sustainability

Article

Implications of Low Carbon City Sustainability Strategies for 2050

Steve Harris [1,*], **Jan Weinzettel** [2] and **Gregor Levin** [3]

[1] IVL Swedish Environmental Research Institute, Aschebergsgatan 44, 411 33 Göteborg, Sweden
[2] Department of Electro-Technology, Faculty of Electrical Engineering, Czech Technical University in Prague, Technická 2, 166 27 Praha6, Czech Republic; Weinzettel@seznam.cz
[3] Department of Environmental Science—Environmental Social Science and Geography, Aarhus University, Frederiksborgvej 399, Building 7407, 135, 4000 Roskilde, Denmark; gl@envs.au.dk
* Correspondence: steve.harris@ivl.se

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Abstract: Cities and urban areas are critical nodes of societal resource flows, responsible for both global and local sustainability implications. They are complex systems and understanding the implications of potential actions by cities is critical for progress towards sustainability. In this paper the future implications of sustainability strategies are assessed for 10 European cities by comparing two scenarios for 2050: a business-as-usual (BAU) and a post-carbon/sustainability scenario (PC2050) (generated by city stakeholders). The effects of the scenarios are assessed using a mixed methodology: a semi-quantitative sustainability indicator analysis, energy and greenhouse gas (GHG) emissions (both production-based and consumption-based accounting (PBA and CBA)), land-use spatial modelling, and cost–benefit analysis. The paper highlights the clear benefits of PC2050 with improved sustainability indicator results, reduced land sprawl (which averages 16% in BAU) and positive cost–benefit results. Nonetheless, inequality and segregation are a common concern. In addition, whilst PBA indicates a significant decrease (average decrease from 4.7 to 1.3 tCO_2eq per capita) CBA demonstrates rising overall emissions from an average of 11 to 14.8 tCO_2eq per capita. This is linked to rising affluence and consumption trends despite local improvements in GHG emissions, which highlights a need for cities to address consumption-based emissions.

Keywords: sustainability assessment; consumption-based accounting; land-use change; scenario analysis

1. Introduction

Globally, the population living in cities is increasing with 66% of people expected to live in urban areas by 2050 [1]. Today, cities are responsible for over 78% of the global energy consumption and over 60% of greenhouse gas (GHG) emissions [2], but less is known about how they drive resource use and sustainability impacts. They are centres of socio-economic strength and are responsible for 85% of gross domestic product (GDP) [3]. They are therefore central in both driving consumption of resources and the associated sustainability implications, and as such are also of critical importance in implementing solutions for sustainability [4].

There has been noticeable progress in reducing GHG emissions with initiatives such as the Covenant of Mayors that has over 7000 signatories from EU cities [5]. Furthermore, C40 cities is a group of 96 global cities that focus on reducing GHG emissions in urban areas and who together represent a quarter of the global economy [4]. Measurement of GHG emissions can be performed using either production-based accounting (PBA) that focuses on the emissions produced by activities within city borders and jurisdiction, or consumption-based accounting (CBA). The latter includes upstream emissions from the production of all products and services consumed by citizens regardless of where production occurs but excludes emissions from exported goods and services [6]. Recent studies that have compared the two accounting methods have found that consumption-based emissions (CBE) can be significantly higher than production-based emissions (PBE) [7]. A study of China, the UK and the US found that CBE was higher than PBE for most cities [8], whilst Harris et al. [9] found that on average CBE were twice as large as PBE for ten European cities. In a study of four Chinese megacities it was found that 48–70% of the CBE occurred upstream and outside the city [10]. Similarly, Chen et al. [11] calculated 50% for Sydney and Melbourne, whilst C40 cities [4] obtained an average of 60% for 79 global cities.

However, current reporting of city GHG emissions almost exclusively focusses on PBE, disregarding CBE [12]. This leads to responses in city strategies limited to actions such as improving public transport and energy efficiency of building stock [7]. Meanwhile, consumption-based emissions that relate to the supply chain and life cycle of resources and products, have barely been addressed in city strategies [13].

This extends to other areas of sustainability. For instance, whilst recycling initiatives have increased [14], measures fostering more encompassing circular economy actions such as reuse, refurbishment and remanufacturing, appear to be in their infancy. Whilst the merits of densification of cities has received attention in literature, many cities continue to grow spatially, impacting on eco-system services, biodiversity and recreation areas [15]. This also has negative ramifications for the health and well-being of citizens, as green and blue space is lost [16–18].

There are an increasing number of studies that recognise the effects of air pollution on health and the resultant costs (from hospital admissions, deaths, illness and medical needs) [19–22]. Nonetheless, the literature on costs and benefits of comprehensive sustainable actions is still developing and is performed at a macro level with few studies examining scenarios for individual cities [23,24]. Recently, however, Gouldson et al. [25] explored the economic case for low GHG responses in five diverse global cities (Leeds, UK; Kolkata, India; Lima, Peru; Johor Bahru, Malaysia and Palembang in Indonesia). They reported that the required investments for reductions of 15–24% in GHG emissions (relative to BAU) would equate to 0.4–0.9% of GDP but result in savings in the form of reduced energy between 1.7% and 9.5%.

There are a growing range of methods available to assess the current status of sustainability of cities from indexes such as the Siemens Green Index [26], material flow analysis methods [27,28], urban metabolism [29] coupled with life cycle analysis [30], through to assessing single indicators such as the ecological footprint, carbon footprint and water footprint. Lavers Westin et al. [31] combined comprehensive material flow analysis with life cycle assessment datasets to understand the consumption hotspots for three Swedish cities.

Few studies examine the effects of future city strategies on sustainability impacts. However, forecasting, modelling and scenario analysis are needed to help understand the future implications of potential city planning and development strategies [32,33]. The complexities of the interactions of different indicators, such as land use, consumption, socio-economic effects and health and well-being, and their interlinkages is an enormous challenge for progress in sustainability [34].

Scenario analysis is one method to help understand the implications of future pathways and aid strategic decision making [35,36]. Three different approaches are used within environmental sciences in scenario storyline development: exploratory, normative and business-as-usual [37]. Qualitative and quantitative scenario methods can be combined into the Story and Simulation (SAS) approach, used for example in the Millennium Ecosystem Assessment and the GEO-4 Scenarios [38].

The aim of this paper is to investigate how city sustainability strategies for 10 European cities can affect the sustainability performance in the future. To do this we compare the current status with a business-as-usual (BAU) scenario for 2050 and a post-carbon sustainability scenario (PC2050). The latter scenario is based on a vision and set of actions, developed by the city stakeholders of each city. A mixed methodological approach is applied to address a wide range of sustainability implications.

We combine a semi-quantitative indicator analysis, GHG accounting, spatial modelling of land-use change and a cost–benefit analysis of improved health from reduced air pollution. The paper seeks to answer the following questions:

- What is the sustainability performance of the cities of the two scenarios compared to the year 2007?
- How do the GHG emissions compare using PBA and CBA for each of the cities?
- What are the potential land-use changes under both scenarios and what are the implications?
- What are the cost implications for health from investing in renewable energy and energy efficiency?

The paper presents the findings from the sustainability assessment work package of the EU FP7 POCACITO project (Post Carbon Cities of Tomorrow). The accounting procedure and results for the GHG emissions have already been extensively covered in a previous publication [9]. The novelty of this paper is that it presents the full assessment combining the findings from four different but complementary methodologies, to assess the sustainability implications of future city scenarios. In order to do so, we repeat the most relevant results of the previous paper in the results section.

In the next section we introduce the background to the research, the modelling approach and the four analytical methods used in our study. We then present the results in Section 3, followed by a discussion of the results for each method in Section 4 and provide a brief concluding summary in Section 5.

2. Materials and Methods

2.1. Background and Overview

Ten European cities are included in the study: Barcelona, Copenhagen, Istanbul, Lisbon, Litoměřice, Malmö, Milan, Turin, Rostock and Zagreb. These cities provide a diverse mix of population sizes ranging from 24,000 to 13.9 million inhabitants and a cross section of European geographic regions, as shown in Table 1. It should be noted that the GHG emissions per capita are based on PBA and only relate to the municipality area of the cities. All cities were participants in the EU-funded project Post Carbon Cities of Tomorrow (POCACITO) which aimed to develop post-carbon pathways and understand the sustainability implications compared to BAU.

Table 1. Key figures for the municipalities of the cities (year 2012). Source: various, please see Supplementary Material 1 (Section 1.2) for sources, or methodology used where own calculations were used.

	Population (000's)	**GDP (EUR)**	**Energy Use (GWh)**	**GHG/Capita (TCO_2e)**
Barcelona, Spain	1600	37,347	16,782	2.3
Copenhagen, Denmark	559	63,000	8366	5.0
Istanbul, Turkey	13,900	9922	15,570	2.7
Lisbon, Portugal	548	48,000	10,786	7.1
Litoměřice, Czech Republic	24	11,800	366	5.7
Malmö, Sweden	313	45,000	7759	5.0
Milan, Italy	1324	51,754	28,167	6.0
Rostock, Germany	203	30,678	3776	4.1
Turin, Italy	902	30,716	18,841	5.7
Zagreb, Croatia	793	18,645	11,300	3.2

The methodology combines a quantitative and qualitative assessment and consists of four main parts and methodologies:

1. Semi-quantitative sustainability assessment based on key performance indicators (KPIs).
2. Quantification of GHG emissions using PBA and CBA.
3. Land-use changes.
4. Simplified cost–benefit analysis.

Each methodology first assesses the current status and then models and assesses the BAU and PC2050 scenarios. The modelling methodology uses linear extrapolation of recent trends for BAU. This then forms the basis for modelling PC2050, by moderating key variables based on a city scenario developed by local city stakeholders.

The PC2050 scenarios were developed in a series of three workshops held in each city with local stakeholders. These involved the creation of a post-carbon 2050 vision, a back-casting exercise, and the development of strategies, actions and milestones [39]. The average composition of local stakeholder groups in the first two workshops is shown in Figure 1. From these visions and actions, a qualitative description of the cities was also developed as a background for interpretation in the quantitative modelling.

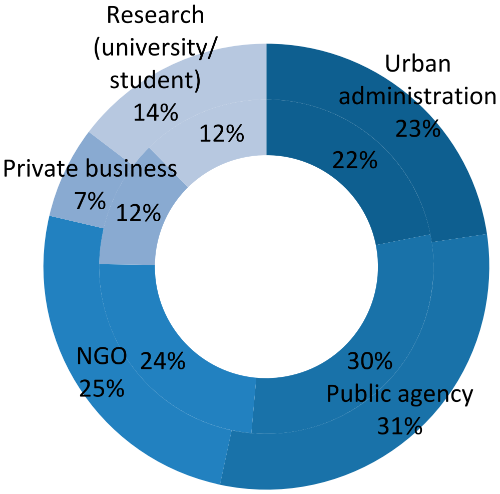


Figure 1. Stakeholder types at first (inner circle) and second (outer circle) workshop. Source: [39].

Data were collected from a variety of sources including literature, municipality websites and publications, surveys and interviews with city stakeholders and national statistics offices. The main data gathering for the cities was structured around 22 sustainability indicators (described in Section 2.3, see [40] for further details). In addition, data on energy use and GHG emissions were derived from municipality publications and Covenant of Mayors [5] (See Supplementary Materials for further information).

Each of the methodologies are described in the following sections and the city model framework is first described. Further details can be found in the Supplementary Materials.

2.2. The City Model Framework

To quantitatively model future scenarios of complex systems such as a city, it is first necessary to identify key components that can effectively represent the city system during the modelling process. The main variables for our model are divided into two categories. The first relates to energy and GHG emissions: energy use and energy sources. The second group consists of variables that have a direct influence on the first group, including population, GDP and transport modal split. Similarly, Feng et al. [41] use the same key components to represent the city of Beijing in a system dynamics model to simulate energy and GHG emissions. Figure 2 illustrates the conceptual basis of the scenario modelling and how the variables relate and interact. It shows that BAU was created by an extrapolation of the recent trends but modified depending on both qualitative influences and the interaction between the variables. For instance, qualitative influences depend on the evidence that current and ongoing policies and projects were inducing changes on the variables (or were likely to). Other factors that influence development were also considered, such as immigration effects on population growth. It was also necessary to make regulating adjustments to model the interaction of variables, such as how population, GDP and transport model share affect each other. PC2050 is modelled by adjusting BAU variables based on an interpretation of the targets and actions developed by the city stakeholders in the PC2050 workshops (see Table S11 of Supplementary Material 1). For population and GDP background the Shared Socioeconomic Pathways (SSPs) produced for the IPCC fifth assessment report were used (IIASA, 2014). Further information on the assumptions for calculating the PC2050 projections of each component can be found in the Supplementary Materials.

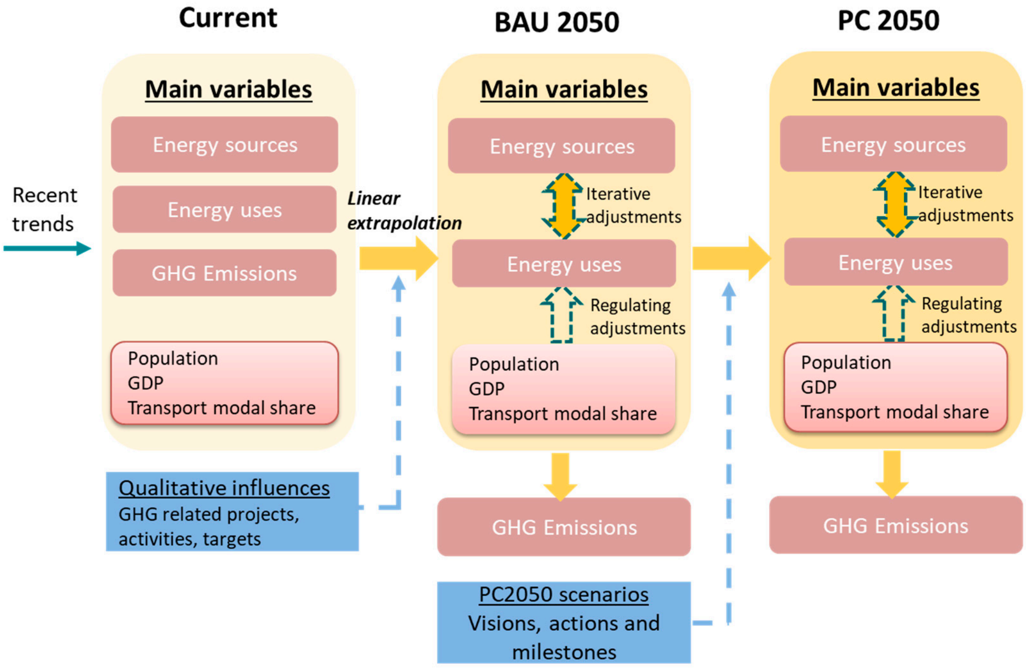


Figure 2. Key variables and modelling structure for linear extrapolation of recent trends for the business-as-usual (BAU and the post-carbon 2050 (PC2050) scenarios.

2.3. Semi-Quantitative KPI Sustainability Assessment

As part of the EU POCACITO project, a Post Carbon City Index was developed consisting of 25 sustainability indicators [42]. The indicators were selected based on a literature review, selection criteria and a series of workshops with the project partners (the selection process is described in Silva et al. [42]) but was also influenced by data availability. A quantitative assessment was performed for each city on the current trends (typically over 10–15 years) for the 25 indicators. This was combined with an extensive qualitative review on the current policies and projects related to sustainability to produce an integrated assessment (see Selada et al. [40]). This yielded significant data and provided the foundation for the subsequent modelling and assessment work of the baseline and future scenarios.

Based on the assessment of recent trends and the city visions, a semi-quantitative modelling of twenty of the indicators (shown in Table 2) for BAU and PC2050 was performed following the same methodology as in Section 2.2. Five of the original indicators were not considered in the scoring as they are not appropriate for scoring in terms of positive or negative developments, e.g., “existence of monitoring system for emissions reduction”, GDP/energy/carbon by sector, building density. To provide a visualisation of the cities’ performance for each of the indicators in the future scenarios, a semi-quantitative scoring was performed on the extrapolation of results. This was based on a five-point scale, on the degree to which the change, in relation to the base year, was either very positive or positive, neutral, negative or very negative.

Table 2. The 20 key performance indicators considered in the modelling.

Indicator	Definition or Unit
Environmental	
Ecosystem protected areas	% of the city surface area covered by the Natura 2000 Network and the National Network of Protected Areas
Energy intensity	Primary energy consumption by gross domestic product (GDP) (toe/EUR)
GHG intensity	Co2-eq per EUR (GHG/EUR)
Carbon intensity per person	Co2-eq per capita
Exceedance of air quality limit	Number of days/year for exceedances of: Ozone (O_3), Nitrogen Dioxide (NO_2), and Sulfur Dioxide (SO_2)
Sustainable transportation	Modal share of transport walk, cycling, car, etc.
Urban waste generation	kg/person/year of waste generated
Urban waste recovery	% of waste recovered for recycling, reuse, energy recovery or composting.
Water distribution losses	m3/person/year of water lost in supply network
Energy-efficient buildings	Number of buildings with A and A+ certified from the EU legislative framework: Directive 2002/91/CE and Directive 2010/31/UE on the energy performance of buildings directive (EPBD)
Economic	
Level of wealth	GDP (EUR) per capita
Business survival rate	Ratio of enterprise survivals based on creation and failure rates of businesses over a three-year period 2008 to 2010
Budget deficit	Annual deficit (%) by GDP
Indebtedness of local authority	Annual debt (%) by GDP
R&D intensity	Total research and development expenditure as % of GDP.
Social	
Unemployment by gender	% of population unemployed
Poverty level	% of population at risk of poverty
Tertiary education by gender	% of population with tertiary level of education
Average life expectancy	Average number of years city citizens are expected to live
Green space availability	km2 of public green (urban forests, parks or green spaces) space availability per capita

2.4. Quantification of GHG Emissions Using PBA and CBA

2.4.1. Production-Based Accounting

Municipal level data were utilised to calculate the production-based energy and GHG emissions. The Global Protocol for Community-Scale Greenhouse Gas Emissions Inventories, which was developed from the GHG Protocol, was utilised [43]. The system boundary includes Scope 1 GHG emissions derived from sources located within the city boundaries (including CO_2, CH_4 and N_2O) and Scope 2 from grid-supplied energy, including those that cross city boundaries. This consists of emissions from activities within the city boundaries that include heating and electricity production (used in housing and buildings), transport, industry and waste incineration. It does not include Scope 3 emissions (e.g., from the production of oil and gas) because this takes place beyond the city borders (it is part of the consumption-based accounting). In addition, we do not include emissions from water, waste or agriculture, fugitive emissions, forestry or land-use changes, as no consistent data across the cities were available. In some cases, data were supplemented with national energy production and consumption trends, as well as industry profile changes and population and GDP growth.

2.4.2. Consumption-Based Accounting

CBE can be calculated using Environmentally Extended Multi-Regional Input-Output analysis (EE-MRIO) of which several databases are now available. For this paper we chose the EXIOBASE database, established under the EU-funded “Compiling and Refining Environmental and Economic

Accounts" (CREEA) project [44], due to its high product resolution (200 product groups) and because it was specifically designed for environmental analysis and the EU focus. We combined household expenditure surveys (containing final demand of households) and government expenditure data with the database to calculate the CBE [9,45]. CBE therefore excludes PBE associated with export to another region, but includes emissions occurring beyond the city borders driven by the city final demand.

Household consumption data were obtained from local authority data sources for Milan and Turin [46] and from Oxford Economics [47] for the remaining cities (purchased under a confidential commercial license). Data for government expenditure were derived from Agenzia per l' Italia digitale [48] for Italy. For the remaining cities, data contained in EXIOBASE on national government spending were scaled down to represent the city populations. The complete description of the CBA method, including all methodological details and data sources, is provided in Harris et al. [9].

2.4.3. Modelling of BAU and PC2050

The three main blocks of the MRIO database, the input coefficients, environmental extensions and final demand, were adjusted manually to model the expected 2050 changes in the scenarios.

The global production system with the MRIO dataset was aggregated into 13 broad regions: one each for the countries of the participant cities (except for Zagreb, which is part of a broader region Rest of World (RoW)—Europe within Exiobase v2) and four rest of the world regions (Japan, Rest of EU, Norway and Switzerland, BRICS (Brazil, Russia, India China and South Africa), US and RoW). It was assumed that the efficiencies of the country-specific technologies will converge due to globalisation. However, since we cannot predict future trading relationships between countries this is assumed to remain constant, which aligns with leading methods [49].

For the 2050 scenarios, the 200 product groups were adjusted for each region within the direct input (technological) coefficient matrix. This stipulates how much of one product is required to produce another product. The expected changes were based on the best available projections for resource efficiency, production and energy use (e.g., from [50] and [51]). The environmental intensity matrices, which represents the emission profiles for the 200 products and for each region, were subsequently adjusted using the same methodology.

Household final demand in the BAU scenario was based on projections purchased from Oxford Economics to 2030 [47], extrapolated to 2050. Further adjustments were then made to the energy profile of the cities to align with the energy profile obtained from the production-based modelling.

The same underlying production system used was maintained for the PC2050 scenario, thereby assuming production systems outside the cities are the same. It was assumed that an increase in GDP results in an increase in final demand, which was adjusted based on the ratio of GDP for BAU and PC2050 for each city. The final demand was then distributed proportionally amongst the product groups, before adjusting the energy demand to reflect the share of energy sources from the scenarios. Finally, final demand of the remaining non-energy products was adjusted based on an examination and interpretation of the difference between the scenarios (detailed in [9]).

2.5. Land-Use Changes

A spatially specific cellular model was utilised to model changes in urban land use and population densities for the BAU and PC2050 scenarios. The model is based on historical changes from 2000 to 2012, combined with future projections of city population. The city boundaries were represented by the NUTS 3 level except for Litoměřice and Malmö, where municipal boundaries were applied. The NUTS classification (Nomenclature of territorial units for statistics) is the standard EU hierarchical system for territorial regions consisting of three different levels of definition. NUTS 1 is the largest subdivision representing regions below national level, NUTS 2 represents the planning regions or provinces and NUTS 3 are the districts or regions that comprise of the municipalities or local councils [52]. Historical change between 2000 and 2012 was mapped by combining land-use data from Corine Land Cover [53,54] with gridded population data derived from Landscan (U.S. Department of Energy).

All spatial analyses were conducted at a cell size of 100 m × 100 m. Corine Land Cover was aggregated into three major classes: urban land, sea and other land (including forest, nature and agriculture). Overlaying land-use and gridded population data for 2000 and for 2012, we identified five types of changes related to land-use and population change (Table 3).

Table 3. The five types of land-use and population changes identified.

Change Type	Description
1. Urban spread	Change from non-urban in 2000 to urban in 2012
2. Urban no change	Urban in 2000 and 2012, with no change in population
3. Population densification	Urban in 2000 and 2012, with population increase
4. Population dis-densification	Urban in 2000 and 2012, with population decrease
5. Non-urban	Non-urban in 2000 and 2012 (no change)

To model the population distribution of the BAU and PC2050 scenarios we matched and extrapolated the modelled 2050 population (Section 2.2) with the 2012 population distribution derived from Landscan. For the BAU scenario, we assumed that up until 2050 the same relationship between land-use change and population change observed from 2000 to 2012 will be followed. A similar method was used to model the areas of reduced population density. To localize types of urban change, we applied the automated cellular model [55].

The underlying assumption is that future change occurs at the same locations or close to those that have historically arisen. For each cell, we calculated the probability of undergoing one of the change types based on the cell's proximity to the same change type from 2000 to 2012. Based on this probability, each cell was assigned a change type, until the expected quantity in terms of km^2 for this change type was reached. Urban spread was restricted from sea and from areas covered by Natura 2000 designations. For the PC2050 scenario, it was assumed that a population increase would not result in urban spread but lead to densification. However, densification was generally not an action identified by the city stakeholders in the PC2050 visions. Nonetheless, this assumption aims to highlight the contrast with BAU. For both the BAU and the PC scenarios, population changes within the different types of urban change were calculated by multiplying cells population number in 2012 with the expected percentage increase for the change type from 2012 to 2050 and adding it to the 2012 population.

2.6. Socio-Economic Analysis

The approach taken for the socio-economic analysis is a simplified cost–benefit analysis. The aim is to compare costs and benefits of the two future scenarios, considering energy, buildings and transport. However, it was not possible to develop detailed sustainable transport systems within the scope of the project, but also data on past transport systems for any modelling or extrapolation (beyond energy used and sources) were insufficient. Therefore, the analysis compares the following costs and benefits of BAU and PC2050:

1. Costs of investment in (a) renewable energy and (b) renovation of buildings for improved energy efficiency.
2. Benefits (economic savings) from reduced premature deaths compared to the baseline year as a result of reduced air pollution.
3. Benefits (economic savings) from reduced energy expenditure.
4. Benefits—the number of jobs created from renewable energy and renovation of buildings.

The main method and assumptions related to each of these and the references used for costs and data are outlined in the following sections (further information can be found in Supplementary Material 1). Finally, the costs and benefits were discounted using different discount rates for comparison.

2.6.1. Investment in Renewable Energy and Building Renovation

Investments costs from 2018 to 2050 in renewable energy (wind, solar, hydro or geothermal) were calculated based on the quantities modelled for the BAU and PC2050 scenarios. It was assumed that 25% of the total investment required was made in four stages in the years 2020, 2030, 2040 and 2049. The average costs of 1400 EUR/kW and 581 EUR/KWp of installed capacity, respectively for wind and solar energy, were used, assuming a decrease over the 2018 to 2050 period [56,57].

The costs of renovating the existing building stock were based on quantities of energy reductions stipulated in the BAU and PC2050 scenarios. Estimations of the residential and service sector floor areas are derived from national statistics on floor area per capita [58]. The BAU and PC2050 floor areas were then calculated based on the populations of the scenario. The costs of renovating these floor areas are based on average costs that depend on the level of renovation ([59]; see Supplementary Material 1). BAU was costed only for minor renovations for all cities, whilst PC2050 was minor to deep based on the PC2050 scenarios.

2.6.2. Reduced Premature Deaths from Air Pollution Reduction

The cost–benefit of changes in energy production and transport (in the BAU and PC2050 scenarios) was calculated by linking fossil fuel use to premature deaths from air pollution. There are three types of effects of air pollution including health, productivity and amenity [60]. We focus on the former as it can be related directly to changes in fossil fuel use, but also because the other two are out of scope of the project and would require extensive studies. Air pollution is associated with several health effects and causes of death. The most prevalent are cardiovascular and cerebrovascular effects which cause 80% of mortalities due to air pollution [61]. Premature mortality is most closely correlated with fine particulate matter smaller than 2.5 microns ($PM_{2.5}$). This relationship is evidenced via remote sensing, such as satellite monitoring, as well as research on exposure levels of populations and its health impacts. Therefore, the relationship between air pollution is dependent on both levels of pollution and exposure and varies for each country (see Table S19 of Supplementary Material 1 and [61] for economic costs of premature deaths from air pollution by country). Emissions from fossil fuel combustion (both stationary and mobile) have been shown to correlate in a linear relationship with $PM_{2.5}$ and CO_2 emissions [62,63]. Fossil fuels have also been shown to be responsible for 91% of particulate matter and over 99% of SO2 and NO_2 in the United Kingdom [62]. Therefore, in our calculations we assume a linear relationship between reductions in fossil fuel use, emissions of PM2.5 and exposure of the population. However, for the exposure of the population and resultant costs (due to premature deaths), country-specific costs are used. These figures are derived from WHO Regional Office for Europe & OECD [61] for the economic cost of premature deaths from both indoor and outdoor air pollution (using a base value for death of US 3 million in 2005, adjusted for differences in per-capita GDP at PPP). The costs are provided as a percentage of GDP for each country [61] and we assume that these are the same for the representative case study cities within those countries. For example, in 2010 the economic cost of premature deaths from air pollution in Sweden was 0.9% of GDP, whereas in Croatia the cost was 10.8% of GDP. To calculate the change in cost for the future scenarios, the 2010 percentage cost is reduced based on the percentage reduction in the total fossil fuel combustion from stationary and mobile sources. Therefore, a 40% reduction in total fossil fuel use in BAU 2050 would reduce the percentage cost in Croatia by 40% to 6.48% of GDP in 2050. However, this is modelled on a yearly basis between 2018 and 2050. A linear change between the baseline and the future scenarios was assumed in order to calculate the trajectory of change. The costs for each year between 2018 and 2050 was then calculated for BAU and PC2050, with the sum providing the accumulative costs or benefits (savings). A discount rate was then applied to the costs and benefits (see Supplementary Information for further description). For the analysis we use differential discount rates of 3% and 1% for the costs and benefits, respectively. This is justifiable because the health effects are based on quantities (premature deaths) and the value of health effects increases over time [64–67]. Whilst several countries' guidelines stipulate a 3% discount rate for both costs and discounts [65] the Dutch guidelines (and formerly those of the

UK's National Institute for Health and Clinical Excellence (NICE)) use differential rates of 4% and 1.5% for costs and effects (benefits), respectively. Finally, it should be noted that despite the results having some sensitivity to the discount rate, a main objective is to compare the difference in effects of the two future scenarios.

2.6.3. Changes in Energy Expenditure

The energy use for the BAU and PC2050 scenarios was calculated as part of the quantification of the main elements of the scenarios that included population, transport modes, and GDP. However, it is extremely difficult to model actual costs of energy for 2050 as this is influenced by markets. Therefore, for our analysis the costs are limited to an indicative percentage based on the difference between the final energy demand per capita for the BAU and PC2050. A reduction in the final demand per capita is regarded as direct savings.

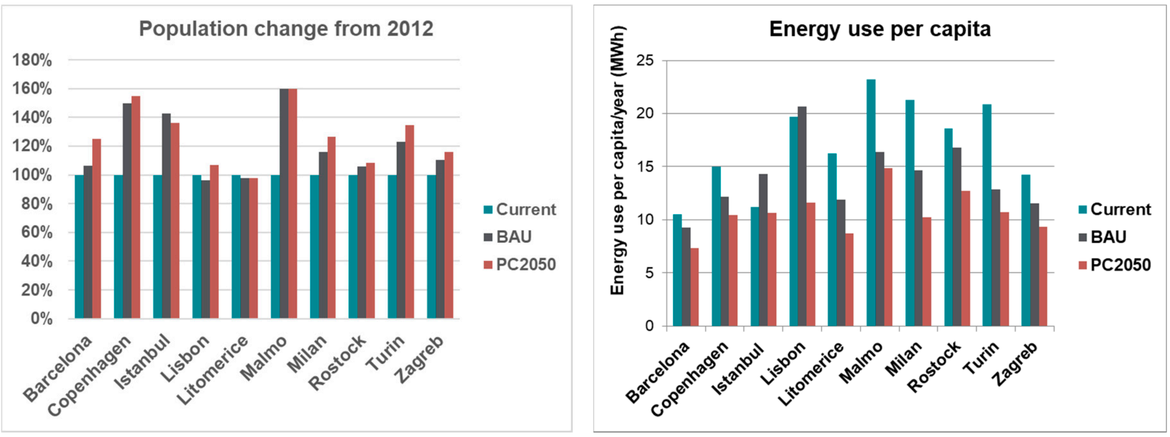
2.6.4. Number of Jobs Created from Renewable Energy and Building Renovation

Jobs from renewable energy are calculated for manufacturing, construction, installation (MCI) and operation and maintenance (O&M) based on figures from IRENA [68], applied to the scenarios. Jobs created by building renovation for energy efficiency are calculated by using the figure of 12 jobs per million EUR, which is the conservative figure from two sources [69,70].

3. Results

3.1. Extrapolation of City Model Components

The modelling results for population change, energy use per capita and GDP per capita are shown in Figure 3 for the baseline year (2010), BAU and PC2050. The population increases for most cities, apart from Litoměřice where a small decrease in population of 500 (or 2%) residents occurs. Population and GDP are generally higher in PC2050 than BAU, which partly reflects the use of the Shared Socioeconomic Pathways as background scenarios for population and GDP. Whilst all cities experience GDP increases under both scenarios, there is a wide variation for PC2050 compared to the base year (from just 17% for Turin up to 194% for Istanbul).



(**a**) (**b**)

Figure 3. *Cont.*

(**c**)

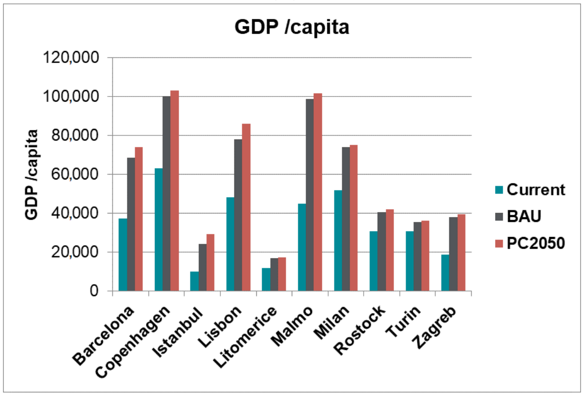


Figure 3. Scenario modelling results of the main elements for the ten case study cities for current (2012), BAU 2050 and PC2050. (**a**) Population change (%) from 2012. (**b**) Energy use per capita. (**c**) GDP per capita. Source: adapted from [9].

3.2. Semi-Quantitative Analysis of Key Performance Indicators

The semi-qualitative KPI analysis is summarised in Table 4, showing that most cities perform well across the three sustainability pillars (environment, economy and social) for both the BAU and PC2050 scenarios. However, PC2050 scores better for most KPIs, particularly the environmental and energy related indicators. The exception is the city of Istanbul, which, due to a large increase in population and affluence, risks increasing overall energy use and GHG emissions. This is also linked to an assumed reliance on the national grid electricity supply (70% of electricity), which due to recent trends was modelled as still being dominated by fossil fuels (60%).

Several cities perform poorly for "poverty level" with negative progress projected for Litoměřice, Milan, Rostock and Turin under BAU. These cities also have either negative progress or no progress under PC2050. For most other cities, progress under PC2050 is projected to be only minor with only Istanbul having very positive progress.

Table 4. Comparison of the semi-quantitative assessment of the key performance indicators (KPIs) under BAU and PC2050 for all cities.

	INDICATOR	Copenhagen		Barcelona		Istanbul		Lisbon		Litoměřice		Malmö		Milan		Rostock		Turin		Zagreb	
		BAU 2050	PC 2050	BAU 2050	PC 2050	BAU 2050	PC 2050	BAU 2050	PC 2050	BAU 2050	PC 2050	BAU 2050	PC 2050	BAU 2050	PC 2050	BAU 2050	PC 2050	BAU 2050	PC 2050	BAU 2050	PC 2050
Environment	Ecosystem protected areas	+	+	N/A	N/A	+	++	+	+	N/A	N/A	+	++	0	+	0	0	0	0	−	0
	Energy intensity (toe/EUR)	+	+	+	++	−	0	+	++	+	+	+	++	+	++	+	++	+	++	+	++
	GHG intensity (GHG/EUR)	++	++	+	++	0	+	+	++	+	++	+	+	+	++	+	++	+	+	+	++
	Carbon intensity per person	++	++	+	++	−	+	+	++	+	++	+	++	+	++	+	++	+	+	+	++
	Exceedance of air quality limit	+	+	++	++	0	+	+	++	0	++	+	+	+	++	+	++	++	++	0	+
	Sustainable transportation	+	+	0	++	0	0	0	+	0	++	+	+	+	++	+	++	−	+	+	+
	Urban waste generation	+	+	++	+	−	−	+	+	0	++	+	++	+	+	+	+	+	+	+	++
	Urban waste recovery	+	+	++	++	+	+	−	−	0	++	++	++	+	+	+	+	++	++	+	++
	Water distribution losses	N/A	N/A	N/A	N/A	+	+	+	N/A	N/A	N/A	N/A	N/A	−	−	++	++	+	+	0	0
	Energy-efficient buildings	+	+	N/A	++	+	+	+	++	+	++	N/A	N/A	0	++	N/A	N/A	+	+	+	+
Economic	Level of wealth	++	++	++	++	++	+	+	+	++	++	++	++	++	++	+	+	+	+	++	++
	Business survival rate	N/A	N/A	N/A	N/A	N/A	N/A	+	+	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	+	+	N/A	N/A
	Budget deficit	+	+	N/A	N/A	N/A	N/A	+	+	N/A	N/A	++	++	N/A	N/A	++	++	N/A	N/A	N/A	N/A
	Indebtedness of local auth.	+	+	N/A	N/A	0	0	+	+	N/A	N/A	++	++	++	++	++	++	0	0	N/A	N/A
	R&D intensity	+	+	N/A	N/A	−	−	+	+	−	−	++	++	+	+	+	+	+	+	N/A	N/A
Social	Unemployment by gender	+	+	−−	N/A	+	+	−	N/A	N/A	N/A	++	++	−	+	0	0	−	0	N/A	N/A
	Poverty level	+	+	−−	N/A	+	++	+	+	−	0	0	0	−	−	−	0	−	−	+	+
	Tertiary education by gender	+	+	+	N/A	+	+	−	0	+	+	+	+	++	++	N/A	N/A	+	+	+	+
	Average life expectancy	+	+	++	++	N/A	N/A	+	+	+	+	++	++	++	++	+	+	++	++	+	+
	Green space availability	+	+	+	+	+	++	++	++	N/A	+	++	++	0	+	++	++	+	++	−−	0

Legend	Scoring of scenario projection compared to current situation
++	likely very positive
+	Likely positive
0	Likely neutral or similar to current situation
−	Likely negative
−−	Likely very negative

3.3. GHG Emissions

Both the PBA and CBA results are shown in Figure 4. In 2007, CBE are more than 50% higher than the PBE for most cities, illustrating that a large portion of emissions occur outside of the city boundaries and upstream in the supply chain. Istanbul has the lowest CBE emissions, linked to lower affluence (GDP) and a lower level of consumption.

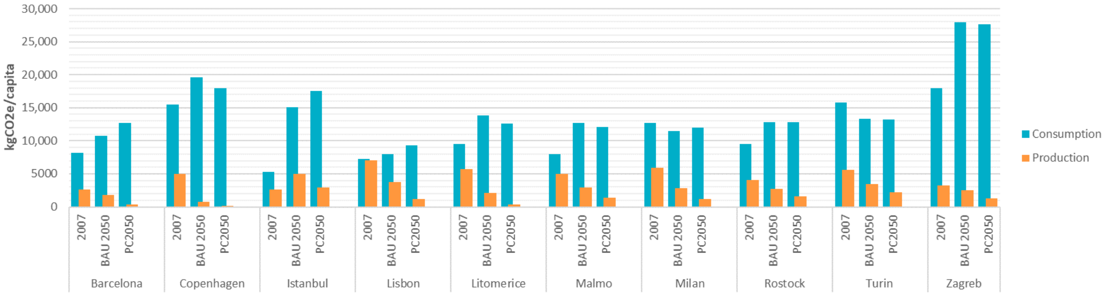


Figure 4. Comparison of production- and consumption-based GHG emissions per capita for 2007, BAU and PC2050. Source: adapted from [9].

Figure 4 shows that using the traditional PBA method (that most cities use) emissions decrease for all cities (except for Istanbul) in BAU and further in PC2050. In contrast, using CBA shows that GHG emissions per capita increase for eight of the cities under BAU and P2050. This illustrates that despite strong efforts to reduce locally derived emissions, the rising affluence of cities leads to greater consumption and therefore GHG emissions from the supply chain.

The PBE for PC2050 are lowest for Barcelona, Copenhagen and Litoměřice, with 0.35, 0.18 and 0.36 tCO_2e per capita/year, respectively. These cities are also the leading performers under BAU, with Copenhagen showing the lowest GHG emissions at 0.7 tCO_2e per capita/year. Under PC2050, the other cities are at between 1 to 2 tCO_2e per capita (except Istanbul and Turin).

3.4. Land-Use Changes

The modelling of land-use changes for BAU and PC2050 indicates that all cities would experience various degrees of urban development and loss of non-urban land (continued urban sprawl). The analysis was performed for the NUTS III areas and greater metropolitan areas, so that the full impacts of the city's economic activities could be captured. Most of the cities will experience densification in some parts, but also reductions in density in other parts where population declines.

Due to the underlying and simplified modelling assumptions that policies would limit the sprawl in PC2050, the main results are derived from the BAU extrapolation results. The modelled changes in population and urban land use for Malmö are shown in Figure 5 as an example of the spatial modelling results (for other cities, see Supplementary Information). At the top of the figure, the recent trends of population and urban development show densification in the centre, but also pockets of urban sprawl on the city outskirts. Below these the figures show the BAU and PC2050 scenario change expected for 2050, indicating significant urban sprawl for BAU.

Table 5 highlights the potential risk of future (BAU) development encroaching on non-urban land. It shows that despite some cities experiencing population decline, all cities would experience development of currently non-urban area if current trends continue. The cities with the highest potential for loss of between 19.9–43.3% of non-urban land are Malmö, Istanbul, Copenhagen and Barcelona.

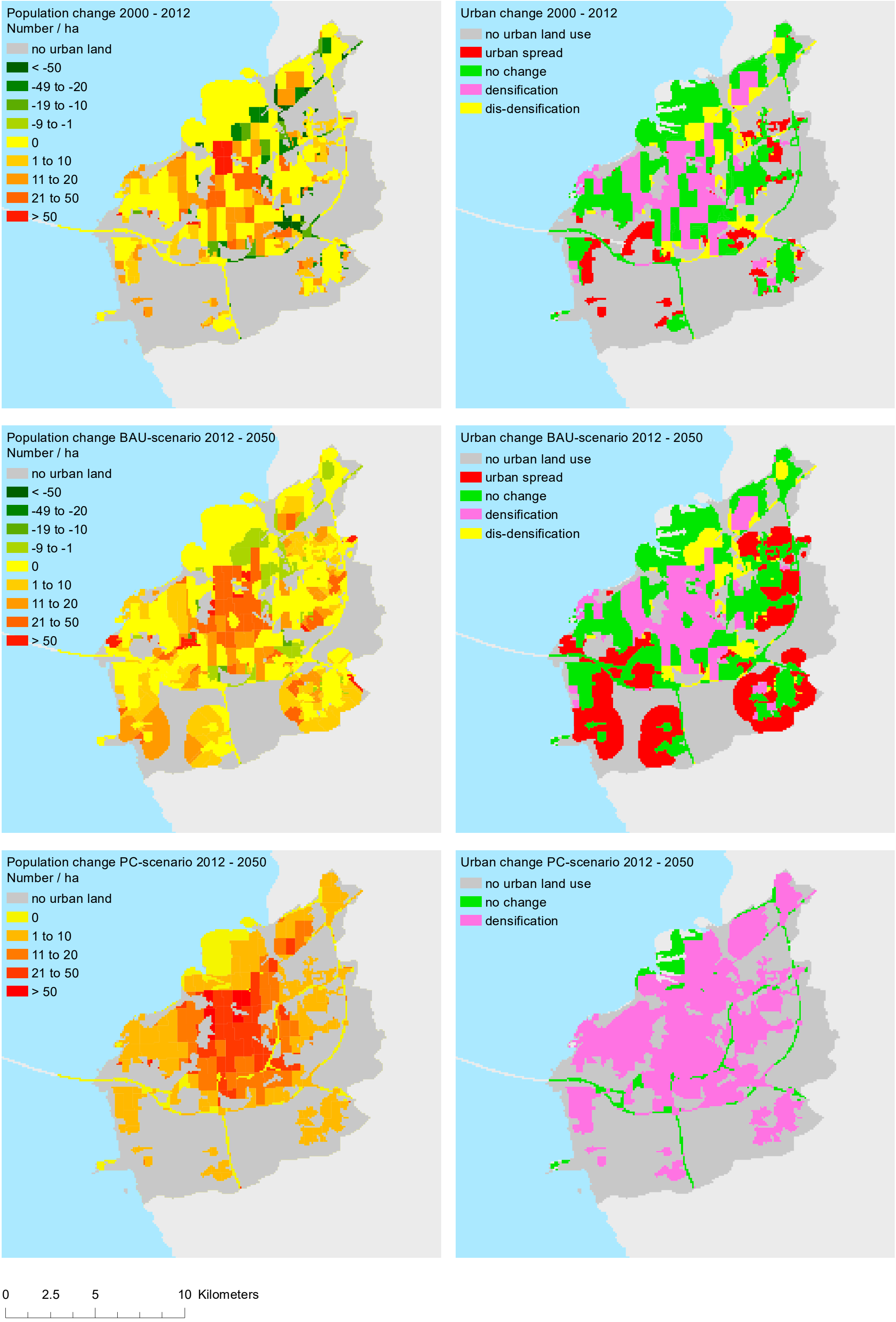


Figure 5. Population and urban change 2000–2012, BAU and PC2050 for Malmö.

Table 5. Change in non-urban land cover (in km^2 and in percentage) calculated over the 2012 to 2050 period under the BAU scenario, for the 10 case study cities.

	Km^2 Change 2012–2050 BAU	% Change 2012–2050 BAU
Barcelona	161.0	19.9%
Copenhagen	74.4	23.6%
Istanbul	331.5	30.1%
Lisbon	64.4	10.6%
Litoměřice	0.1	1.9%
Malmö	37.4	43.7%
Milan	40.4	5.6%
Rostock	5.7	10.8%
Turin	32.6	7.1%
Zagreb	11.5	7.1%

3.5. *Socio-Economic Analysis*

3.5.1. Cost Benefit Analysis

The discounted costs and benefits analysis of the future scenarios for all cities is shown in Table 6, which displays the costs of renewable energy and renovation of buildings compared to the benefits. The benefits represent the reduction in costs (compared to the base year) that result from reduced premature deaths due to a decrease in fossil fuel consumption and the resultant reduction in air pollution. Thus, a negative value denotes increased costs due to increased air pollution.

Table 6. Costs and benefits comparison of the scenarios. A differential discount rate is used for costs and benefits [64–66] (see Section 2.6.2 for further explanation).

	Discount Costs (Rate 3%)		% of GDP		Discounted Benefits (Rate 1%)		Ratio of Benefit/Cost	
	BAU	PC2050	BAU	PC2050	BAU	PC2050	BAU	PC2050
Barcelona	2792	6597	0.15%	0.31%	19,178	36,063	6.9	5.5
Copenhagen	2291	4397	0.18%	0.35%	−2199	2499	−1.0	0.6
Istanbul	19,644	32,814	0.28%	0.45%	−438,731	−94,711	−22.3	−2.9
Lisbon	1064	2873	0.28%	0.69%	1008	7340	0.9	2.6
Litoměřice	66	132	0.77%	1.53%	294	447	4.5	3.4
Malmö	830	2230	0.13%	0.35%	−154	2258	−0.2	1.0
Milan	2903	14,299	0.15%	0.73%	29,552	54,193	10.2	3.8
Rostock	528	1085	0.34%	0.63%	808	2179	1.5	2.0
Turin	1768	4869	0.26%	0.68%	8313	13,968	4.7	2.9
Zagreb	1385	3557	0.30%	0.76%	6363	22,897	4.6	6.4

The range of costs for PC2050 is related to both the size of the city and the degree of actions stipulated in the city visions (which were used as a basis for the modelling), which limits the comparability of costs between the cities. Therefore, the percentage of cumulative city GDP (from 2018 to 2050) for the costs is also provided in the fourth and fifth columns. The estimated costs of PC2050 in terms of cumulative GDP range from only 0.31% to 1.53% for Barcelona and Litoměřice, respectively.

The two last columns in Table 6 represent the ratio of benefits to the costs. Hence, a value above one denotes that the benefits outweigh the costs. It highlights that the benefit–cost ratio is positive even under BAU for all cities apart from Copenhagen, Istanbul and Malmö. Under PC2050 the benefit–cost ratio is positive for all cities (apart from Istanbul) with the ratio ranging from 0.6 to 6.4. The highest benefit–cost ratios occur for the cities of Zagreb, Barcelona, Milan and Litoměřice. The negative ratio for Istanbul is related to the lack of actions in the PC2050 vision and actions to reduce the use of fossil fuels, leading to continued poor air quality. For four of the cities, the benefit–cost ratio is higher for BAU than PC2050. This is the result of ambitious PC2050 targets for renewable energy or building renovation incurring relatively high costs (compared to BAU), coupled with diminishing benefits of health effects from reduced air pollution.

3.5.2. Reduced Energy Use and Expenditure

The difference in total energy consumption of the cities between the PC2050 and BAU scenarios provides an indicative approximation of the change in total energy costs. Table 7 shows that PC2050 has lower energy consumption and therefore potentially lower costs in all cities. The highest reduction is in Lisbon with 43.8%, whilst the lowest for Barcelona is demonstrative of low energy consumption per capita in both scenarios.

Table 7. Estimation of potential reduced energy costs of PC2050 compared to BAU due to reduced energy consumption.

City	Reduction per Capita in Energy Costs
Barcelona	21.0%
Copenhagen	14.1%
Istanbul	27.7%
Lisbon	43.8%
Litoměřice	26.8%
Malmo	9.0%
Milan	30.0%
Rostock	23.9%
Turin	16.7%
Zagreb	18.9%

3.5.3. Number of Jobs Created

Table 8 shows the additional number of jobs created due to the installation of renewable energy and building renovations of PC2050 compared to BAU. It suggests the creation of a significant number of jobs in manufacturing, construction and installation (MCI) from both renewable energy and renovation. The number of jobs expected to be created in the operation and maintenance (O&M) phase is moderate for all cities. The high value for building renovation for Milan is due to the target stipulated in the stakeholder visions of 60% increased efficiency in buildings. Due to a high level of uncertainty, it is not possible to estimate how long the jobs will last, or convert this into hours, but again a major aim is to highlight potential differences between BAU and PC2050.

Table 8. Estimated job creation. Additional number of PC2050 jobs created compared to BAU during the different life cycle phases of manufacturing, construction and installation (MCI) and operation and management (O&M).

	Renewable Energy		Building Renovation
	MCI	O&M	MCI
Barcelona	23,665	310	82,002
Copenhagen	9563	115	53,674
Istanbul	331,500	4649	427,500
Lisbon	14,600	209	32,700
Litoměřice	1164	13	1143
Malmo	10,935	121	22,764
Milan	38,100	540	273,000
Rostock	3424	61	13,398
Turin	20,237	324	55,157
Zagreb	27,054	367	32,141

These figures should be considered indicative only but reflect the ambition of the PC2050 scenarios. Some of the job quantities for building renovation appear exorbitantly high even though the lower estimate of 12 jobs per million EUR was used (as opposed to 17 jobs). Many of the jobs are in the construction and manufacturing sectors with fewer required for the operation and maintenance of the renewable energy systems.

4. Discussion

The analysis has provided some valuable insights about the potential future pathways of low carbon strategies compared to BAU. The mixed methodological approach highlights how the PC2050 strategies are advantageous from one perspective but that challenges remain for others. The following sections discuss the results for each of the methods.

4.1. Semi-Quantitative Analysis of KPIs

The assessment of sustainability indicators showed that cities are moving in a positive direction for most indicators under BAU but the performance of PC2050 is superior. However, this improvement primarily relates to the environmental indicators, with less difference noticeable for the economic or social indicators. This reflects the focus of the city stakeholder actions and targets in creating the scenarios. A noted issue for several cities is "poverty level" which is indicative of the increasing disparity between rich and poor in many European and global cities (Tammaru et al., 2016), and is also linked to segregation of housing (a particular issue for Malmö).

4.2. GHG Accounting

In the baseline year 2007, upstream emissions were on average 48% of the total CBE demonstrating the importance of considering supply chain emissions in addition to PBE. This is comparable to Mi et al. (2019) who found that CBE accounted for over 50% for four Chinese cities (with a similar range of 4–25 tCO2e). For the future scenarios, the share and importance of CBE increases.

Under both BAU and PC2050 there are significant reductions in PBE compared to 2007, decreasing by 31% and 68% respectively. This is due to existing plans for most cities under BAU to reduce PBE, which are improved under the PC2050 city strategies. However, only Copenhagen comes close under BAU to achieving zero PBE with 0.7 tCO_2e per capita. Most cities remain in the range of 2–4 tCO_2e per capita, with Istanbul being the highest with 5 tCO_2e per capita. However, CBE increases for eight cities, for both BAU and PC2050 rising by an average of 33% and 35%, respectively. This increase is primarily linked to rising GDP and the associated increase in spending and final demand, which overrides gains in local and global (production) efficiency improvements.

The results show that the visions and actions of stakeholders for PC2050 made a significant reduction in PBE. Nonetheless, consumption-based impacts were not considered, and the focus was on traditional production-based responses, whilst the CBE still increased. This is consistent with global approaches of cities [23]. Therefore, using PBA would suggest a decoupling of GHG emissions and economic output, which is often touted by governments [71] but using CBA shows the opposite trend [9].

Cities are in a unique position to mobilise and influence local actors [8] and therefore have an opportunity to address CBE more fully. Two overall approaches are fostering action in the supply chain by imposing standards and capturing the full value of imported components and materials through the circular economy [8,9]. The latter can be achieved through facilities such as repair cafes, exchange locations for used goods [72], by supporting local companies that refurbish, remanufacture and recycle, as well as sharing schemes. Alternatives such as reducing food waste may be as effective but less expensive than the option of retrofitting buildings or upgrading transport systems [45].

One limitation of our analysis is the age of the EXIOBASE database whose underlying data is from 2007. However, our main aim was to understand the implications of PC2050 strategies compared to BAU and not make forecasts. Our methodologies for both scenarios were consistent in the use of EXIOBASE. In addition, we used the most robust projection available (e.g., IEA, 2015) to adjust the underlying data tables within that represent the global production systems.

4.3. Ecosystem Services—Land-Use Changes

The results show that the encroachment of urban land on non-urban land is a risk under BAU for virtually all of the cities, with Malmö being the highest with a 43.3% increase in urban land derived from non-urban land.

This is of concern for two primary reasons. Firstly, the importance of green recreational areas and non-urban land is increasingly recognised by research in terms of benefits for health, well-being and quality of life [16–18,73]. Secondly, research also shows that sprawling cities require more infrastructure and are therefore more resource intensive and less energy efficient [74]. Therefore, they have a higher carbon footprint than dense city areas.

Densification and urban sprawl were generally not well covered in the city visions and actions of POCACITO case study cities. Therefore, there is a need to ensure policies and strategies are developed to incorporate dense development.

4.4. Socio-Economic Analysis

The simplified cost–benefit analysis of improved health from a reduction in fossil fuel use showed positive results for seven cities under BAU and nine cities for PC2050. The only exception is Istanbul which incurs increased health costs due to rising pollution from transport and energy production under BAU and to a lesser extent PC2050. The results mirror other studies which are beginning to recognise the costs and implications of air pollution [20,22,75]. For instance, the costs in 2009 of damage caused by emissions just from industries of the European Pollutant Release and Transfer Register (E-PRTR) were estimated at EUR 102–169 billion. Meanwhile, Cui et al. [19] showed that reductions in air pollution in Jinan led to US$318 million between 2013 and 2017, but further reductions could have translated to $US 1.3 billion in economic benefits.

The average benefit–cost ratio is 1.0 for BAU and 2.5 for PC2050 which aligns with Urge-Vorsatz et al. [70] who modelled a deep efficiency scenario for building renovations in the EU27 with cumulative costs of $US 5.1 trillion to 2050 and cumulative costs of $US 9.8 trillion.

Our study showed that the estimated costs of renewable energy transitions and house renovations are only 0.31% to 1.5% of GDP between 2018 and 2050. The study used a discount rate of 3% for costs but 1% for benefits to provide maximum value to potential future benefits [76]. This provides a slight bias towards the benefits over costs, although we argue that it is justified. Firstly, the underlying figures for economic costs we utilized are based on a percentage of premature deaths of the country GDP, thereby averaged across the country. However, cities are more affected by air pollution and hence the benefits are likely to be higher. In addition, there are many other benefits to reduced air pollution (e.g., increased recreational facility) other than reduced deaths which were not included. A major limitation of our study is that it omits costs for the transport infrastructure. This would have been impossible to do or estimate within the project due to the complexity of cities and the need to design the systems. In addition, one could argue that the overall cost of development to 2050 of sustainable transport would be no greater than developing an unsustainable network. For instance, remodelled costs for the UK to reach net zero GHG emissions by 2050 show that it can be achieved without financial penalty [77]. However, some of the costs, e.g., for household renovation, would need to be carried out by private owners, and so subsidies might be needed to incentivise.

Energy demand of PC2050 compared to BAU was projected to be 9% to 43% (an average of 23%) lower than BAU, which are associated with similar reductions in energy costs.

In addition, a significant number of jobs would result from implementation of the modelled level of renewable energy. These numbers are highly uncertain and indicative only. It is also not certain whether these are direct or indirect jobs, what sectors would benefit, if the jobs are in the EU or outsourced, and what the net effect on the labour market is. However, it does suggest that a significant quantity of jobs would be created for building renovation and for SMEs within the EU, consistent with other studies [69,78].

Overall, the assessment suggests that the benefits of the PC2050 strategies and the implementation of renewable energy and building renovation are far greater than BAU and more than compensate for any costs incurred.

5. Conclusions

This paper has used a combination of qualitative and quantitative methods to provide a comprehensive sustainability assessment of the BAU and PC2050 scenarios. It has shown the value of using a mixed-method approach so that the qualitative analysis can support and increase the robustness of quantitative modelling.

The analysis shows clear benefits of the PC2050 sustainability strategies compared to BAU, although critical challenges remain for most of the cities. Chief among these is that despite significant decreases in PBE emissions, primarily from actions on transport, buildings and energy, the CBE for almost all cities was projected to grow in PC2050, compared to 2007. This is mainly due to increasing affluence, linked to increasing consumption. Notably, the results also imply that none of the cities are currently on course to achieve the objectives of the 2016 Paris Agreement on GHG mitigation. Cities must therefore begin to address this, first by recognition and accounting of CBE. Secondly, through implementation of measures to support more sustainable production and consumption strategies such as the circular economy.

The KPI analysis highlighted the wide environmental benefits and to a lesser extent social and economic benefits of PC2050. However, there were some notable concerns in the areas of inequality and poverty, which is an increasing global challenge. The land-use change study demonstrated the continuing trend of urban sprawl and the potential for this trend to be sustained. Since green and blue areas are linked to health and amenities, there is a clear risk to health and costs if densification does not occur. Finally, the cost–benefit study indicated that the PC2050 strategies can be cost positive in the long term, provide significant jobs and improve the health of the city's citizens by reducing air pollution.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/13/5417/s1, Supplementary Material 1: Modelling information and Supplementary Information 2: Maps showing population and urban change 2000, 2012, BAU and PC2050 for all case study cities.

Author Contributions: Overall methodology was developed by S.H., with J.W. developing the CBA method (in addition, and G.L. developed the land use method and analysis. Research and modelling was led by S.H. with input from J.W. Formal Analysis was performed by S.H., J.W. and G.L. Original Draft Preparation, S.H. supported by J.W.; Writing—Review & Editing, S.H., J.W. and G.L. Conceptualisation, management and submissions was performed by S.H. All authors have read and agreed to the published version of the manuscript.

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