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Abstract

Due to the role of cities in driving the transition to a more sustainable future, an urban level perspective becomes fundamental to support decision-makers in defining long-term coordinated strategies.

The driving idea of this paper is to examine different urban retrofit scenarios and study them from an energy, environmental and economic point of view assessing their sustainability at the district level. Energy savings and avoided emissions by different cross-sectorial strategies were calculated, with a particular focus on buildings. Secondly, a socio-economic model was developed through the Cost-Benefit Analysis to delineate the most suitable combination of retrofit actions.

Introduction

In 2013 it was estimated that urban areas in the world would produce almost 23.8 Gigatons of GHG emissions. This value represents 70% of the total global production with the major responsibility attributed to buildings and industry, followed by transport. This is one of the main reasons why, to achieve a sustainable society, the attention has to be paid mainly on urban areas where the majority of human activities take place (IEA, 2016). Furthermore, since the percentage of global population living in urban areas will increase over 75% by 2030, urban level strategies will become fundamental in driving the transition to a more sustainable future. Indeed, scholars and international authorities are discussing concepts such as nearly-zero energy district (nZED) and post-carbon cities (PCCs), (Becchio et al., 2016; Chatterton, 2013; Chance, 2009; European Commission, 2012a; Jersen et al., 2016; Kennedy and Sgouridis, 2011; Marique and Reiter, 2014). The pathway towards low-carbon societies implies a rupture in carbon-dependent urban systems, lowering the anthropogenic greenhouse gases and establishing new types of cities, environmentally, socially and economically sustainable, according to a new paradigm that affects all urban sectors. In particular, in cities characterized by cold climatic conditions, like most of the European ones, buildings space heating and mobility are the two sectors with the highest responsibility in terms of energy consumptions and correlated carbon emissions (IRENA, 2016). The latter increases its share on total urban energy consumptions in cities characterized by a low population density, while the weight of the former is lower in cities with hot climates. Thus, the transition to low-carbon societies requires a transformation of the transport system, promoting green mobility solutions. Furthermore, since buildings are the main components of cities, we need to rethink also the built environment. Indeed, one of the key sectors of the low-carbon pathway defined by the POCACITO (Post-Carbon Cities of Tomorrow) Roadmap (CEPS, 2006) is the building sector. However, to achieve the goal of reducing cities carbon-intensity, energy efficiency measures have to be defined, adopting a cross-sectorial approach. Indeed, in the cities where these policies have been already applied, the most evident results are the ones in which different sectors are involved in the transformation. In Pesce (2018), the authors listed numerous examples of districts, areas or cities in which policies with positive impacts on environment, society and economy are applied. In these case studies, measures were applied in different sectors such as mobility, public spaces, buildings energy efficiency, water management and smart grids.

Such a cross-sectorial vision will require a portfolio of technologies to deliver secure and affordable energy services reducing emissions (IEA, 2017). The adoption of some technologies related to four urban sectors (namely buildings, mobility, waste management and public lighting) was analysed within the study reported in this paper. Moreover, since end-uses electrification is increasing, bringing new opportunities and challenges for the future, also some electrification scenarios were analysed.

Stated the importance of taking actions across all the main urban sectors in reaching European target, namely an 80% reduction of GHG emissions in 2050 with respect to 1990 (European Commission, 2012a), a challenging issue consists in considering the socio-economic and environmental sustainability at the district and urban scale, providing tools to support decision-maker in defining long-term coordinated strategies.

Accordingly, the study reported in this paper aimed to define a methodology for supporting the planning of energy efficiency measures at district level involving different urban sectors.

The driving idea of this work to facilitate the decision-maker is to create a reference district of the city of Turin in order to have results that can be valid in defining guidelines for planning urban energy efficiency strategies. The idea is connected to the willingness of reproducing

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and analysing the main sectors of an urban system taking into consideration an area with the average dimension of a district and characterised by all the main features which represent the entire city. Since the fields that could be considered were manifold, we decided to focus on buildings, mobility, waste and public street lighting sectors. Energy consumptions and emissions for current and future scenarios configurations were estimated within this work.

However, since the concept of sustainability is threefold (environment, society and economy), to assess socio-economic performance in analysing alternative scenarios, an evaluation tool is introduced in the proposed methodology. The selected tool consists of the Cost-Benefit Analysis (CBA) approach. In fact, its use in the energy field is relevant and partially explored in other studies (Becchio et al., 2019a). Its definition as a decision-aiding tool is introduced in this work through its application on the reference district with the aim to select the most suitable energy efficiency scenario.

The rest of the paper is structured as follows. The methodological approach is presented reporting the steps of its application to a case study. Contextually, the main tools composing the method are introduced. In this context, the reference district characterization process is described, as well as the choice for the main key performance indicators (KPIs), to be calculated for the district on the current state and under different retrofit scenarios. Once the methodological steps and tools are described, the results of the application on Turin are discussed.

Methods

The application proposed in this study was organized in two subsequent processes; in the first phase, a reference district was defined and characterized, constructing a simulation model to identify its current energy and environmental behaviour through specific key performance indicators (KPIs). Thanks to the developed model, savings and emissions reductions were calculated under different retrofit strategies. Secondly, a socio-economic model was built by applying the Cost-Benefit Analysis to delineate the best combination of retrofit actions for the reference district.

In the next sub-sections, data sources, tools and possible metrics to measure the performances of an urban district are introduced. Then, the reference district characterization process concerning building, mobility, public lighting and waste management sectors is described. At the end, scenarios definition is addressed, and the Cost-Benefit Analysis methodology is introduced.

Data sources and tools

In order to characterize the reference district, statistical data about population, building stock, private and public vehicle fleets and waste management policies were collected from different sources. In particular, census data from "Istat" and the web-GIS service "Geoportale della Città di Torino" (Turin Municipality, 2017) were used to characterize the building stock, while the "mobility urban plan" had a fundamental role in defining the features of the mobility sector.

Concerning the building stock, two important tools were used within the study. The first one, TABULA - Typology Approach for Building Stock Energy Assessment (Ballarini et al., 2014), was fundamental to determine the energy performance of buildings in their current state, since it represents a catalogue of some reference buildings, namely buildings that can be considered representative of the national building stock (clustered in typological classes and periods of construction), for which the energy performance is provided. To assess the energy performance of buildings after the retrofit, a semi steady-state simulation software, MasterClima was used.

The methodological process followed within the study presented in this paper is described in the followings.

Key performance indicators

An important issue to address in evaluating the performances of a district concerns the definition of the proper metrics. For this reason, some key performance indicators (KPIs) were defined. In particular, total primary energy consumption (MWh/year), equivalent carbon dioxide emissions (tCO_{2eq}/year) and particulate matter emissions (t/year) were selected. Total primary energy consumption has been selected as the energy-related KPI since the application of the Cost-Benefit Analysis requires a synthetic index measurable for all the alternatives assessed. Equivalent carbon dioxide emissions cannot be excluded by the set of KPIs, since the European target are based on such environmental constraints. Finally, since local pollution issues are more and more relevant and discussed, in opposition to global environmental phenomena (like global warming, which GHG emissions are responsible for), particulate matter emissions are considered among the performance criteria.

Reference district characterization

In this study, the proposed methodological approach was tested not on a real case study, but on a reference district created for the city of Turin. It was designed to be representative of the overall urban system, basing on some statistical data related to the city (i.e. population density, building stock distribution, number of public buses, etc.).

First of all, we identified an area of the city with an average building density and heterogeneity of building stock that could represent an average of the city of Turin. The street pattern of that area was assumed as characteristic of the city.

Buildings model

Starting from the medium population density of that area, the overall surface of residential buildings was estimated and distributed in the different typological classes (assumed by TABULA project) proportionally to their statistical distribution across the city (Mutani et al., 2016). Their technological features in terms of envelope and systems features were assumed equal to the ones of the reference buildings that TABULA identifies for each building typological class, then in accordance to what has been defined to be most common across the Italian residential building stock. Performances and technical parameters for both envelope and systems have been defined by consequence from the TABULA database, varying in accordance with the typological class and period of construction. Moreover, to fit better the current condition of the energy system of the city of Turin, the thermal plants' distribution was adjusted according to the data about the residential volume currently heated by the urban district heating system (DH). Non-residential buildings (namely offices and schools) were included proportionally to their medium distribution in Turin. While for the non-residential buildings the energy-environmental performance in terms of overall primary energy consumptions and related CO_{2eq} and PM emissions have been assessed from data from the literature about typical energy consumption per square meter and none retrofit options have been assessed, for the residential building stock the energy models per each reference buildings have been developed to evaluate their performance under current the retrofitted conditions. A quasi steady-state simulation approach has been selected for this application. The quasi steady-state simulation was performed with the support of a professional software and in accordance with the national Technical Specification UNI/TS 11300 (CTI, 2014; CTI, 2016; CTI, 2019) as an energy balance to determine space heating energy needs (considering thermal capacities of the building components and internal gains, as well as solar gains through windows, assuming to have no obstructions and shading effects), to which thermal losses due to the subsystems of the plants (emission, regulation, distribution, storage and generation) are added to compute the final energy consumption for space heating. The same approach is used for domestic hot water production, whose needs at final users' level are estimated based on square meters of the households, in accordance to the procedure suggested by the UNI/TS 11300.

Mobility

As long as mobility is concerned, we focused on cars, considered as private vehicles, and on buses as public means of transports. Firstly, the number of cars owned by inhabitants of the district were obtained rescaling them to the number of cars per inhabitants in Turin. With regard to the local public transport service, the hypothesis is that 4 hypothetical lines will be improved in order to satisfy the needs of the RD, starting from the number of inhabitants present in the area in question. The bus lines were designed starting from the road framework of the city of Turin used to define the RD. KPIs in terms of consumptions and emissions are calculated basing on the distances currently travelled by the different vehicles.

Public lighting

Given the street patterns previously identified and fixing their mutual medium distance to 50 meters, the total number of street lights were calculated. Typologies distribution of lamps follows the one statistically estimated for Turin. KPIs on the current state are calculated basing on the street lamps stock electric consumptions and the energy-related emissions.

Waste Management

As long as waste management sector is concern, KPIs in terms of consumptions and emissions are calculated basing on the distances currently travelled by the rubbish tracks crossing the district on a daily base.

Measures and scenarios definition

After having defined the current situation of the district, calculating its consumptions (MWh/year), CO_{2eq} (tCO_{2eq}/year) and PM_{10} emissions (tCO_{2eq}/year) for each energy carrier and sector, we started thinking about different ways to renovate the area. For each sector, we identified more than one intervention. In particular, for mobility (T), public lighting (PL) and waste management (W) sectors, we analysed two different measures, according to two levels of invasiveness. They are described in the following table (Table 1).

Since the buildings sector has a significant influence on the district, four different energy efficiency alternatives were established for it. They include progressive substitution of gas boilers with more efficient ones (Carbon alternative "C") or with heat pumps and photovoltaic (PV) panels (Electric alternative "E"), in parallel with DH expansion, basing on two different rates of penetration (50% "base" "B" or 100% "advanced" "A" of the district is involved).

Table 1: Measures for mobility, public lighting and waste management sectors.

Measures	1	2
T	Substitution of buses with electric ones	Substitution of buses with electric ones + increase in fares
PL	50% substitution of lamps with LED	100% substitution of lamps with LED
W	Buried rubbish storage + rubbish tracks twice a week	Buried rubbish storage + rubbish tracks once a week

Table 2: Measures for residential buildings.

Measures	B (Base)	A (Advanced)
C (Carbon)	Envelope retrofit + Efficient gas boilers + DH expansion For **50%** of the heated volume	Envelope retrofit + Efficient gas boilers + DH expansion For **100%** of the heated volume
E (Electric)	Envelope retrofit + Heat pumps and PV panels + DH expansion For **50%** of the heated volume	Envelope retrofit + Heat pumps and PV panels + DH expansion For **100%** of the heated volume

The combination of "C" and "E" measures with the two rates of penetration "B" and "A" made up the four energy efficiency alternatives for the residential building sector. The retrofit of the envelope is always included. The alternatives are summarized in the table reported above (Table 2).

It was adopted a semi steady-state approach regulated by the technical specifications UNI/TS 11300 (CTI, 2014; CTI, 2016; CTI, 2019) to assess the post-retrofit energy performance. In particular, for each reference building composing the district, we built a model in MasterClima software. Once each model was calibrated according to the energy performance that TABULA catalogue defines for it, we run different simulations under the measures previously defined.

Energy savings, CO_{2eq} and PM_{10} emissions reduction were calculated for the overall district under different combination of the sectorial measures. Indeed, six cross-sectorial energy efficiency scenarios were identified and assessed, to be compared with the current state and among themselves. The scenarios were defined including the most and the less invasive one, where the former combines the first level of intervention for each sector (CA+T2+W2+PL2), while the latter is based on the combination of measures with the highest impact (CB+T1+W1+PL1). Further, four heterogeneous and intermediate scenarios were included in the study.

Cost-Benefit Analysis

The Cost-Benefit Analysis was chosen as the evaluation tool able to compare the six retrofit scenarios obtained through the combination of the measures previously defined. According to the European Commission, "the Cost-Benefit Analysis (CBA) is an analytical tool for judging the economic advantages or disadvantages of an investment decision by assessing its costs and benefits in order to assess the welfare change attributable to it" (European Commission, 1997). Thus, costs and benefits per each scenario were identified, calculated and distributed across the lifespan of 30 years. After their discounting at the present moment, two economic indexes are calculated to assess the social convenience of the alternative scenarios, ranking them. The chosen economic indexes are the Net Present Value (NPV) and the benefits-costs ratio (B/C), (1) and (2) equations respectively.

$$\mathrm{NPV} = \sum_{t=1}^{n} a_t S_t = \frac{S_1}{(1+i)^1} + \frac{S_2}{(1+i)^2} + \cdots + \frac{S_n}{(1+i)^n} \quad (1)$$

where $a_t = \frac{1}{(1+i)^t}$ represents the discounting formula. S_t is the balance of cash flow at time t and i is the discount rate.

$$\mathrm{B/C} = \sum_{t=1}^{n} \frac{a_t B_t}{a_t C_t} \quad (2)$$

where B_t is the benefits at time t and C_t is the costs at time t.

If NPV is major than zero the benefits produced by the investment overcome the relative costs. The ratio between the two cash-flows, namely benefits and costs, represent the indicator B/C. The more the indicator is high, the more the benefits overcome the costs. The strength of the CBA analysis is in its capability to include non-financial or indirect impacts of a project that could be beneficial for the whole society, influencing the final result of the assessment drastically (Buso et al., 2017).

The results obtained through the application of the methodological steps reported in this paper are presented and discussed in the followings.

Figure 1: Reference district layout with building stock characterization in terms of typologies distribution.

Results

The application proposed in this research deals with the analysis of six urban retrofit scenarios in which we included all the measures applied in each urban sector. As already discussed, the case study is represented by the reference district constructed for the city of Turin, which is reported in Figure 1. Firstly, we analysed the percentage reduction of primary energy need, CO_{2eq} and PM_{10} emissions (namely, the identified KPIs) of the current state with respect to the new scenarios. We decided to carry out this comparison as these factors will be considered as benefits for the entire district or, in case of GHG emissions, society.

Table 3: Energy consumption and environmental pollutions reduction.

No	Scenario	Primary Energy	CO_{2eq}	PM_{10}
1	CB+T1+W1+PL1	-31%	-29%	-38%
2	CB+T2+W2+PL2	-31%	-29%	-38%
3	EB+T1+W2+PL1	-32%	-31%	-42%
4	EB+T2+W2+PL2	-32%	-31%	-43%
5	CA+T2+W2+PL2	-49%	-43%	-54%
6	EA+T2+W2+PL2	-50%	-50%	-58%

Table 3 shows the percentage of reductions. From this analysis, we noticed that the major percentage reduction of primary energy need, CO_{2eq} and PM_{10} emissions is present in Scenario 6. Scenario 6 considered DH implementation, envelope improvement, and heat pumps and photovoltaic panels systems installation for all buildings.

Considering the surplus of electricity produced and exported by photovoltaic panels, we can assume that this energy could be used to cover the electricity extra-needs of buildings sector (e.g. new cooling systems). As for mobility, Scenario 6 involves replacing existing buses with electrical ones and increasing the number of bus rides of 20% with the consequent reduction of the number of cars journey. As far as waste management is concerned, containers for underground waste have been provided and the frequency of garbage trucks to be reduced to once a week. In this way, the total fuel consumption and the production of CO_{2eq} and PM_{10} decrease in this sector. In the second measure, we introduced the use of LED lightbulbs replacing all the street lightbulbs of reference district, drastically reducing public electricity consumption (-32%).

Table 4. Financial and economic variables considered.

Costs	
Name	*Description*
Investment costs	Initial amount of money spent for the retrofit interventions for buildings and urban solutions (Piedmont Region, 2018; Milan Municipality, 2018; Autonomous Province of Bolzano, 2018)
Running costs	Annual costs for maintaining the initial performance of the measures according to UNI EN 15459/2018 (CIT, 2018). Annual energy consumption for heating and cooling, street lighting, etc. Environmental costs related to CO_2 and PM_{10} emissions (European Commission, 2012b).
Replacement costs	Amount spent to replace buildings and urban system components at the end of their service life.
Benefits	
Name	*Description*
Running benefits	Annual benefits coming from retrofit of buildings and urban solution in terms of energy savings and avoided emissions.
Green Jobs	Shadow wage for each new job created (Copenhagen Economics, 2012).
Reduction unemployment subsidies	Social benefit due to the reduction of unemployment subsidies (Copenhagen Economics, 2012).
Real estate market value increasing	Increased economic value of buildings related to the increase in energy efficiency (Bottero et al., 2018).
Fuel costs avoided	Avoided costs linked to the use of fossil fuels for public and private mobility (cars, waste trucks, buses).
Bus tickets	Monetary earnings of the public transport company resulting from the sale of more travel tickets.
Energy costs avoided for street lighting	Annual avoided costs coming from a LED system installation for public lighting.
Residual value	Value of measures implemented at the end of the calculation period.

Once the energy and environmental performance of the six scenarios, as well as of the other scenarios, have been calculated (as explained in “Material and methods” section), we identified the possible co-benefits produced by the project, to estimate the net benefit of the retrofit scenarios (IEA, 2019). Table 4 shows the costs and benefits included in the evaluation table.

Firstly, we calculated costs and benefits separately for each measure and aggregated them in a CBA framework for each scenario (European Commission, 1997). We calculated the costa and benefit according to different formulas coming from European standards or literature review. Table 5 presents the estimation procedures used to monetize the considered impacts.

Table 5: Estimation procedures.

Costs	
Name	*Estimation procedure*
Investment costs	Analytical estimation of the implemented measures, including material, installation and ancillary works (Dell’Anna et al., 2019b)
Running costs	Calculation of maintenance costs as a percentage of the investment costs according to CTI (2018). Operational costs estimated multiplying the Energy cost [€/kWh] × Energy used [kWh]

Replacement costs	Investment cost to spent to at the end of component working life according to UNI EN 15459-1:2018 (CTI, 2018).
Benefits	
Name	*Estimation procedure*
Running benefits	Energy cost [€/kWh] × Energy used [kWh], Equivalent CO_2 cost [€/CO_{2eq}] × Energy used [kWh], Equivalent PM_{10} cost [€/CO_{2eq}] × Energy used [kWh]
Green Jobs	Number of new jobs (Janssen and Staniaszek, 2012) multiplied by the average shadow salary (European Commission, 2014).
Reduction unemployment subsidies	Number of new jobs multiplied by the average Italian subsidy for unemployed (called NASPI, "New social insurance benefit for employment").
Real estate market value increasing	The benefit was calculated in terms of consumer appreciation for buildings in the energy efficient class using the hedonic pricing method (Bottero et al., 2018)
Fuel costs avoided	Unit fuel cost [€/fuel cost] × Fuel saved
Bus tickets	Ticket price for Turin's public transport (1.70€) × tickets sold (European Commission, 2014)
Energy costs avoided for street lighting	Energy cost [€/kWh] × Energy saved [kWh]
Residual value	Benefit estimated by [1-(Calculation period/Useful life of component)] × Investment cost of component (Roscelli, 2014)

We compiled six tables with the annual total costs, total annual benefits, and calculated the cash flows considering a calculation period of 30 years and a discount rate equal to 2% (Becchio et al., 2018; Bottero et al., 2019b). Then, we computed the economic indicators to identify the most suitable environmental, social and economic scenario for the reference district.

Table 6: B/C ratio results.

Scenario	**1**	**2**	**3**	**4**	**5**	**6**
B/C	0.38	0.38	0.47	0.47	0.51	1.14

The results obtained show that all the scenarios, except for Scenario 6, are not sustainable from the economic point of view (Table 6). Indeed, their cash-flows are negative for all the years of the lifetime of the investment with a consequent ratio between benefits and costs with a value less than one. Despite energy efficiency measures for buildings and neighbourhood sustainability measures proposed for scenarios 1 to 5, the benefits are unable to cover the costs to be incurred. The only scenario, in which the B/C is positive, is the most invasive one. For this reason, this will be the most suitable one for the reference district. We can notice that the buildings sector is the most influential as the results of the scenarios change drastically when we modify the measure foreseen for the buildings sector (Barthelmes et al., 2016). An improvement in the performance of buildings has allowed an increase in the energy class with a consequent increase in the assets' value (Bottero et al., 2018). A major investment in the installation of heating systems and photovoltaic panels would allow the creation of new green jobs. As a result, new jobs are reflected in a reduction in unemployment benefits. Despite the increase in buses racing, the scenario is best performing thanks to the increase in users of the public transport service and a reduction in car traffic. The conversion of the public lighting system into a system based on LED technology would allow a reduction in electricity consumption, with benefits in terms of energy, environment and economic for public spending. A waste collection system with the underground bins, reducing the crossing of the collection trucks allows a reduction in fuel costs for the service operators.

Starting from the Scenario 6, we decided to analyse the possible scenarios that include the EA (Energy Advanced) measurement for the building sector and the W2 (Waste measure 2) measure as it is the most sustainable for the waste sector.

For these reasons, the other scenarios analysed were:

- EA+T1+W2+PL1
- EA+T1+W2+PL2
- EA+T2+W2+PL1

These new scenarios were also analysed with a CBA, and the results were summarized in Table 7.

The CBA results are similar among the advanced scenarios. The best performing scenario is the EA+T1+W2+PL2 as it has the highest Net Present Value (NPV) and B/C ratio. Although costs for the scenario are higher due to the cost of investing for energy retrofits and implementations of more efficient measures, the net benefits are more significant and determine positions in the rankings.

Table 7: Economic performance indicators.

Scenario	**NPV**	**B/C**
EA+T1+W2+PL1	42,079,071 €	1.15
EA+T1+W2+PL2	42,965,375 €	1.15
EA+T2+W2+PL1	42,811,481 €	1.15
EA+T2+W2+PL2	40,865,803 €	1.14

In detail, the benefit that leads to the greater economic sustainability of the EA+T1+W2+PL2 scenario compared to the others is the increase of new jobs in the green sector for the installation and maintenance of measures with a consequent effect on public expenditure given by the reduction of unemployment benefits. The replacement for 100% of the street lights envisaged by the measure PL2 (Public Lighting measure 2) allows to reduce more energy consumption, and the environmental impacts accordingly.

Conclusion

This paper reflects the need for decision-makers of disposing of more informed assessments for choosing a cost-effective mix of measures. The paper is grounded on the consideration that traditional cost-benefit criteria do not relate the upfront investments of the measures to its whole benefits portfolio, which may lead to underestimate the potential benefits of energy efficiency.

The proposed case study presents innovation related to the identification and monetization of the co-benefits associated with different options for the renovation of an entire district, from a cross-sectoral perspective. From the result, there is evidence that greater importance should be placed on buildings as part of a larger energy system, where the cost-optimal measures for buildings also reflect the site-dependent characteristics of a district or a city, balancing supply and demand solutions (Becchio et al., 2019b). The proposed indirect co-benefits are an added value to traditional cost-benefit analyses, highlighting societal, economic and environmental benefits that go beyond current practices (Bottero et al., 2019a; Dell'Anna et al., 2019a). The inclusion of co-benefits can shift a package of measures from being economically sustainable to not being anymore and vice-versa. In future applications, the steps of the methodologies need to be further enhanced by strengthening the scenario building parts, further improving the choice of individual measures and their combination. Future developments will also involve the introduction of other co-benefits, nowadays too uncertain to be used as decision support variables.

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