ScienceDirect

IFAC PapersOnLine 51-5 (2018) 102–107

Integrating Economy, Energy, Air Pollution in Building Renovation Plans

Giorgio Guariso*, Matteo Sangiorgio**

Department of Electronics Information and Bioengineering, Politecnico di Milano, Via Ponzio 34/5, 20133 Milano, Italy

**Tel: 02 2399-3559; e-mail: giorgio.guariso@polimi.it).*
*** e-mail: matteo.sangiorgio@polimi.it)*

Abstract: Residential buildings represent a considerable portion of the energy demand of a temperate country. Old European regions, where most of the buildings were often built in periods of low energy prices, have a large margin for improvement. The study shows how energy saving measures can be optimally planned at regional level, taking into account the specific features of the building stock, and what the consequences of an optimal choice are in economic and environmental terms.

Keywords: Building renovation, Air pollution, Air quality planning and control, Machine learning for environmental applications, Large scale optimization problems

1. INTRODUCTION

Residential buildings represent, as it is well known, a considerable portion of the energy demand of a temperate country. This has obvious consequences also in terms of economic and environmental costs. This is particularly true in old European countries where most of the buildings were built in periods when the attention to energy saving and pollutant emissions was much lower than today.

According to the energy budget of the Lombardy Region (Sirena, 2012), for instance, the energy consumption of residential buildings constituted 31% of the overall energy used in the region in 2012. Accordingly, this sector was responsible for 40% of PM_{10}, 9% of NO_x and 20% of CO_2 equivalent emissions. Quite similar results emerge from the emission inventory of Emilia-Romagna region: CORINAIR macro sector 2 (non-industrial combustion) is responsible for 52% of PM_{10} emissions, 8% of NO_x and 31% of CO_{2eq} emissions (INEMAR, 2014).

The situation is critical since domestic heating emissions are mainly located in urban areas and at low levels (normally few tens of meters). Thus they remain in the local atmosphere producing a relevant impact on citizens and their health.

One immediate measure, that is often adopted when critical pollution level are reached, is to impose a reduction of the heating temperature within buildings in order to reduce the consequent emissions. Such a measure is adopted when the limits for pollution defined by the current European regulations are reached. This happens frequently in the coldest winter period when the air over the Padana plain is particularly stable. Other measures are however possible and consist in renovating the particularly old building stocks introducing energy efficiency measures. In this case, the problem is to determine the best type and diffusion of such reduction measures. The problem has been addressed many times in the literature with reference to the individual building (e.g. Machairas et al., 2014; Evins, 2013; Hamdy et al., 2013; Kurnitski et al., 2011) and many software packages allow an optimal determination of the insulation measures to adopt (see, for instance, the list of about 200 software tools on www.buildingenergysoftwaretools.com). Recently, the problem has been dealt with at city level (De Miglio et al., 2017; Yamagata and Seya, 2013; Kostevšek et al., 2013), but much more rarely at a regional level (an exception is perhaps, Brandoni and Polonara, 2012). Regional plans must indeed evaluate all the consequences of alternative renovation options considering both GHG emissions and those of local pollutants, i.e. PM_{10} and NO_x, and their impacts on the overall air quality.

This study addresses the last problem in three steps: first, on the basis of a large set of detailed building data, the trade-offs between energy savings and their implementation costs are determined by repeatedly solving a linear programming problem. Second, a classical cost-benefit analysis has been performed to select the best type and spatial diffusion of energy saving measures in the region. Third, the correspondent reductions of CO_2 and classical pollutants are computed and their distribution over the regional territory is evaluated. The study considers in particular the Lombardy region, which is characterized by a high number of residential buildings (about 1.5 million) and where exceedances of pollution limits are frequent.

The paper is organized as follows: the next section revises the situation of the residential building stock in the region and explains the type of energy saving measures taken into consideration. Section 3 formulates the cascade of three problems outlined above, while results are presented in the following section. Limits and possible extensions of the procedure are discussed in the concluding section.

2. DETAILED DATA ON BUILDINGS

The Directive 2012/27/EU of the European Parliament and of the Council on energy efficiency foresees that “Member

2405-8963 © 2018, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2018.06.218

States shall establish a long-term strategy for mobilizing investment in the renovation of the national stock of residential and commercial buildings, both public and private. This strategy shall encompass: (a) an overview of the national building stock based, as appropriate, on statistical sampling; (b) the identification of cost-effective approaches to renovations relevant to the building type and climatic zone; (e) an evidence-based estimate of expected energy savings and wider benefits."

To comply with this and preceding directives, Lombardy region has approved a series of regulations (the latest of which is the D.g.r. 17 July 2015 - n. X/3868 "Provisions on the energy efficiency discipline buildings and the relative certificate of energy performance") to check and improve the energy situation of buildings. Among these regulations is the creation of an open catalogue of energy performance certificates (APE, in the Italian acronym) where all the characteristics of a building from the energy point of view are stored, as assessed by a certified technician. The interest of such a database, named CENED, is that it also includes the suggested energy saving actions with an estimate of their cost and foreseen benefit in terms of reduced energy use.

More precisely, for the purpose of this study, three possible actions have been considered:

- A thermal insulation of the opaque building envelope
- A change of windows material which reduces the heat loss from the home
- A full restructuring of the building including the two preceding actions.

The database presently includes a complete energy analysis of more than 400,000 dwellings and non-residential building thus representing a large sample of the regional building stock.

More than 150,000 records represent residential houses. They were thus considered as a sufficient numerical base for the current study.

A simple summary of these data is sufficient to provide a general picture of the current regional situation. For instance, the number of buildings with only one dwelling (single family houses) represent the 42% of the total, which perfectly agrees with the general data of the National Statistical Institute (ISTAT, 2011), 16% of the sample refers to buildings with three to eight flats while 34% are houses with more than eight flats.

Figure 1 shows the distribution of building ages of the sample: 11% of the stock dates back to years prior to the '30s and only 4% is after 2006, i.e. it was built under the most recent energy saving regulations. The '60s were the period of more intense construction activity and coincides with the fastest economic development. The pressure for cheap new houses induced a rush to new constructions not paralleled with an attention to their environmental impact. Buildings from that period still constitute the 31% of the total stock.

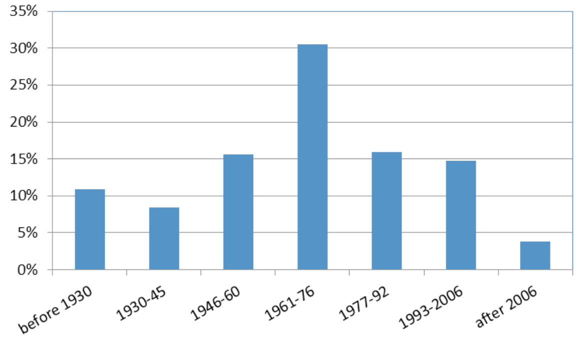

Fig. 1. Age distribution of the sample of the building stock in Lombardy.

Indeed, as shown in figure 2, the median of the energy consumption in residential buildings is around 180 kWh/m^2 per year, with 26% using between 180 and 270 kWh/m^2 per year and 24% exceeding the last value. This is a clear indication of how inefficient the energy use is. In fact, more than half (about 51%) of the houses in the sample belongs to the G class (the least efficient, which corresponds to the use of 16 m^3 of methane per square meter per year). A renovation of the stock is thus not only possible, but also highly desirable for the strong improvement it may entail in both the use of energy and the air pollution.

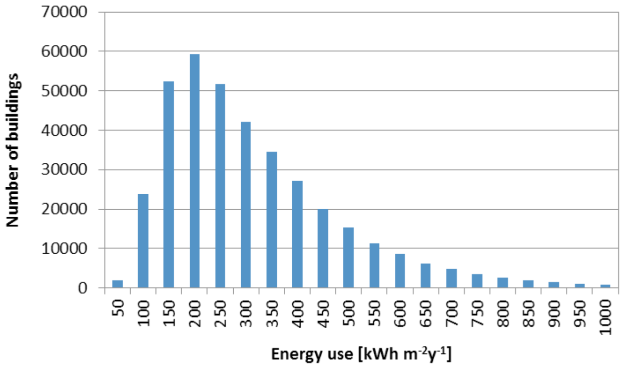

Fig. 2. Distribution of the energy consumption in the sample.

2.1 A subdivision of the building stock

To better manage the overall planning process, the building stock has been subdivided into a number of classes (or archetypes) as already done in various European projects such as EPISCOPE (Stein et al. (eds.), 2016) or InSMART (Gargiulo et al., 2017) and corresponding to some of the characteristics assessed by the National Statistical Institute. These characteristics are:

- Construction year: the 7 different classes shown in figure 1 were used;
- Number of dwellings: 4 classes: 1, 2, 3-8, more than 8;
- Sub-region (or Province): grouped into 6 classes to take into account different construction traditions;

- Elevation: 2 classes, below and above 600 m a.s.l. since the construction characteristics in the mountains have always been quite peculiar.

In the end, a total of 224 classes of buildings is generated, since some of the sub-regions only have one elevation level. This means that each class is represented in the sample by an average of about 700 instances, even if of course there are case for which the number of building reduces to few tens (typically, in the post 2006 class).

Each class is also characterized by the cost and possible advantages of implementing an improved insulation of walls and/or windows. More precisely, the investment cost, the reduction in energy use, and the consequent reduction of GHGs emission can be computed from the available data.

The total number of buildings of each class actually present in the territory is derived from the national statistics for each municipality. The municipality in turn belongs to a given province and has an average elevations; this allows the extrapolation of the values obtained from the CENED database to the global building stock of the region.

2.2 *Determining the joint effect of two actions*

Unfortunately, the consequences of adopting both the actions on the walls and on the windows are not always reported in the database. The full restructuring activity is obviously more efficient than the two separate actions on walls and windows, but is normally slightly less efficient than the sum of the two. This is confirmed by all the detail studies catalogued for instance in the TABULA project.

In order to evaluate the joint effects of both the walls and the windows actions, instead of developing 224 separate functions, we developed three feed-forward artificial neural networks (ANNs). Given the categorical inputs defining the class of the building and the separate effects of the walls and the window actions, they compute the energy savings, the investment cost, and the annual savings respectively (see for instance, Nguyen et al., 2014).

Such an approach, that closely follows that proposed by Magnier and Haghighat (2010), gave excellent results as shown by the scatterplots in figure 3.

The identification set is composed of 19,800 samples. 70% of the cases were used to train the ANNs, 15% composes the cross validation set, and the remaining 15% represents the test set. The correlation between actual values and reconstructed ones was always above 0.98. Considering energy saving and investment cost, the result obtained are similar to those shown in figure 3 for the money saving.

3. OPTIMAL PLANNING PROBLEM

Given the information described above, we formulate here the optimization problem that shows the trade-off between investment costs and energy reduction at the regional level.

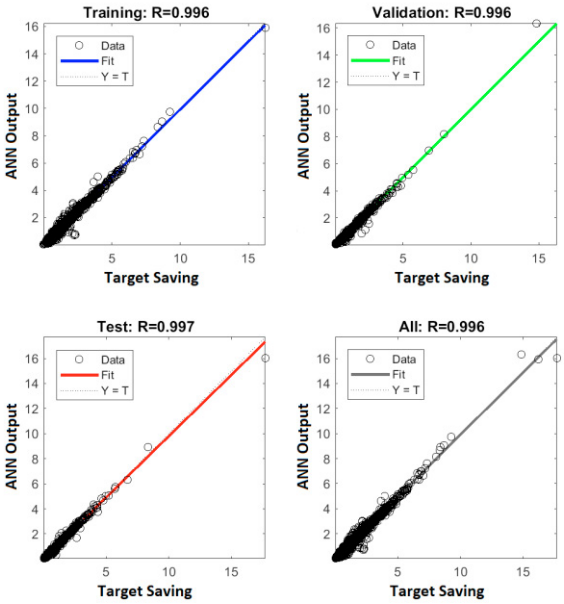

Fig. 3. Scattergrams of the training, cross validation and test results for the annual savings (k€) corresponding to full restructuring.

We will assume, as normally done in air quality plans (see Guariso and Volta, 2017), that the decision variables are the number n_{ij} of buildings in each class i that adopt the action j. These values are sometimes referred to as "application rates" of the improvement action (Guariso et al., 2016). The objectives of the problem to be optimized are the global investment cost and the energy reduction. The first must be minimized and the second maximized. We can thus write:

$$OptJ = \left[\min \sum_{i,j} c_{ij} \cdot n_{ij} \qquad \max \sum_{i,j} r_{ij} \cdot n_{ij} \right] \tag{1}$$

Where c_{ij} is the investments cost and r_{ij} the energy reduction deriving from the adoption of action j on a building of class i. Such a problem is subject to the following constraints.

$$\sum_{j} n_{ij} \le N_i \quad \forall i \tag{2}$$

Meaning that, in each class i, each building may undergo only either action 1 on the walls, or action 2 on the windows, or action 3, i.e. full restructuring.

$$\sum_{i} n_{ij} \le K_j \quad \forall j \tag{3}$$

Where K_j is the allowable number of actions type j that can be adopted. Not all the buildings can in fact adopt the same measure. K_j is estimated on the base of the fraction of buildings in the CENED database for which action j was recommended. Finally, the traditional non negativity constraints of the decision variables hold.

The Pareto front of this problem is shown in figure 4 and presents an almost linear shape, meaning that the reduction in energy consumption is more or less proportional to the investment in efficiency actions.

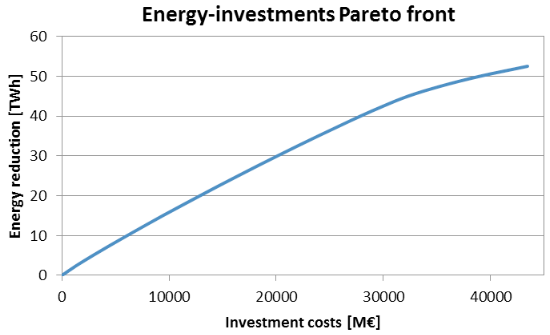

Fig. 4. The trade-off between investment cost and energy reduction.

Perhaps the most important result of this analysis is the value of the upper right point of the Pareto front. It shows that the maximum reduction that can be attained is of the order of 38% of the current use of energy, and this corresponds to a total investment of over 46 billion euros. To put this value in perspective, the GDP of the region is about 360 billion euros.

3.2 *Cost-benefit analysis*

In order to select a meaningful value within the Pareto front, several different approaches are possible. A traditional one is cost-benefit analysis, which is very close to the point of view of the individual citizens (who should pay for the investment in energy saving actions). Direct benefits are the annual reduction in the energy bills, consequent to the reduced use of fuels. These reductions are always positive since the CENED database reports the time needed to recover the initial investment and this averages around 12 years for action 1, and 20 years for action 2. They occur in time and thus, to be fairly compared with the cost, must by actualized with the traditional formula of the net present value (Kurnitski et al., 2011). To adopt it, one has to fix the temporal horizon and define the discount rate. For the current study, we adopted 15 years and 4%, i.e. something close to real estate loans. An extensive sensitivity analysis around this value has not shown significant variations of the results.

We can thus formulate the cost benefit problem as:

$$\max\,[B(R) - C(R)] \tag{4}$$

Where the decision variable is the global energy reduction *R*, and *B(R)* and *C(R)* are the correspondent total actualized benefit and total investment costs. This net benefit function is reported in figure 5 and shows that the optimal choice is to select not a full adoption of the energy saving measures, but something which is approximatively around two third of the maximum.

This situation corresponds to the adoption of action 1 (i.e. wall insulation) on about 60% of the buildings and of action 3 (combination of action 1 and 2) on about 5%. It would require an investment of 24.6 G€, saving about 36 TWh per year. Action 1 should be implemented on about 80% of the houses built between 1930 and 1976; 58% of those built between 1977 and 1992; 33% of those built after 1992 and before 2006, and only 8% of those built later. About one fourth of action 1 should take place in municipalities above 600 m of elevation, despite these houses represent only 11% of the total stock.

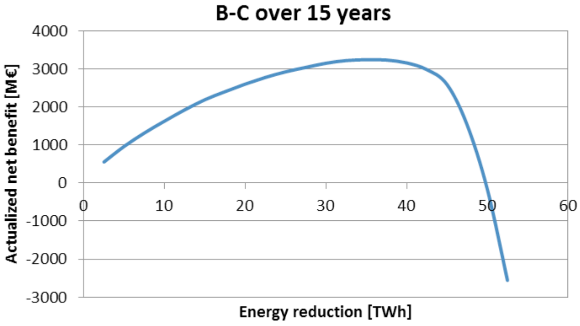

Fig. 5. The net benefit curve.

It is interesting to note that action 2 (i.e. windows replacement) is never taken into account. It is recommended only few times (5%) in combination with wall insulation, and this produces a decreasing in the derivative of the Pareto front represented in figure 4. These facts prove that windows replacement has a low benefit-investment ratio.

3.3 *Environmental impacts*

The set of decisions corresponding to the maximum difference between benefits and costs, can also be evaluated under the perspective of environmental impacts. These are of two different types: greenhouse effect, represented by the reduction of CO_{2eq} emissions, and health related, that can be measured by the reduction of emission of traditional pollutants such as PM_{10} and NO_x.

As to GHGs emissions, their calculation is straightforward, since they are directly related to the reduction of energy use. The regional emission inventory (INEMAR, 2014) estimates in 10.7 Mt CO_{2eq} per year the emission from residential buildings. The energy reduction corresponding to the economically most convenient choice means a decrease of 2.7 Mt per year or about 4% of the overall GHGs emission of the region (domestic heating being just 15% of regional CO_2 emissions).

Local pollution can be evaluated in the same way. Given that the current emission estimate for PM_{10} and NO_x are respectively 7170 t and 8073 t per year, the adoption of the measures outlined above would entail a reduction of about 1700 and 1750 t per year for PM_{10} and NO_x. This is particularly significant for PM_{10}, since it would represent almost 10% of the total regional emission. However, these values are not sufficient to understand the complete consequences of the plan. It is in fact important also to determine where these reductions are located and thus what is their impact on the overall air quality of the region.

For this purpose, we have to map the set of decisions computed above on the building stock of each municipality, and compute in this way the reduction with respect to the emission in the regional inventory. Figures 6 and 7 show the result of this operation for PM_{10} and NO_x, respectively. It clearly emerges that emission reduction is not uniform over the territory. For instance, the relatively small province of

Milan accounts for 17.5% of the reduction of NO_x since it is densely built and served by a capillary methane network. On the contrary, the provinces of Bergamo and Brescia, where the tradition of burning wood for domestic heating is more diffused account respectively for 17 and 21% of the PM_{10} reduction.

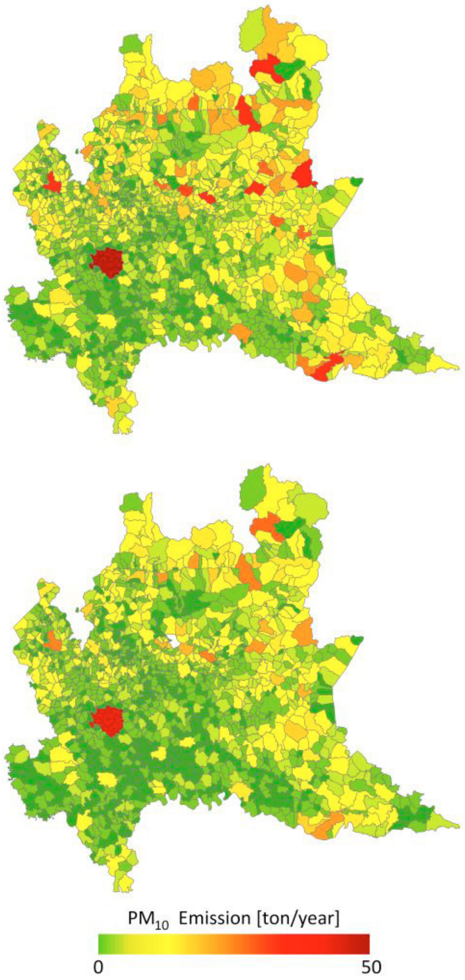

Fig. 6. Municipal emissions of PM_{10} before (top) and after (bottom) the reduction.

4. CONCLUSIONS

The problem dealt with in this study could, in principle, be formulated as a complete benefit-cost analysis. The economic value of the avoided GHGs emissions (for instance, by referring to its value on the emission market) and the decrease in human health problems due to reduced pollution concentration can also be considered. However, it should be noted that these indirect economic effects are generally lower than the direct savings due to the reduced use of fuels (see for instance, Chae and Park, 2011).

The possible energy saving actions considered in this study are not the only contribution that the building sector can provide to a complete energy and environment plan. A change of the heating system as well as an increased use of renewable source (specifically, photovoltaic and thermal panels) may play an important role in the overall energy system. However, dealing with this type of changes requires a number of additional assumptions that may take the study outside the current scope. On the contrary, the reductions computed here, since they refer only to the passive behaviour of the building envelope, are somehow granted. Though depending in part from the specific meteorological conditions of each year, they should certainly be undertaken.

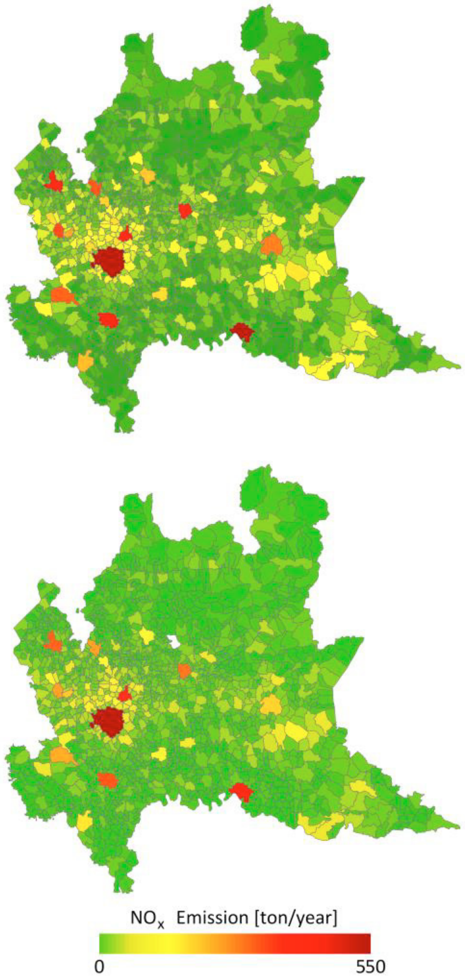

Fig. 7. Municipal emissions of NO_x before (top) and after (bottom) the reduction.

One of the reasons why they are not being applied so widely is the large initial investment required. The current Italian legislation provides a subsidy to energy saving measures as a 65% reimbursement of the investment in terms of reduced taxes over a ten year period. However, since the investment is of the order of tens of thousands of euros per flat or house, in an economic situation like the current one, the availability of the necessary capital still constitutes a relevant barrier. New forms of bank loans could be possible to overcome this problem and may constitute a win-win solution since they can be effective for both the economic and the environmental points of view.

REFERENCES

Brandoni, C., Polonara, F. (2012). The role of municipal energy planning in the regional energy-planning process, *Energy*, 48, 323-338.

Chae, Y., Park, J. (2011). Quantifying costs and benefits of integrated environmental strategies of air quality management and greenhouse gas reduction in the Seoul Metropolitan Area, *Energy Policy*, 39, 5296-5308.

De Miglio, R., Chiodi, A., Burioli, S., Giovannini, E., and Gargiulo, M. (2017). Exploring integrated energy action plans for a sustainable transition of the municipality of Cesena, *Procedia Engineering*, 198, 541-548.

Evins, R. (2013). A review of computational optimisation methods applied to sustainable building design, *Renewable and Sustainable Energy Reviews*, 22, 230-245.

Gargiulo, M., Chiodi, A, De Miglio, R., Simoes, S., Long, G., Pollard, M., Gouveia, J.P., and Giannakidis, G. (2017). An integrated planning framework for the development of sustainable and resilient cities – the case of the InSMART project, *Procedia Engineering*, 198, 444-453.

Guariso, G., Maione, M., Volta, M. (2016).A decision framework for Integrated Assessment Modelling of air quality at regional and local scale, *Environmental Science & Policy*, 65, 3-12.

Guariso, G. and Volta, M. (2017). *Air Quality Integrated Assessment, A European Perspectives*. Springer International Publishing.

Hamdy, M., Hasan, A., and Siren, K. (2013). A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010, *Energy and Buildings*, 56, 189-203.

INEMAR (2014). INventario EMissioni Aria, (in Italian). Avalable at: http://www.inemar.eu. Last accessed Jan. 2018.

ISTAT (2011). Censimento Popolazione e Abitazioni 2011 (in Italian). Available on http://dati.istat.it. Last accessed Jan. 2018.

Kostevšek, A., Petek, J., Čuček, L., and Pivec, A. (2013). Conceptual design of a municipal energy and environmental system as an efficient basis for advanced energy planning, *Energy*, 60, 148-158.

Kurnitski, J., Saari, A., Kalamees, T., Vuolle, M., Niemelä, J., and Tarke, T. (2011). Cost optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA definition for nZEB national implementation, *Energy and Buildings*, 43, 3279-3288.

Machairas, V., Tsangrassoulis, A., and Axarli, K. (2014). Algorithms for optimization of building design: A review, *Renewable and Sustainable Energy Reviews*, 31, March, 101-112.

Magnier, L., and Haghighat, F. (2010). Multiobjective optimization of building design using TRNSYS simulations, genetic algorithm, and Artificial Neural Network, Building and Environment, 45, 739-746.

Nguyen, A-T., Reiter, S., and Rigo, P. (2104). A review on simulation-based optimization methods applied to building performance analysis, *Applied Energy*, 113, 1043-1058.

Regione Lombardia (2015) Piano Regionale degli Interventi per la qualità dell'Aria (PRIA), (in Italian). Avalable at: http://www.regione.lombardia.it. Last accessed Jan. 2018.

Sirena (2012). Sistema Informativo Regionale ENergia Ambiente, (in Italian). Avalable at: http://sirena20.energialombardia.eu. Last accessed Jan. 2018.

Stein, B., Loga, T., and Diefenbach, N.(eds.) (2016). Monitor Progress Towards Climate Targets in European Housing Stocks - Main Results of the EPISCOPE Project, Institut Wohnen und Umwelt GmbH, Darmstadt, Germany.

Yamagata, Y., Seya, H. (2013). Simulating a future smart city: An integrated land use-energy model. *Applied Energy*, 112, 1466-1474.