominant sources of PM emissions over time, from about 47% in 2015 to 85% in 2050.

For Amsterdam, the NOx emissions are highly reduced in both scenarios but going further with FUPS. The difference between both scenarios is explained mainly due to gas-free measures for the residential sector and the transport restriction measures presented by the FUPS scenarios. The PM emissions in the city centre would increase in the BAU scenario as a result of higher emissions from cars (due to the non-exhaust emissions of transport, i.e., the brake and tyre wear and tear), but would strongly decrease in the FUPS as a result of the ban of wood burning from residential and commercial sources included as a measure.

For Ljubljana, the BAU scenario would reduce NOx emissions to about 62% of 2015 levels in 2025 and about 19% of the base year value in 2050. The FUPS scenario includes no measures related to the IRCI sector, so the changes, when compared to the BAU, are only observed in the transport sector. The FUPS scenario measures as modelled lead to a slight increase of NOx emissions compared to BAU, mainly because the selected measures contribute to a modal shift from private cars to buses, however none promote the replacement of the public transport fleets with electric vehicles. Therefore, when comparing FUPS to BAU, slight increases can be seen in 2025 and even higher in 2035 due to an increase of public transport of 10% by 2027. The PM emissions show a strong decrease in the BAU with a great reduction of residential solid fuel consumption but would not go further in the FUPS due to the lack of specific measures targeting these emissions.

For Sosnowiec, the FUPS scenario adds an additional decrease in emissions (e.g., around 5% in the short term and less in the longer term) beyond the reductions in the BAU. For the NOx emissions, the decrease is mainly due to decreasing transport emissions, through measures pushing citizens away from car use towards active travel and public transport (being cleaner compared to the BAU due to additional investments in zero-emission buses). A similar downward trend is observed for PM emissions. The main driver for the reduction is linked to heating in the residential sector. Already in the BAU, a gradual improvement is expected, leading to stronger reductions with the FUPS scenarios due to more ambitious measures for the replacement of residential heating sources. The FUPS will generate an additional decrease in PM emissions compared to the BAU. However, a decrease in PM emissions from transport will continue to have a limited impact on the overall emissions.

For the Aveiro Region, the NOx emissions exhibit a significative trend of reduction in both scenarios, with the FUPS scenario allowing a slight extra reduction comparing to BAU. Reductions in both scenarios result mainly from decreasing transport emissions. In the FUPS, due to the encouragement of a modal choice, a stronger reduction in emissions from cars and an increase in bus emissions were observed, with a net emission reduction. However, by 2050, emission reductions from BAU and FUPS will be almost the same. For PM, the emission reductions are limited for both scenarios, mainly observed for residential solid fuel consumption. The measures in FUPS have a similar effect to BAU due to the lack of specific measures in FUPS targeting, for example, residential heating. Given the low contribution of transport to PM emissions, the emission savings from transport in the FUPS compared to BAU are negligible in the overall result.

For the Liguria Region, the NOx emissions show a clear trend of reduction over the three time-horizons. The FUPS scenario leads to a limited decrease in emissions beyond the reductions already in the BAU for most sectors. Moreover, the decrease of passenger car NOx emission is offset by a rebound of emissions from buses. This is because FUPS measures increase the use of buses by citizens but present no measures concerning the improvement of public transport emissions. So, buses emissions are expected to increase in the FUPS scenario. In 2050, the total emissions in the BAU scenario and the FUPS will be almost the same. A similar trend is observed for PM emissions, without the rebound from bus emissions. This decrease in PM emissions is mainly a result of a decrease in residential emissions linked to heating. The FUPS does lead to a slight additional reduction of PM emissions compared to the BAU (2.6%), mainly due to reductions in transport emissions. Given the low contribution of transport to PM emissions, the emission savings from transport in the FUPS compared to BAU are very small.

### 3.2 Air quality outcomes

To better understand the impact of the emission reductions described in subsection 3.1 on air quality, the number of computational cells with annual exceedances to the EU limits and WHO guidelines by case study for each scenario is present in Table 1. For NO2 the limit values established by the EU and the ones recommended by WHO are equivalent, being 40 μg.m-3 for the annual mean. As for particulate matter, the limits diverge between both standards, with WHO showing stricter limits. PM10 values under the EU annual mean limits are 40 μg.m-3 and under WHO guidelines are 20 μg.m-3, for PM2.5 the EU established a limit value of 25 μg.m-3 for the annual mean and the WHO recommends 10 μg.m-3.

Table 1 shows that mainly PM2.5 is still and will be, even by 2050, a big concern in the cities, especially for Ljubljana, Sosnowiec and the Liguria Region.

Table 1- Number of computational cells (cells with 0.04km2, except for the Aveiro Region with cells of 0.16km2) with annual exceedances to the EU limits and, in parenthesis, to the WHO guidelines by case study and scenario

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Bristol** | **Amsterdam** | **Ljubljana** | **Sosnowiec** | **Aveiro Region** | **Liguria Region** |
| EU/ (WHO) | EU/ (WHO) | EU/ (WHO) | EU/ (WHO) | EU/ (WHO) | EU/ (WHO) |
| NO2 |
| 2015 | 231 | 214 | 170 | 915 | 11 | 97 |
| BAU25 | 5 | 3 | 34 | 493 | - | 7 |
| FUPS25 | 1 | - | 45 | 459 | - | 7 |
| BAU35 | - | - | - | 252 | - | 3 |
| FUPS35 | - | - | - | 214 | - | 3 |
| BAU50 | - | 2 | - | 180 | - | 2 |
| FUPS50 | - | - | - | 171 | - | 2 |
|  | PM10 |
| 2015 | - (16) | - (179) | - (2) | 46 (3800) | - (-) | 3 (924) |
| BAU25 | - (8) | - (37) | - (-) | 16 (2670) | - (-) | 1 (656) |
| FUPS25 | - (-) | - (35) | - (-) | 14 (2505) | - (-) | 1 (661) |
| BAU35 | - (5) | - (35) | - (-) | 5 (1740) | - (-) | - (541) |
| FUPS35 | - (-) | - (35) | - (-) | 5 (1547) | - (-) | - (536) |
| BAU50 | - (3) | - (35) | - (-) | 4 (1385) | - (-) | - (553) |
| FUPS50 | - (-) | - (35) | - (-) | 3 (1245) | - (-) | - (514) |
|  | PM2.5 |
| 2015 | - (655) | - (3609) | - (3792) | 372 (5755) | - (1997) | 5 (2637) |
| BAU25 | - (406) | - (2261) | - (3792) | 170 (5755) | - (279) | 3 (2637) |
| FUPS25 | - (192) | - (55) | - (3792) | 155 (5755) | - (234) | 3 (2637) |
| BAU35 | - (338) | - (1616) | - (3792) | 69 (5755) | - (250) | 1 (2637) |
| FUPS35 | - (100) | - (11) | - (3792) | 65 (5755) | - (61) | 1 (2637) |
| BAU50 | - (249) | - (1394) | - (3792) | 47 (5755) | - (267) | 1 (2637) |
| FUPS50 | - (21) | - (13) | - (3792) | 45 (5755) | - (71) | 1 (2637) |

For NO2, in 2015 all the cities/regions presented some exceedances problems in some areas of the domain. By 2025, significant reductions are showing a big impact of the measures from both scenarios, resolving the NO2 issues for the majority of the case studies. By 2050, Sosnowiec, although with a big reduction of the number of cells with exceedances (a reduction around 81% from 2015), is the only case study that still presents some major exceedances to NO2. The potential problems in Sosnowiec by 2050 are caused mainly by the residential sector, which indicates a necessity for more ambitious measures for that sector.

For PM10 and PM2.5, when looking at the EU legal limit concentrations for the baseline, only Sosnowiec shows exceedances of particulate matter and the Liguria Region with a located problem in a reduced area (3 cells for PM10 and 5 cells for PM2.5 that are exceeding the EU annual limits) of the domain. The application of the scenarios improves the PM10 concentrations significantly, showing no exceedances by 2035 in the Liguria Region, and by 2050 with FUPS scenarios, only 3 cells are exceeding the EU limits in Sosnowiec. On the other hand, when applying the stricter WHO guidelines limit, Table 2 shows that mainly PM2.5 is still and will be, even by 2050, a big concern in the cities, especially for Ljubljana, Sosnowiec and the Liguria Region.

Figure 3 shows the percentage of reduction of the maximum concentration value for the annual average compared to 2015 of NO2, PM10 and PM2.5 for each case study when applying BAU and FUPS scenarios for the three-time horizons (2025, 2035, and 2050).

Overall, the reductions of the maximum value range between 19% and 85% for NO2, 5% and 40% for PM10, and between 3% and 43% for PM2.5, showing generally bigger reductions for the FUPS comparing to BAU scenarios.

Figure 3- Reduction (in %) for each scenario (2025, 2035, 2050) of the maximum annual average concentration in the domain of NO2, PM10 and PM2.5 in each case study.

 By looking at the reductions is possible to identify the cities/regions with the most ambitious/efficient measures. For example, Bristol FUPSs shows a significant improvement when compared to the BAU scenario, being even more evident when looking at PM. While the Aveiro Region shows huge reductions for NO2, when looking at PM10 and PM2.5, it is one of the least ambitious, as previously explained, by presenting no measures for the residential and commercial sector for the FUPS scenario. Sosnowiec and the Liguria Region show the highest reductions of the maximum value for PM10 and PM2.5 concentrations while exhibiting a low reduction in terms of NO2.

### 3.3 Population exposure

Directly related to air quality outcomes is the population exposure. Table 2 shows the percentage of population potentially exposed to the annual NO2, PM10 and PM2.5 concentrations considering the EU limits and WHO guidelines (in parentheses) for each scenario. The status of population exposure is distinguishable in the 6 cities and regions under study.

A general reduction of the population potentially exposed was obtained in the BAU scenario when compared with the baseline, with an average reduction of 6%, 8% and 9% for the three time-horizons (2025, 2035 and 2050), respectively. This improvement is explained by the overall reduction of PM10, PM2.5 and NO2 concentrations due to the reduction in transport and residential combustion emissions, as discussed in section 3.1 . For the BAU scenarios, Sosnowiec will still be the city that has the highest rate of population potentially exposed to PM10, PM2.5 and NO2 concentrations. The percentage of exposure ranges between 44.9% (BAU 2025) and 28.3% (BAU 2050) for NO2; for PM10 and PM2.5 the percentage of exposure is higher than 2%, reaching 100% for PM2.5 regarding the WHO standard. For the remaining cities and regions, the population exposed to high levels of NO2, PM10 and PM2.5 concentrations are less than 1% for BAU 2025, BAU 2035 and BAU 2050 when the EU annual limit values are considered. For the PM10 WHO target, the Liguria Region showed a high rate of population exposure, varying between 63.5% (BAU 2025) and 55.3% (BAU 2050). As observed in the baseline, PM2.5 will still be the most critical pollutant in the BAUs, for all the cities and regions except Aveiro Region, having more than 10% of the population exposed to PM2.5 concentrations above 20 µg.m-3.

FUPS also showed a trend of reduction of the population exposure, with significant reductions for Bristol and Amsterdam when compared to BAUs. In FUPS scenarios, Sosnowiec, Ljubljana and the Liguria Region showed no major reductions in the percentage of population exposure compared to BAUs. This outcome is explained by the low ambition of the overall measures regarding transport and energy, not going further than the established in BAUs. On the other hand, for the remaining cases – Bristol, Amsterdam and Aveiro Region, FUPS showed a substantial reduction compared to BAU for the three time-horizons, and by 2050 less than 1% of the population will be exposed to the EU and WHO annual standards for PM2.5 and PM10.

Table 2- Population potentially exposed (expressed in percentage) to the annual NO2, PM10 and PM2.5 concentrations considering the EU limits and WHO guidelines (in parentheses) for each scenario in the 6 cities/regions.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Bristol** | **Amsterdam** | **Ljubljana** | **Sosnowiec** | **Aveiro Region** | **Liguria Region** |
| % of population potentially exposed to NO2 |
| Baseline | 5 | 3 | 5 | 59 | 1 | 8 |
| BAU 25 | - | - | 80 | 45 | - | 25 |
| FUPS 25 | - | - | 80 | 44 | - | <1 |
| BAU 35 | - | - | - | 34 | - | - |
| FUPS 35 | - | - | - | 31 | - | 5 |
| BAU 50 | - | - | - | 28 | - | - |
| FUPS 50 | - | - | - | 28 | - | - |
|  | % of population potentially exposed to PM10 |
| Baseline | - (<1) | - (2) | - (-) | 13 (95) | - (-) | <1 (78) |
| BAU 25 | - (<1) | - (<1) | - (-) | 6 (89) | - (-) | - (64) |
| FUPS 25 | - (-) | - (<1) | - (-) | 5 (88) | - (-) | - (64) |
| BAU 35 | - (<1) | - (<1) | - (-) | 3 (80) | - (-) | - (54) |
| FUPS 35 | - (-) | - (<1) | - (-) | 3 (78) | - (-) | - (54) |
| BAU 50 | - (<1) | - (<1) | - (-) | 2 (75) | - (-) | - (55) |
| FUPS 50 | - (-) | - (<1) | - (-) | 2 (73) | - (-) | - (53) |
|  | % of population potentially exposed to PM2.5 |
| Baseline | - (25) | - (71) | - (100) | 13 (100) | - (49) | <1 (100) |
| BAU 25 | - (18) | - (59) | - (100) | 29 (100) | - (9) | - (100) |
| FUPS 25 | - (10) | - (<1) | - (100) | 28 (100) | - (7) | - (100) |
| BAU 35 | - (15) | - (50) | - (100) | 16 (100) | - (8) | - (100) |
| FUPS 35 | - (5) | - (<1) | - (100) | 16 (100) | - (1) | - (100) |
| BAU 50 | - (12) | - (47) | - (100) | 13 (100) | - (8) | - (100) |
| FUPS 50 | - (1) | - (<1) | - (100) | 13 (100) | - (2) | - (100) |

### 3.4 Health impact

Health impacts were estimated for the baseline and the future emission scenarios. The health impact assessment for the baseline, with the number of premature deaths (PD) and life-years lost (YLL), is presented in Table 3. The health benefits from implementing emission control measures for PM2.5, PM10 and NO2 in 2025, 2035 and 2050 are presented in Figure 4. The benefit is estimated by benchmarking the future health outcome values with the values estimated for 2015.

Table 3-Health outcomes related with exposure to PM2.5, PM10, and NO2 concentration levels in 2015 (baseline).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Baseline** | **PM2.5** | **PM10** | **NO2** |  | **PM2.5** | **PM10** | **NO2** |
| **Bristol****(pop. 675908)** | **PD** | 577 | 290 | 439 | **Liguria Region****(pop. 566483)** | **PD** | 590 | 506 | 418 |
| **YLL** | 6170 | 3102 | 4696 | **YLL** | 5014 | 4294 | 3549 |
| **YLL/1e5 inhabitants** | 913 | 459 | 695 | **YLL/1e5 inhabitants** | 885 | 758 | 626 |
| **Amsterdam****(pop. 838153)** | **PD** | 568 | 557 | 697 | **Ljubljana****(pop. 314691)** | **PD** | 255 | 185 | 219 |
| **YLL** | 5933 | 5821 | 7277 | **YLL** | 2687 | 1950 | 2306 |
| **YLL/1e5 inhabitants** | 708 | 695 | 868 | **YLL/1e5 inhabitants** | 854 | 620 | 733 |
| **Aveiro Region** **(pop. 347589)** | **PD** | 194 | 154 | 63 | **Sosnowiec****(pop. 624542)** | **PD** | 879 | 664 | 1194 |
| **YLL** | 2235 | 1766 | 720 | **YLL** | 12552 | 9479 | 17039 |
| **YLL/1e5 inhabitants** | 643 | 508 | 207 | **YLL/1e5 inhabitants** | 2010 | 1518 | 2728 |

Figure 4-Health benefits from implementing emission control measures in 2020, 2035 and 2050.

For Bristol, it shows that the FUPS scenario significantly improves human health compared to the current situation and the BAU scenario. For the baseline year, the number of premature deaths as a result of PM2.5, PM10 and NO2 is 404, 336 and 429, respectively. The BAU scenario reduces these numbers by 87%, 17% and 26% in 2050 respectively, but the FUPS scenario results in far larger reductions: 94%, 79% and 52%. The reduction in the number of premature deaths is higher than the average concentration reduction when comparing the baseline and future emission scenarios. This discrepancy confirms that the reduction occurs more in areas with a high population.

For Amsterdam, the FUPS scenario significantly improves human health compared to the current situation and the BAU scenario. The health benefit of implementing citizen measures in the FUPS is considerable. In 2015, the number of premature deaths as a result of PM2.5, PM10 and NO2 is 568, 557, and 697, respectively. In 2050, the BAU scenario reduces these numbers by 8%, 10% and 46%, respectively, but the FUPS scenario results in larger reductions: 23% for PM2.5, 17% for PM10, and 84% for NO2. The FUPS scenario is therefore effective in reducing the long-term health effects of NO2 as well as PM concentrations. The health benefit from the emissions reduction is in line with the concentration levels reduction predicted for Amsterdam. However, the reduction in the number of premature deaths and the numbers of years of life lost is far more than the average concentration levels reduction. This is explained by the emission reduction measures targeting the more densely populated areas, thus benefiting the population health.

For Ljubljana, the health improvements derived from PM10 and PM2.5 concentration reductions are the same for both scenarios, showing only a slight difference for NO2. The health benefit from implementing the control measures behind the future emission scenarios is considerable. For the baseline year, the number of premature deaths as a result of PM2.5, PM10 and NO2 is 169, 185 and 219, respectively. The scenarios, in 2050, respectively, reduce these numbers by 3%, 5% and 67% (64% for the FUPS). The health benefit from the reduction of emissions is in line with the reduction of concentration levels predicted for Ljubljana.

For Sosnowiec, the FUPS scenarios significantly improve human health compared to the current situation, however, offers only a moderate improvement over the BAU. The health benefits from implementing the control measures behind the future emission scenarios (BAU and FUPS) are considerable for NO2 but not as significant for neither PM10 nor PM2.5. For the baseline year, the number of premature deaths as a result of PM2.5, PM10 and NO2 is 879, 664 and 1 194, respectively. The BAU scenario reduces these numbers by 18% (19% for the FUPS), 21% and 40% (41% for the FUPS) by 2050 respectively.

For the Aveiro Region, both FUPS and BAU scenarios lead to moderate improvements in human health when considering exposure to PM concentrations, but substantially improves human health when considering exposure to NO2 concentrations. For the baseline year, the number of premature deaths as a result of PM2.5, PM10 and NO2 is 194, 154, and 63, respectively. The health benefit from implementing the control measures behind the future emission scenarios (BAU and FUPS) is considerable for NO2 but moderate for particulate matter. In 2050, the BAU scenario will reduce premature deaths as a result of PM2.5, PM10 and NO2 by 2% (3% for the FUPS), 5% (7% for the FUPS) and 100% in 2050 respectively, when compared to the baseline.

For the Liguria Region, the positive impact on human health prompted by the FUPS and the BAU scenario is virtually the same. The health benefit from implementing the control measures behind the future emission scenarios (BAU and FUPS) is considerable for NO2 but not as significant for neither PM10 nor PM2.5. For the baseline year, the number of premature deaths as a result of PM2.5, PM10 and NO2 were 590, 506, and 418, respectively. By 2050, the BAU scenario will reduce these premature deaths by 6%, 10% (11% for the FUPS), and 79%, respectively. The health benefits from the emissions reduction in terms of the number of premature deaths and the number of years of life lost are lower than average concentration levels reduction.

### 3.5 Lessons learned and recommendations

For future application of the proposed methodology, it is necessary to consider the existence of limitations and a set of recommendations are advised.

When looking at the social aspect, public engagement is a critical step for the success of the results but also a big source of uncertainty. To fully realise the goal of citizen-led air pollution reduction in cities, researchers and policymakers need to work hard to ensure that the engagement is reflective of city demographics by including different age and socioeconomic groups. Engagement activities should be designed accordingly to the target audience, since the more enjoyable the engagement activities are, the more people gain understanding about the issues and show more willingness to change and improve their behaviour.

During the engagement process, it was evident that citizens were not always keen on policies that require investment or a significant change of behaviour, while for policymakers, the main barriers were the investment costs and the implementation deadlines. Therefore, it is important to set a guidance in the discussion to find common ground between both parties, allowing to filter out unreasonable policies. However, in the case of very high environmental ambitions, such as in Amsterdam, it was also found that there might still be a substantial gap between what policymakers wish and the specific contribution that citizens are willing to make by changing behaviour.

For future replications of this methodology, it is important at first to examine what are citizens’ most desired policies to be applied in the future, setting different ambition levels for each measure, and analyse into what extent these coincide with existing policies. Second, presenting the citizen scenarios to policymakers with different ambition levels so policymakers can discuss implementation barriers and enabling factors and then choose the more feasible ones. At last, it is important to identify policy options that do seem to have relatively little popular support or that are subject to public debate. Consider if the implementation of such options should be pursued and, if so, what should be done to increase support for them (Slingerland and Artola, 2020).

The co-creation of the scenarios should always follow an iterative process by returning the quantification results back to those involved, to calibrate the vision of citizens, stakeholders, and policymakers, as opposed to a unilateral process of involvement. In the framework of this work, a debate was held between citizens and stakeholders (the Stakeholder Dialogue Workshop) during the scenarios building process, to discuss the results of the Delphi and Mutual Learning Workshop evidence and co-create scenarios. The scenarios generated in the SDW were quantified and then returned to the local citizens/stakeholders to discuss at a Policy Workshop and to agree a single Final Unified Policy Scenario. Performing an impact assessment between steps of the co-creation process, allowed to provide quantified evidence to guide the debate between the different players. This may also help to point out possible gaps or less effective measures to improve air quality, which should be known to an effective air quality management.

The impact analysis of the scenarios in terms of emission, concentrations, health impacts and costs are highly relevant to quantify the importance of the measures and to support decision making. It is relevant to mention that the whole process, from behaviour quantification to the air quality and health assessment presents uncertainties associated. The modelling framework, as presented before, proved to be an efficient way to support the choice of citizens and stakeholders in the participatory process of the ClairCity project. However, several uncertainties are associated to it. The emission inventories usually represent one of the largest sources of uncertainty in the air quality modelling chain (Russell and Dennis, 2000). Then, for the air quality approach inherent uncertainties are linked to the air quality models, through difficulties in representing all the atmospheric processes which are depending on the spatial and temporal scale. Moreover, the health impact quantification shows uncertainties due to a lack of specific epidemiological data for each study site.

In order to handle these uncertainties, the assessment and communication of uncertainties should play a key role in the discussion of the results. This was carefully addressed during the whole ClairCity framework, even though they were not quantified for each step. Uncertainties were addressed for the baseline year when estimating emissions, by comparing the results with national and European emission inventories; when simulating air quality, through a process of model calibration, verification and validation, by comparing with available air quality measurements; when assessing health indicators, through a benchmark with the annual estimates for premature deaths and years of lost life reported by the European Environment Agency. These uncertainties were communicated to citizens, stakeholders, decision- and policymakers during the engagement and co-creation activities. The outcomes of these debates, depending on the level of expertise of the attendees in those activities, allowed the modelers to double-check their input data, simulations and results, contributing to their improvement.

## Conclusions

This work focuses on the quantification of impacts on emissions, air quality and human health for the ClairCity future scenarios. ClairCity scenarios were established following a co-creation approach consisting of 3 main vectors: i) establish the baseline, ii) engage citizens, stakeholders and local policymakers, iii) deliver the Policy Package. The assessment of the existing problems for the baseline in each city/region marked the first phase of the scenario’s framework. Then, along the process, a set of measures and policies with different levels of ambition were proposed to policymakers. These measures came from citizens and stakeholder's consultation. In general, policymakers found the measures realistic which indicates some common ground between citizens’ visions for their future city and what policymakers consider implementable. Any eventual disagreement lied mostly on timeframe and ambition level, e.g. citizens typically wanted more ambitious measures and faster implementations.

Bristol and Amsterdam stand out by having ambitious local policies that go beyond the legal obligations on a national and EU level. The ambition set for the final scenario is significantly higher than the BAU targets. On other hand, the remaining 4 cities/ regions tend to impose the same level of ambition in the final scenario as in the already established BAU policies. Furthermore, both Bristol and Amsterdam were the ClairCity pilots with higher concern and ambition regarding reducing residential emissions, which is a sector of great concern in other cities.

Concerning the residential practices, Ljubljana, Aveiro and Liguria had no measures affecting this sector on their Policy Packages. Consequently, the reductions on PM emissions and concentrations are similar both in BAU and FUPS scenarios, and thus there are no benefits from the FUPS. This means that either from now to 2050, citizens, stakeholders, and local policymakers will need to work harder towards more ambitious policies and targets to solve their air quality issues. Additionally, in Sosnowiec, despite the measure aiming to ban coal for residential heating accounted on their Policy Package, this seems to be insufficient to address their PM pollution problems.

The population will benefit the most in terms of NO2 exposure for all the cities. The benefit in terms of population exposed to particulate matter varies a lot across the study areas, with only Bristol and Amsterdam showing substantial differences between fine and coarse particulate matter. Three areas target the pollutants with the highest health impact on their population: Amsterdam (NO2), Bristol and Sosnowiec (PM2.5); Aveiro Region and Liguria Region are mostly targeting the pollutant with the least health impact (NO2). This limited health benefit from emission control measures is either due to low emission reductions or the measures being implemented in low populated areas.

Overall, the main findings of this paper highlight a decreasing trend of NO2, PM10 and PM2.5 up to 2050 considering the implementation of the already established BAU scenario. These achievements will be possible due to a set of policies technologically-centred. On the other hand, future policy scenarios centred on citizens visions, followed by stakeholders and policymakers calibration may have a crucial impact towards clean air in European cities. However, this requires further ambition from those players. In addition, the implementation of the recommendations from ClairCity will lead to better support, more effective and more cost-effective air quality policies from now until 2050. Within the six pilot cities, ClairCity has quantified how EU Air Quality Directives targets can be achieved through low-cost high-gain behaviour changes, bringing significant benefits through several different health outcome pathways, and demonstrate how this is adaptable across any city.

The scope of this work was to quantify the impacts of defined scenarios as a whole, so for further investigation, it would be extremely relevant to quantify each measure, and to link each one to a specific emission reduction.

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## References

Artola, I., Slingerland, S., 2019. D6.6 Policy Workshop – Last City. https://doi.org/10.5281/ZENODO.3972927

Borrego, C., Amorim, J.H., Tchepel, O., Dias, D., Rafael, S., Sá, E., Pimentel, C., Fontes, T., Fernandes, P., Pereira, S.R., Bandeira, J.M., Coelho, M.C., 2016. Urban scale air quality modelling using detailed traffic emissions estimates. Atmos. Environ. 131, 341–351. https://doi.org/10.1016/j.atmosenv.2016.02.017

CBS, 2015. Statistics Netherlands [WWW Document]. URL https://www.cbs.nl/en-gb/society/population (accessed 4.20.21).

ClairCity, 2020. Outputs - ClairCity [WWW Document]. URL http://www.claircity.eu/outputs/ (accessed 4.20.21).

Council Directive 2009/125/EC, 2009. Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products [WWW Document]. OJ L 285. URL https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:32009L0125 (accessed 4.1.21).

Dias, D., Amorim, J.H., Sá, E., Borrego, C., Fontes, T., Fernandes, P., Pereira, S.R., Bandeira, J., Coelho, M.C., Tchepel, O., 2018. Assessing the importance of transportation activity data for urban emission inventories. Transp. Res. Part D Transp. Environ. 62, 27–35. https://doi.org/10.1016/j.trd.2018.01.027

EEA, 2020. Air quality in Europe - 2020 report, European Environment Agency.

EEA, 2019. Air quality in Europe — 2019 report.

EEA, 2018. Europe’s urban air quality — re-assessing implementation challenges in cities, EEA Report No 24/2018.

EU, 2008. Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe [WWW Document]. OJ L 152. URL https://eur-lex.europa.eu/eli/dir/2008/50/oj (accessed 2.21.21).

Fogg-Rogers, L., Sardo, M., Laggan, S., Boushel, C., Judge, D., 2020. D2.8 ClairCity FInal Evaluation Report. https://doi.org/10.5281/ZENODO.4268329

INE, 2011. Instituto Nacional de Estatístico [WWW Document]. URL https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine\_indicadores&contecto=pi&indOcorrCod=0008273&selTab=tab0 (accessed 4.20.21).

Istat, 2011. Istituto Nazionale di Statistica [WWW Document]. URL http://dati.istat.it/Index.aspx?lang=en&SubSessionId=f924de58-e4ae-4abf-acd9-d2db30b2fddd (accessed 4.20.21).

Matthias, V., Bieser, J., Mocanu, T., Pregger, T., Quante, M., Ramacher, M.O.P., Seum, S., Winkler, C., 2020. Modelling road transport emissions in Germany – Current day situation and scenarios for 2040. Transp. Res. Part D Transp. Environ. 87. https://doi.org/10.1016/j.trd.2020.102536

McKinsey & Company, 2012. Mobility of the future Opportunities for automotive OEMs.

ONS, 2015. Office for National Statistics [WWW Document]. URL https://www.bristol.gov.uk/statistics-census-information/the-population-of-bristol (accessed 4.20.21).

Pisoni, E., Christidis, P., Thunis, P., Trombetti, M., 2019. Evaluating the impact of “Sustainable Urban Mobility Plans” on urban background air quality. J. Environ. Manage. 231, 249–255. https://doi.org/10.1016/j.jenvman.2018.10.039

Purwanto, J., De Ceuster, G., Vanherle, K., 2017. Mobility, Vehicle fleet, Energy use and Emissions forecast Tool (MOVEET), in: Transportation Research Procedia. Elsevier BV, pp. 3421–3434. https://doi.org/10.1016/j.trpro.2017.05.239

Rafael S., Rodrigues V., Oliveira K., Coelho S., Lopes M. (2021). How to compute long-term averages for air quality assessment at urban areas?. Science of The Total Environment, 795. Article number 148603. https://doi.org/10.1016/j.scitotenv.2021.148603.

Rodrigues, V., Lopes, M., Rafael, S., Coelho, S., Oliveira, K. de, Vanherle, K., Papics, P., Himpe, W., Diafas, I., Kewo, A., Trozzi, C., Piscitello, E., Soares, J., 2020. D5.7 City Impact Analysis Report. https://doi.org/10.5281/ZENODO.3972940

Russell, A., Dennis, R., 2000. NARSTO critical review of photochemical models and modeling. Atmos. Environ. 34, 2283–2324. https://doi.org/10.1016/S1352-2310(99)00468-9

Slingerland, S., Artola, I., 2020. D7.6 Final Cross–City Policy Analysis Report. https://doi.org/10.5281/ZENODO.3972951

Slingerland, S., Artola, I., Bolscher, H., Rodrigues, V., Oliveira, K., Lopes, M., Csobod, E., Trozzi, C., Knudsen, S., Soares, J., 2020. D7.4 Final City Policy Package – First City. https://doi.org/10.5281/ZENODO.3972897

Soares, J., Horálek, J., González, A., Ortiz Guerreiro, C., Gsella, A., 2019. Health Risk Assessment of Air Pollution in Europe Methodology description and 2017 results - Eionet Report - ETC/ATNI 2019/13.

Statistics Poland, 2011. Statistics Poland [WWW Document]. URL https://stat.gov.pl/en/regional-statistics/ (accessed 4.20.21).

SURS, 2011. Statistical Office of the Republic of Slovenia [WWW Document]. URL https://pxweb.stat.si/SiStat/en/Podrocja/Index/100/population (accessed 4.20.21).

Thunis, P., Clappier, A., Pisoni, E., Degraeuwe, B., 2015. Quantification of non-linearities as a function of time averaging in regional air quality modeling applications. Atmos. Environ. 103, 263–275. https://doi.org/10.1016/J.ATMOSENV.2014.12.057

Thunis, P., Degraeuwe, B., Pisoni, E., Trombetti, M., Peduzzi, E., Belis, C.A., Wilson, J., Clappier, A., Vignati, E., 2018. PM2.5 source allocation in European cities: A SHERPA modelling study. Atmos. Environ. 187, 93–106. https://doi.org/10.1016/j.atmosenv.2018.05.062

Vicente, E.D., Alves, C.A., 2018. An overview of particulate emissions from residential biomass combustion. Atmos. Res. https://doi.org/10.1016/j.atmosres.2017.08.027

WHO, 2018. Burden of disease from the joint effects of household and ambient Air pollution for 2016 Summary of results. World Heal. Organ. 2, 1–5.

WHO, 2015. Residential heating with wood and coal: health impacts and policy options in Europe and North America [WWW Document]. URL https://www.euro.who.int/en/publications/abstracts/residential-heating-with-wood-and-coal-health-impacts-and-policy-options-in-europe-and-north-america (accessed 2.21.21).

WHO, 2013. Health risks of air pollution in Europe – HRAPIE project, Recommendations for concentration–response functions for cost–benefit analysis of particulate matter, ozone and nitrogen dioxide, World Health Organization.

WHO, 2006. Air quality guidelines: Global update 2005 — Particulate matter, ozone, nitrogen dioxide and sulphur dioxide [WWW Document]. URL https://apps.who.int/iris/bitstream/handle/10665/69477/WHO\_SDE\_PHE\_OEH\_06.02\_eng.pdf;jsessionid=C9A622837270C3630216CD4A48F5124A?sequence=1 (accessed 2.21.21).

York Bigazzi, A., Rouleau, M., 2017. Can traffic management strategies improve urban air quality? A review of the evidence. J. Transp. Heal. https://doi.org/10.1016/j.jth.2017.08.001