Evaluating the Health-Related Social Costs Associated with the Thermal Uses of the Residential Sector: The Case of Turin

Evaluating the health-related social costs associated with the thermal uses of the residential sector: the case of Turin

Giulia Crespi[1[0000-0001-5087-939X]], Federico Dell'Anna[2[0000-0001-6447-3331]], Tiziana Binda[3], Cristina Becchio[1[0000-0001-9501-5026]], Marta Bottero[2[0000-0001-8983-2628]]

[1] TEBE-IEEM Research Group, Energy Department, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[2] Interuniversity Department of Regional and Urban Studies and Planning, Politecnico di Torino, Viale Mattioli 39, 10125 Torino, Italy
[3] Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

giulia.crespi@polito.it

Abstract. Nowadays, due to the constant increase of outdoor air pollution, the impact on people's health is alarming. Moreover, in the current vulnerable and crucial historical period during which society is experiencing and dealing with the COVID-19 pandemic consequences, this issue is becoming even more important. In line with this, there is an urgent need to provide scientific input to decision-makers to include the assessment of the health-related benefits and costs into urban planning processes. Special attention is devoted to the building sector since the heating service is considered among the main sources of air pollution in the urban environment. In the light of this, the paper aims to estimate the social costs associated with the thermal uses of the residential buildings in Turin (Northern Italy), integrating the energy assessment of the residential building stock, taking advantage of the Reference Building approach for the stock characterization, and the economic quantification and monetization of the air pollution health impacts, using the Cost of Illness (COI) method. Starting from the current situation, different retrofit scenarios for the residential buildings of Turin are hypothesized, to evaluate their capability in reducing the environmental impact of the sector, as well as to increase the social benefits they can guarantee.

Keywords: Outdoor Air Quality, Health Effects, Human Capital Approach, Retrofit Scenarios, Reference Building approach.

1 Introduction

Today, due to the significant impact that outdoor air pollution has on people's health causing 4.2 million deaths in 2017, the concept of outdoor air quality is becoming increasingly important [1,2]. In this context, the COVID-19 pandemic has highlighted the importance of adopting resilient spaces to ensure high air quality. However, as early as 2015 the issue was raised by the introduction of health and welfare insurance as a goal for all countries within the Sustainable Development Goals defined by the United Nations [1]. In particular, Goal 3 aims to ensure a healthy life and to promote well-being at all ages for sustainable development [1].

The literature has identified air pollutants involved in urban processes and their effects on different categories of damage, including impacts on human health, damage to buildings and materials, crop and biodiversity losses, and loss of ecosystem services in general [3-6]. Among these damage categories, the health impacts caused by air pollution contribute to most of the estimates of external costs [7,8]. Public health experts linked air pollution inevitably to worsening morbidity (especially respiratory and cardiovascular diseases) and premature mortality (e.g., Years of Life Lost) [9,10].

Due to the current high levels of pollutants concentration in cities, the problem of outdoor air quality is becoming particularly relevant in the urban context. Indeed, anthropogenic activities, which are the main sources of pollutants, are more concentrated in urban areas, rather than rural ones. Moreover, according to future projections, almost two-thirds of the world population will live in cities by 2050 [1]. The significant weight of the consequences of atmospheric pollution on people's health, combined with increasing urbanization, requires the identification and development of suitable tools to quantify and estimate the social costs associated with the pollutants emissions on health [11]. In particular, among the anthropogenic causes of outdoor air pollution, the building sector is recognized as one of the main ones, especially considering the heating sector [12]. Indeed, at European level, heating systems alone represent about 30% of total PM10 emissions [13]. This is because space heating and domestic hot water production end-uses cover almost 80% of total final consumption, and a significant portion of this energy is still met by using fossil fuels [14].

In line with this, the study intends to provide scientific outcomes for decision-makers, to support and guide a new form of urban planning, capable of putting people at the center, giving relevance to health and well-being aspects. In detail, the study aims to investigate the relationship between buildings, air pollutants, and people in urban environments, examining the health impacts caused by the PM10 emissions associated with thermal uses of residential buildings. PM10 was selected for the analysis, as it was found to be among the most dangerous pollutants, being responsible for severe respiratory and cardiovascular diseases [15]. In addition, attention was also devoted to the quantification of the CO_2 emissions caused by the residential sector, in line with the global attention on reducing greenhouse gas emissions and with the ambitious targets defined for the building sector at local, national, and international scales. These considerations are also in line with the EU Green Deal, which aims to move the European Union towards a climate-neutral society by 2050, giving importance to satisfy the quality of life for current and future generations [16]. Moreover, the EU Green Deal recognizes the building sector as promising for energy and economic savings [17].

Given the complexity in the design and implementation of energy re-development strategies for buildings and the rigid constraints of financial resources, multiple objectives related to energy saving and environmental compatibility must be pursued. In this perspective, a comprehensive view of costs and benefits is necessary [18-20]. To this end, a multi-step methodological approach was proposed, and applied to the case study of the residential sector of the city of Turin, in the North-West of Italy. First, its urban residential stock was classified and characterized using the Reference Building (RB) approach [21]. The identified RBs allowed estimating the impact of the sector in terms of PM10 and CO_2 emissions. Then, to investigate and quantify the relationship between air pollutants and health effects, the social costs associated with emissions from the residential sector in its current state were estimated using the Cost of Illness (COI) method to translate the health impacts related to PM10 emissions from buildings in monetary terms [22]. By associating the energy analysis with the socio-economic one, a multi-domain Key Performance Indicator (KPI) was identified, named Social Cost Index, able to estimate the total social cost generated by each unit of emitted PM10. To investigate the effects of different retrofit strategies on the overall social health costs for the case study, a scenario analysis was proposed, to study possible renovation pathways for the residential sector, able to guarantee a reduction of its energy and environmental impact, as well as an increase of the associated social benefits, guaranteed by a lowering of air pollution.

The paper is structured as follows: after the conceptualization of the methodological framework in Section 2, Section 3 is dedicated to the description of the case study and the main assumptions; Section 4 shows the main results of the application, while section 5 draws the main conclusions, illustrating the possible future perspectives.

2 Methods

This section aims to describe the multi-step methodological approach exploited to investigate the impact of the residential building stock in terms of health-related social costs, as well as to explore possible renovation pathways for it, to both reduce its air pollutant emissions and increase the social benefits for the community. The methodological approach couples the energy and environmental assessment of the residential building stock in its current state (developed using the archetype modeling approach) with the socio-economic quantification and estimation of the health-related social costs associated with PM10 pollution. Going into detail, based on the current state analysis, a multi-domain KPI, named Social Cost Index (SCI), was defined to couple the energy and the socio-economic dimensions, allowing to develop an analytical tool able to identify the total social costs associated to the PM10 emissions generated by the building sector. Then, by developing a scenario analysis, diverse renovation pathways are compared and assessed using the developed KPI, to investigate the strategies able to reduce the environmental impact of the sector (in terms of air pollutants emissions reduction) and to increase the social benefits for the community (in terms of social cost reduction) with respect to the current state.

2.1 Energy and environmental assessment of the current state

This section focuses on the estimation of the energy and environmental impact of the residential sector in its current state. Due to the difficulty in individually modeling all the buildings within the stock, the RB approach was used. This term is used to indicate a real or statistically determined typical building, which can be considered representative of a portion of the building stock [21]. The archetype modeling allows estimating the energy consumption of a specific RB, which can be then scaled up to estimate the energy consumption of the whole portion of building stock the RB is representative of, by means of appropriate multiplicative factors (e.g., the total floor area of the portion of building stock represented by the RB or the number of buildings represented by the RB) [21].

In line with this, once the RBs were fully characterized in energy terms, it was possible to estimate the Total Energy Consumption (TEC) of the building stock, as in Eq. (1):

$$TEC(j)\left[\frac{kWh}{y}\right] = \sum_{i=1}^{N} EC(i,j) \cdot SF(i) \quad (1)$$

where j represents the j-th energy vector (e.g. natural gas, oil, biomass, electricity) used to provide the energy service, $EC(i,j)$ represents the annual specific energy consumption of the j-th energy vector of the i-th RB (expressed in kWh/(m^2·y)), N is the total number of RBs used to represent the whole residential stock, and $SF(i)$ represents the total stock floor area represented by the i-th RB (expressed in m^2).

Then, using appropriate emission factors for each j-th energy vector, it was possible to estimate the Total Pollutants Emissions (TPE) generated by the building stock, according to Eq. (2):

$$TPE(z)\left[\frac{kg}{y}\right] = \sum_{j} TEC(j) \cdot EF(j,z) \quad (2)$$

where z represents the pollutant under investigation (e.g., CO_2, PM10, etc.), $TEC(j)$ represents the total energy consumption of the j-th energy vector (expressed in kWh/y), as resulting from Eq. (1), and $EF(j,z)$ represents the emission factor of the z-th pollutant under investigation for the j-th energy vector (typically expressed in kg/kWh or g/kWh).

2.2 Socio-economic evaluation of health-related social costs

To estimate the health-related social impacts caused by the air pollutants emissions from the residential sector, it is necessary to correlate the emissions with the social costs [23]. The estimation of the social costs was developed using the COI method, which allows estimating the economic burden that an illness imposes on the entire society, according to Eq. (3):

$$COI = DC + IC + INC \quad (3)$$

where DC represents the direct costs, IC the indirect costs and INC the intangible costs. The former represents all the healthcare and non-healthcare costs due to treatment and care, which are usually estimated based on market values. Indirect costs, instead, are those associated with productivity losses, as a consequence of workers' absence from workplaces due to the occurrence of the disease. Finally, intangible costs, which are the most difficult to estimate, represent all the costs associated with more subjective factors (e.g., quality of life, pain, and suffering perceptions, etc.) [22].

In order to estimate the total costs associated with air pollution effects, two methods were exploited: the Human Capital Approach (HCA), which was used to estimate the tangible costs (both DC and IC) and the Willingness to Pay (WTP), which was deployed to quantify the intangible costs (INC). On the one side, the HCA approach is based on the loss of productivity, which is estimated as the total amount of time from the moment of the pathological event occurrence for the worker and his/her return to work [24]. According to this approach, direct costs are computed by taking into account all the hospitalization and healthcare costs (e.g. ticket visits, exams, medications, etc.) potentially associated with air pollution diseases (e.g. respiratory diseases, cancers, cardiac diseases, etc.). Instead, indirect costs were assumed based on the Work Lost Days (WLD) metric, which is defined as the total number of days during which a worker is unavailable for working [25].

On the other side, the WTP method allows the estimation of non-marketed goods and the measurement of the amount of money that an individual is willing to pay to reduce his/her probability of illness or premature death [24]. This approach estimates the intangible costs, quantified in terms of the Years of Lost Life (YLL) metric, which represents the total years of potential life lost due to premature deaths correlated to PM10 emissions [26].

2.3 Definition of the multi-domain KPI

Based on the results coming from Sections 2.1 and 2.2, the environmental impact of the building stock and the associated health-related social costs were calculated. To couple the energy-environmental analysis with the socio-economic assessment, a multi-domain KPI was developed, named Social Cost Index (SCI), aiming to estimate the total social costs associated with each PM10 unit emitted by the building stock under investigation. The indicator was calculated according to Eq. (4):

$$SCI\ \left[\frac{€}{t\cdot person}\right] = \frac{COI\left[\frac{€}{person\cdot y}\right]}{TPE_{PM10}\left[\frac{t}{y}\right]} \tag{4}$$

where COI represents the total annual health-related social costs per person (expressed in €/(person·y)), computed using the COI approach, while TPE_{PM10} corresponds to the total annual PM10 emissions caused by the building stock (expressed in t/y).

2.4 Definition and assessment of retrofit scenarios

With the scope of exploring the potential for reducing the environmental and socio-economic impacts of the residential building stock, different retrofit scenarios were hypothesized, all assuming to intervene on the sole HVAC system, by substituting the existing thermal generators. The scenarios allowed to investigate the capability of the renovation strategies to reduce the environmental impact of the analyzed buildings, in terms of reductions of CO_2 and PM10 emissions. Moreover, by keeping fixed the SCI metric calculated in Section 2.3 (Eq. (4)), and, thus, keeping fixed the ratio between the socio-economic and the environmental impact in the different scenarios, depending on the changes in PM10 emissions, it was possible to estimate the potentiality of the diverse retrofit scenarios in reducing the total social costs.

3 Application

The methodological framework was applied to the residential sector of the city of Turin (886837 inhabitants [27]), located in the Piedmont Region, in the North-West of Italy. According to the last national census [28], Turin has 63764 buildings, 98% of which are occupied. The analysis described in this paper focused on the residential sector, which represents approximately 57% of the total occupied buildings. In particular, the study was devoted to the assessment of the impact of the thermal uses (space heating and domestic hot water) on urban emissions, since these end-uses represent the most relevant voice of energy consumption in residential buildings and are still mostly based on combustible fuels. Indeed, in Turin, almost 80% of residential buildings use natural gas for thermal uses and less than 1% of the residential stock is equipped with renewable energy systems (e.g., solar thermal collectors, photovoltaic systems, etc.) [28].

3.1 Energy and environmental assessment of the current state

As previously mentioned, to estimate the energy and environmental impact of the residential building stock, the RB approach was used [21]. RBs were derived from the outcomes of the European project "Typology Approach for Building stock energy Assessment (TABULA)", conducted between 2009 and 2012 [21]. The project aimed to create a well-defined database of residential building typologies in Europe, including Italy [21]. According to the TABULA project, 32 typologies of buildings were identified for Italy (and mainly for the Piedmont Region), sub-divided in terms of building typology (apartment block (AB), multi-family house (MFH), terraced house (TH) and single-family house (SFH)) and period of construction (before 1900, 1901-1920, 1921-1945, 1946-1960, 1961-1975, 1976-1990, 1991-2005 and after 2005) [29]. Within the project, each RB was fully characterized in terms of geometry, envelope thermal properties, and space heating (SH) and domestic hot water (DHW) systems characteristics (i.e., type of generator, type of distribution system, type of emission system, and associated efficiencies). Per each RB, SH and DHW energy needs and primary energy consumptions were computed.

In this paper, the whole set of TABULA RBs was considered as representative for the residential stock of Turin, and information on the total stock floor area of Turin households in each construction period identified by TABULA was gathered. Per each RB under investigation, starting from the energy needs for SH and DHW and knowing the efficiencies of the installed sub-systems (generation, distribution, emission, storage), the specific energy consumption associated with each RB ($EC(i, j)$ of Eq. (1)) was computed. Moreover, according to the distribution of the total stock floor area, the total energy consumption per each j-th energy vector was calculated (see Eq. (1)). Finally, using appropriate emission factors for the energy vectors used to satisfy SH and DHW needs [30, 31], CO_2 and PM10 emissions were assessed for the entire residential stock (Eq. (2)).

3.2 Socio-economic evaluation of health-related social costs

To estimate the health-related social costs due to PM10 emissions, the COI approach was considered and the HCA and WTP methods were used to compute the different cost voices. Specifically, HCA was used to compute the tangible costs (both direct and indirect). Direct costs were calculated as the sum of hospitalization and medication costs for cardiovascular and respiratory system diseases, using statistical values from [32-34]. Regarding the indirect costs, which are typically computed based on the WLD metric, the value of a single working day (equal to 130.73 €) was estimated as the ratio between the average value of an employee's annual salary [27] and the number of annual productivity days [35]. Total indirect costs were then calculated by multiplying the daily cost by WLD [36]. Finally, WTP was used to estimate the intangible costs. The method is usually exploited by submitting surveys to the concerned population, in order to estimate the value they give to a year of life; due to time constraints, a reference value equal to 145320 €/y was derived from [26] and used as an estimation of the YLL metric.

Based on the results of Section 3.1 (in terms of total PM10 emissions generated by the residential sector) and on the obtained COI estimations, SCI was computed for the current state, allowing to quantify the total social costs associated with each PM10 unit emitted by the building stock under analysis.

3.3 Definition and assessment of retrofit scenarios

To explore the potential social benefits associated with the renovation of the residential building stock of Turin, different retrofit scenarios were hypothesized. Specifically, two scenarios were defined for the residential buildings under investigation, assuming to retrofit only SH and DHW generation systems, by substituting the original RB energy systems, without intervening on the envelope. Assuming not to retrofit the most recent buildings (built after 2005) and the oldest category (built before 1945) due to retrofit restrictions for historical or artistical reasons, retrofit scenarios were applied only to buildings built between 1946 and 2005, which represent approximately 75% of the urban residential stock.

The developed System Retrofit (SR) scenarios differ in the alternative technological options considered eligible for retrofit. Specifically, the first SR scenario (SR1) considered the substitution of the original generation system of the RBs with either a condensing gas boiler, a biomass boiler, or an electric heat pump. The distribution of the technologies among the RBs to retrofit was done based on the available information of the total number of incentive requests in Italy in 2018 for the three considered technologies [37]. Moreover, in order to highlight the impact of the biomass source in terms of local air pollution, the second SR scenario (SR2) assumed to have at disposal for the substitution of the original RB system only condensing gas boilers and electric heat pumps.

For both SR1 and SR2 scenarios, four diverse renovation rates were considered, assuming to intervene on the 25%, 50%, 75%, and 100% of the portion of building stock to be potentially retrofitted (i.e. 75% of the residential building stock, as previously mentioned).

4 Results and discussion

From the energy-environmental standpoint, according to the RB-based modeling of Turin residential building stock in its current state, a total of approximately 1735 kt/y of CO_2 emissions and 12 t/y of PM10 emissions was obtained. Moving to the socio-economic analysis and focusing solely on PM10 emissions (due to their well-known impact on people's health), an overall social cost of 1192 €/(person·y) was obtained, in accordance with the COI approach. In particular, based on the HCA method, a social cost of 492 €/(person·y) was attained, regarding the sole direct and indirect costs, while, according to the WTP method, a value of 700 €/(person·y) was correlated to the intangible costs. Based on these results, the multi-domain KPI was calculated to show the link between the PM10 emissions generated by the residential buildings and the associated social costs estimated according to the COI method. A SCI value of approximately 98 €/(t·person) was obtained, meaning that ton of PM10 emissions caused a total social cost of almost 100 € per person.

The scenario analysis allowed, on the one side, to estimate the potential environmental benefits of the assumed renovation strategies, assessing both global (CO_2) and local (PM10) emissions reductions. On the other side, socio-economic benefits (or costs) associated with the retrofit scenarios can be estimated, based on the developed SCI multi-domain metric.

According to the first topic, Fig. 1 and Fig. 2 summarize the results obtained for SR1 and SR2 scenarios, respectively, in terms of CO_2 and PM10 emissions for the four considered renovation rates. Both scenarios guarantee improvements in terms of CO_2 emissions, obtaining approximately 27% and 24% reductions with respect to the current state for SR1 and SR2 scenarios, respectively, considering the 100% renovation rate. In particular, the presence of the biomass source in SR1 (see Fig. 1a) guarantees a higher reduction of CO_2 emissions, due to the lower emissions generated by biomass boilers with respect to the other alternative solutions (due to lower emission factors for biomass). Conversely, when moving to PM10 emissions trends, an opposite result is visible; indeed, the SR1 scenario provokes an increase of PM10 emissions (see Fig. 2a), being the biomass option the highest PM10 emitter among the considered alternatives; moreover, biomass generators efficiencies are lower with respect to the other technological options, for both SH and DHW. For this reason, when moving to the biomass-free SR2 scenario, indeed, a decrement of PM10 emissions is visible (see Fig. 2b), reaching a 30% reduction with respect to the current state, for the 100% renovation rate. Clearly, the renovation rate influences the results; as mentioned, both scenarios were built assuming different renovation rates, varying from 25% to 100%, to simulate strong retrofit uptakes. As expected, the higher the renovation rate, the higher the associated emissions reductions are.

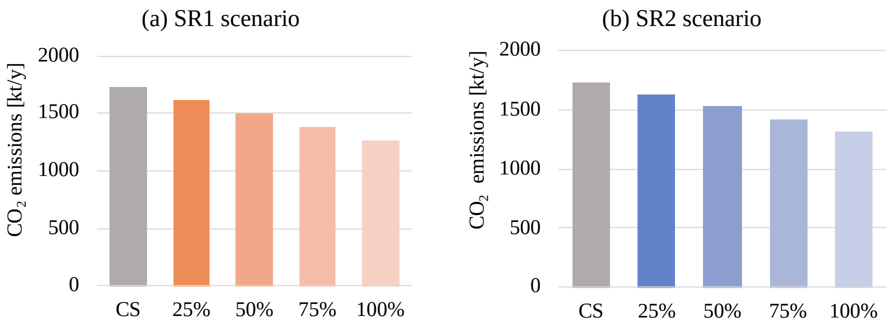

Fig. 1. CO_2 emissions trends for the current state (CS) and the four renovation rates (25%, 50%, 75%, 100%), for SR1 (a) and SR2 (b).

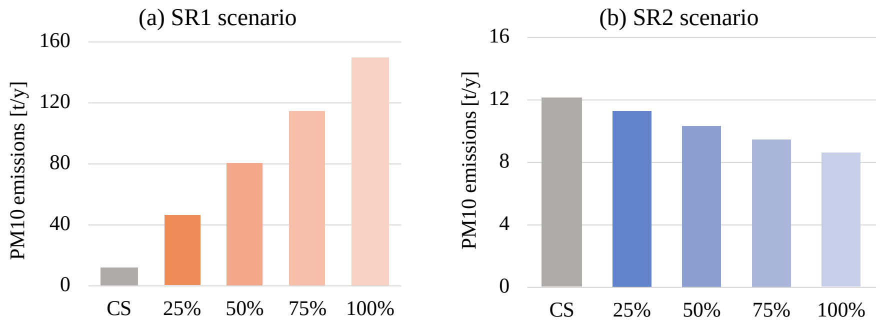

Fig. 2. PM10 emissions trends for the current state (CS) and the four renovation rates (25%, 50%, 75%, 100%), for SR1 (a) and SR2 (b).

Furthermore, the scenario analysis allowed to estimate the social benefits (or costs) induced by the variations of PM10 emissions per each scenario and renovation rate. Fig. 3 shows the obtained environmental benefits, in terms of avoided PM10 emissions (expressed in t/y) and the health-related social benefits (expressed in €/(person·y)) for SR1, while Fig. 4 summarizes the same results for SR2. In both figures, a negative value for the emissions corresponds to an increment of buildings-related emissions with respect to the current state, while a negative value for the net social benefits represents a cost (i.e., increment of social costs compared to the current state).

As expected, the SR1 scenario provokes an increase in social costs with respect to the current state, due to the increment of PM10 emissions. As reported in Fig. 3, an economic loss of 3351 €/(person·y) is visible for the lowest renovation rate (25%), which increases up to approximately 13406 €/(person·y) for the 100% renovation rate case. Conversely, when considering the SR2 scenario, a socio-economic benefit is highlighted; in particular, the highest renovation rate of 100% allows achieving a social benefit of 351 €/(person·y).

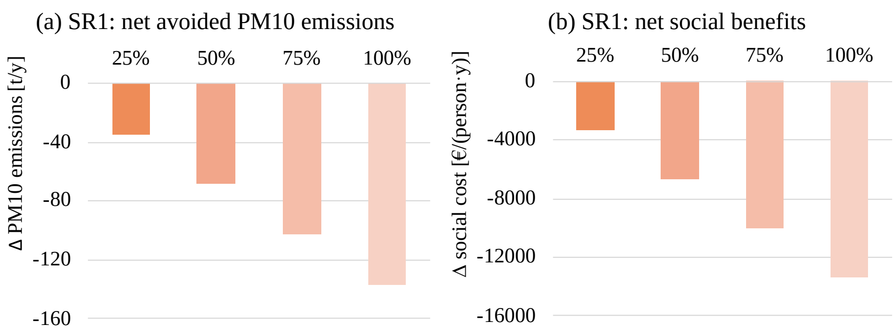

Fig. 3. Net avoided PM10 emissions (a) and net social costs/benefits (b) for SR1 scenario.

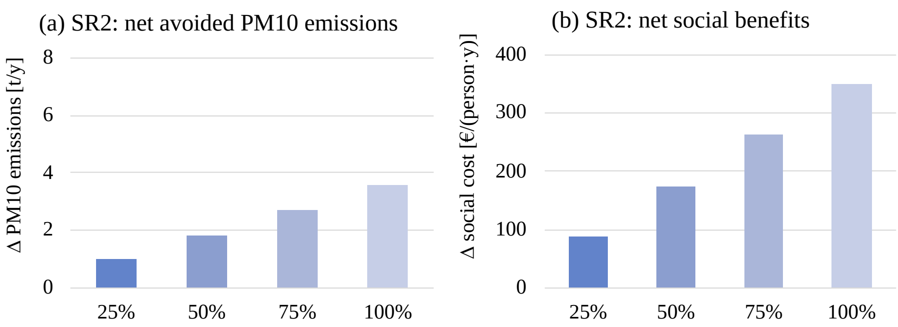

Fig. 4. Net avoided PM10 emissions (a) and net social costs/benefits (b) for SR2 scenario.

5 Conclusions and future perspectives

Nowadays, outdoor air quality is a challenge for the urban environment, especially considering the impact that air pollutants have on people's health. This topic needs to be carefully addressed and introduced in new urban energy planning, aiming to put people's well-being, health, and satisfaction at the center, and to transform cities into safer and healthier environments. In the future energy transition of cities, the role of the building sector is crucial, due to its still high environmental impact, mainly associated with the use of heating systems, which are still mostly based on fossil fuels.

The paper fits with this background, aiming to explore the relationship between the air pollution caused by the residential building sector (and mainly by thermal uses) and the health-related social costs for the community, using the city of Turin as case study. Moreover, thanks to the definition of a multi-domain KPI, named Social Cost Index, the work allowed to estimate the social cost due to the PM10 emissions generated by the building stock under investigation. The social cost estimation was developed using the Cost of Illness approach, coupling two evaluation methods (Human Capital Approach and Willingness to Pay).

Starting from the energy and socio-economic assessment of the current state, the work developed a scenario analysis, evaluating the capability of diverse retrofit strategies for the heating systems substitution to reduce the environmental impact of the sector, and, thus, to obtain benefits for the entire society. The results brought out that the use of biomass can produce a negative local environmental effect, increasing PM10 emissions with respect to the current state; on the other side, when biomass is excluded from the renovation strategies, a 30% PM10 emission reduction can be achieved. Based on the SCI metric, the social costs related to the developed retrofit scenarios were estimated, allowing to compute the possible benefits achievable thanks to the renovation of the building stock. As a consequence of the environmental considerations, only the SR2 scenario (which does not consider the possible exploitation of biomass boilers in urban environments) permits to obtain some benefits for the society, clearly increasing with the increment of the renovation rate.

In conclusion, the obtained results have shown the impact of residential heating on outdoor air quality, allowing to estimate the health-related social costs associated with PM10 emissions, which is a major theme today. For this reason, the outcomes of the work can be used to support the urban planning decision-making process, giving value to the need to reduce the health impacts of urban air pollution.

The study opens the way to future work in this field. On the energy side, the paper concentrated on traditional technologies (i.e., condensing gas boiler, biomass boiler, electric heat pump) and without intervening on the envelope. Future work will be devoted to the assessment of additional retrofit scenarios focusing on the improvement of the envelope, to evaluate how energy demand reduction could further boost the outdoor air quality improvement in cities. Moreover, other technologies could be included in the analysis, among which also renewable energy sources and district heating. Finally, concerning the socio-economic assessment, future work can be deployed to estimate the local WTP, by submitting ad-hoc surveys to the population of Turin.

References

1. United Nations, Department of Economic and Social Affairs, Sustainable Development, https://sdgs.un.org /, last accessed 2021/05/10.
2. Becchio, C., Crespi, G., Binda, T., Corgnati, S.P.: Air pollution and health effects: review of indicators and evaluation methods, Proceedings of the 15th ROOMVENT Conference - Energy efficient ventilation for healthy future buildings (2021).
3. Assumma, V., Bottero, M., Datola, G., Pezzoli, A., Quagliolo, C.: Climate Change and Urban Resilience. Preliminary Insights from an Integrated Evaluation Framework. In: Bevilacqua, C., Calabrò, F., and Della Spina, L. (eds.) New Metropolitan Perspectives. NMP 2020. Smart Innovation, Systems and Technologies. pp. 676–685. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-48279-4_63
4. Mutahi, A.W., Borgese, L., Marchesi, C., Gatari, M.J., Depero, L.E.: Indoor and outdoor air quality for sustainable life: A case study of rural and urban settlements in poor neighbourhoods in Kenya. Sustain. 13, 1–18 (2021). https://doi.org/10.3390/su13042417
5. D'Alessandro, D., Gola, M., Appolloni, L., Dettori, M., Fara, G.M., Rebecchi, A., Settimo, G., Capolongo, S.: COVID-19 and living space challenge. Well-being and public health recommendations for a healthy, safe, and sustainable housing. Acta Biomed. 91, 61–75 (2020). https://doi.org/10.23750/abm.v91i9-S.10115

6. Underhill, L.J., Milando, C.W., Levy, J.I., Dols, W.S., Lee, S.K., Fabian, M.P.: Simulation of indoor and outdoor air quality and health impacts following installation of energy-efficient retrofits in a multifamily housing unit. Build. Environ. 170, (2020). https://doi.org/10.1016/j.buildenv.2019.106507
7. Becchio, C., Bottero, M.C., Corgnati, S.P., Dell'Anna, F.: Evaluating Health Benefits of Urban Energy Retrofitting: An Application for the City of Turin. In: Bisello A., Vettorato D., Laconte P., Costa S. (eds) Smart and Sustainable Planning for Cities and Regions. SSPCR 2017. Green Energy and Technology. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-75774-2_20
8. Silveira, C., Roebeling, P., Lopes, M., Ferreira, J., Costa, S., Teixeira, J.P., Borrego, C., Miranda, A.I.: Assessment of health benefits related to air quality improvement strategies in urban areas: An Impact Pathway Approach. J. Environ. Manage. 183, 694–702 (2016). https://doi.org/10.1016/j.jenvman.2016.08.079
9. Boesch, H.-J., Kahlmeier, S., Sommer, H., van Kempen, E., Staatsen, B., Racioppi, F.: Economic valuation of transport related health effects: Review of methods and development of practical approaches, with a special focus on children. 150 (2008). https://doi.org/10.5167/uzh-152023
10. Pervin, T., Gerdtham, U.G., Lyttkens, C.H.: Societal costs of air pollution-related health hazards: A review of methods and results, http://www.resource-allocation.com/content/6/1/19, (2008)
11. Saptutyningsih, E., Ma'ruf, A.: Measuring the Impact of Urban Air Pollution: Hedonic Price Analysis and Health Production Function. J. Ekon. Pembang. Kaji. Masal. Ekon. dan Pembang. 16, 146 (2015). https://doi.org/10.23917/jep.v16i2.1459.
12. Caprioli, C., Bottero, M., De Angelis, E.: Supporting Policy Design for the Diffusion of Cleaner Technologies: A Spatial Empirical Agent-Based Model. ISPRS Int. J. Geo-Information. 9, 581 (2020). https://doi.org/10.3390/ijgi9100581
13. European Environmental Agency (EEA): Air quality in Europe – 2018 Report (2018).
14. European Commission, https://ec.europa.eu/energy/topics/energy-efficiency/heating-and-cooling_en, last accessed 2020/04/18.
15. Silvera, C., Lopes, M., Roebeling, P., Ferreira, J., Costa, S., Teixeira, J.P., Borrego, C., Miranda, A.I.: Economic Evaluation of air pollution impacts on human health: an overview of applied methodologies. WIT Transaction on Ecology and The Environment, 198, 181-192 (2015).
16. European Commission: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of Regions, The European Green Deal, COM/2019/640 final (2019).
17. Napoli, G., Barbaro, S., Giuffrida, S., Trovato, M.R.: The European Green Deal: New Challenges for the Economic Feasibility of Energy Retrofit at District Scale. In: Bevilacqua C., Calabrò F., Della Spina L. (eds) New Metropolitan Perspectives. NMP 2020. Smart Innovation, Systems and Technologies, vol 178. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-48279-4_116
18. D'Alpaos C., Bragolusi P. (2019) Prioritization of Energy Retrofit Strategies in Public Housing: An AHP Model. In: Calabrò F., Della Spina L., Bevilacqua C. (eds) New Metropolitan Perspectives. ISHT 2018. Smart Innovation, Systems and Technologies, vol 101. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-92102-0_56
19. Gabrielli, L., Ruggeri, A.G.: Developing a model for energy retrofit in large building portfolios: Energy assessment, optimization and uncertainty. Energy Build. 202, 109356 (2019). https://doi.org/10.1016/j.enbuild.2019.109356

20. Dell'Ovo, M., Frej, E.A., Oppio, A., Capolongo, S., Morais, D.C., de Almeida, A.T.: FITradeoff method for the location of healthcare facilities based on multiple stakeholders' preferences. In: Lecture Notes in Business Information Processing. pp. 97–112. Springer Verlag (2018)
21. Ballarini, I., Corgnati, S.P., Corrado, V.: Use of reference building to assess the energy saving potentials of the residential building stock: The experience of TABULA project. Energy Policy 68, 273-284 (2014).
22. Marisha, S., Sunarya, S., Yustiana, Y.: Economic valuation on carbon sequestration and carbon stocks at green open space based on cost of illness. IOP Conf. Ser. Earth Environ. Sci. 528, 012035 (2020). https://doi.org/10.1088/1755-1315/528/1/012035
23. Jo, C.: Cost-of-illness studies: concepts, scopes and methods. Clinical and Molecular Hepatology 20(4), 327-337 (2014).
24. Grattini, L., Ghislandi, S., Tediosi, F.: L'inclusione dei costi indiretti nella valutazione economiche: la situazione italiana. Centro di economia sanitaria (2000).
25. Martuzzi, M., Mitis, F., Iavarone, I., Serinelli, M.: Health impact of PM10 and Ozone in 13 Italian cities. World Health Organization Regional Office for Europe (2007).
26. Hurley, F., Hunt, A., Cowie, H., Holland, M., Miller, B., Pye, S., Watkiss, P.: Service contract for carrying out cost-benefit analysis of air quality related issues, in particular air for European (CAFÉ) program. Methodology for the cost-benefit analysis for CAFÉ, Volume 2: health impact assessment, AEA Technology Enviroment (2005).
27. ISTAT Statistics, http://dati.istat.it/Index.aspx?QueryId=18540, last accessed 2021/03/25.
28. ISTAT Statistics, http://dati-censimentopopolazione.istat.it/Index.aspx?DataSetCode=DICA_EDIFICIRES, last accessed 2021/03/25.
29. Corrado, V., Ballarini, I., Corgnati, S.P.: Building Typology Brouchure - Italy, Fascicolo sulla tipologia Edilizia Italiana (2014).
30. European energy agency. EMEP/EEA air pollutant emission inventory guidebook 2019 (2019).
31. ISPRA Istituto Superiore per la Protezione e la Ricerca Ambientale, http://www.sinanet.isprambiente.it/it/sia-ispra/serie-storiche-emissioni/fattori-di-emissione-per-le-sorgenti-di-combustione-stazionarie-in-italia/at_download/file, last accessed 2020/03/25.
32. Prezzario Regione Piemonte, https://www.regione.piemonte.it/web/sites/default/files/media/documenti/2018-10/tariffario_prestazioni_ricoveri_rp.pdf, last accessed 2020/03/31.
33. Prezzario Regione Piemonte, https://www.regione.piemonte.it/web/sites/default/files/media/documenti/2018-10/tariffario_prestazioni_specialistiche_rp.pdf, last accessed 2020/03/31.
34. Agenzia Italiana del Farmaco (AIFA), https://www.aifa.gov.it/storico-liste-di-trasparenza, last accessed 2020/03/31.
35. Agenzie delle Entrate, https://www.agenziaentrate.gov.it/, last accessed 2020/04/20.
36. Ostro, B., Feng, W.Y., Broadwin, R., Green S., Lipsett, M.: The effect of components of fine particulate air pollution on mortality in California: results from CALFINE. Environmental Health Perspectives, 115 (1), 13–19 (2007).
37. Bertini, I., Federici, A.: Analisi e risultati delle policy di efficienza energetica del nostro paese. Rapporto Annuale Efficienza energetica (2019).