Valuing the Cost of Delayed Energy Actions

G. Guariso* M. Sangiorgio*

*Department of Electronics, Information, and Bioengineering, Politecnico di Milano, Milan, I-20133 Italy
(e-mail: giorgio.guariso, matteo.sangiorgio@polimi.it)

Abstract: Most of the building stock in Europe and, in particular, in Lombardy, North of Italy, were built without sufficient attention to energy efficiency. It must be restructured to spare energy, fuel costs, and emissions of traditional pollutants and GHGs. The paper defines an optimization problem that determines the most cost-effective interventions and where they should be actuated, considering different scenarios of evolution of economy and technology. The results are compared with real data, showing that the current pattern of adoption of energy-saving measures is definitely slower than desirable. The economic loss due to such a delayed adoption may reach billions of euros.

Keywords: Climate change impact and adaptation measures, Environmental decision support systems, Air quality planning, Building Stock Renovation, Regional Energy Planning.

1. INTRODUCTION

Planning the restructuring of the building stock at regional scale is fundamental in order to quantify the incentives or taxes that the authorities must adopt to foster a more efficient and environmentally friendly transition. It is a complex task since it requires to estimate the investment costs of each restructuring action, comparing them with the related energy savings, which produce economic (energy and environmental) benefits in the following years. An efficient solution to this problem would turn out to be crucial in particular in those countries where the majority of the buildings were built in periods when the concern about issues such as energy-saving and air pollution were much lower than today. This happened for instance in Europe, where the current energy performance of the residential building stock are far from optimal levels (Hermelink, 2009). For this reason, in the last decade, the European Commission proposed some measures which aim at gradually moving from current levels to cost-optimal levels for the energy performance of new and existing buildings (European Parliament, 2009).

The planning of energy-saving measures is traditionally formulated in terms of net present value: costs incurred and benefits produced within the project horizon are actualized in order to account for the value of the investments. Considering a traditional investment project where a single action must be evaluated, the investment costs are concentrated at the beginning of the planning horizon, while the benefits are distributed along the considered period. This is not realistic when a multiplicity of individual actors is involved as in the context of residential building stock renovation. The authorities cannot impose to the individual owners the timing or the magnitude of the restructuring actions. The main way the government has to steer the renovation process is thorough market-based policy instruments (taxes and incentives), that drive a progressive adoption of efficiency measures.

In the recent years, the problem of valuing the effects and costs of delaying energy-related actions has been debated by many authors. Most of these works focus on a global scale, stating the importance of adopting early energy measures in order to meet the international climate agreements (see, for instance: van Vliet et al., 2009; Bosetti et al., 2009a; Bosetti et al., 2009b; Krey et al., 2009; Jakob et al., 2012; Luderer et al., 2013; Tokimatsu et al., 2018; Chen et al., 2020). Some other papers deal with the optimal restructuring of a single building (Kumbaroğlu and Madlener, 2012; Matschoss et al., 2013; Cho and Yoon, 2015; Desideri and Asdrubali, 2019) and only a few tackle the problem at the local scale (e.g., Kurnitski et al., 2014; Friedman et al., 2014), which is the proper spatial resolution to efficiently consider financial, energy and environmental aspects, as discussed in Guariso and Sangiorgio (2018).

Additionally, most studies on the cost of delaying environmentally-friendly measures are simply based on the comparison of alternative scenarios selected externally (e.g., OECD, 2012; Semprini et al., 2017; Yang et al., 2019). In this paper, we propose a methodology that allows to quantify the economic and environmental costs of delaying the adoption of the restructuring with respect to the endogenously computed situation where the most efficient actions are progressively deployed in time or are all implemented at the beginning of the planning period.

We consider as a case-study the Lombardy region (Northern Italy), which is well known for the severity and frequency of air pollution episodes especially in winter, when residential heating is in operation and the meteorological conditions (stability of the atmosphere and lack of wind) prevent a significant pollutants dispersion (Vecchi et al., 2004; Vecchi et al., 2007). A recent study by Caserini et al. (2017) concluded that the situation will be even worse in the future due to the effects of climate change. For this specific case, we estimate the difference between the renovation process actually taking place in the region (almost 80,000 actions every year), and a more efficient one, where the same number of actions are selected maximizing their energy and environmental benefits. Finally, the proposed method allows to determine the

improvement the energy-saving technologies should have in the future to make the current policy as efficient to the best one.

2. MATERIAL AND METHODS

2.1 Lombardy Building Stock Data

We consider four different datasets to determine the value of energy-saving policies.

CENED (http://www.cened.it/dati-cened) is an open dataset developed by the regional authority that contains about 850,000 (as of April 2020) detailed reports on the energy characteristics and performances of dwellings in the region. The reports are compiled by certified assessors and suggest restructuring actions with the related investment cost and the foreseen energy savings. An analysis of such reports (which cover about 16% of the residential building stock) confirms that the improvement of the external shell of existing buildings offers, in principle, a huge saving potential. This is a common situation all over Europe and it has been estimated that an annual 60 Mtoe/year can be spared by 2030 for the EU27 (Lechtenböhmer and Schüring, 2011). Using data from the CENED sample, the residential building stock of the region has been subdivided into 73 classes of buildings that differ from the energy viewpoint. These classes are defined taking into account the geographical location, the age, and the number of dwellings of the houses.

ENEA (http://www.acs.enea.it/), the National Italian Agency for Alternative Energies, collects and analyses the actual implementation of energy-saving measures for the entire country and for individual regions. Figures about the actual situation of the renovation process are published every year. This dataset contains the number, type, and cost of energy-saving actions, classified by type and age of buildings. It was mandated by the national government to check that the tax discounts entitled for energy-savings were documented and justified.

ISTAT (www.istat.it), the Italian National Statistical Institute, provides a classification of all residential buildings in each of the more than 1,500 municipalities of the Lombardy region, catalogued by age and size. It was compiled with 2011 census data and allows the extrapolation of the CENED sample to the whole regional building stock.

INEMAR (www.inemar.eu) is the regional air emission inventory and contains 2017 emission values for each pollutant and each emission source (domestic heating, in the present case) for each municipality.

2.2 Scenarios to 2035

To evaluate the differences between alternative policy choices in the future, it is necessary to make some assumptions about the external conditions. Three parameters may reasonably be assumed to vary: the price of fuels, the values of CO_2 emissions, and the efficiency of the energy-saving technologies. These variations may combine in many different ways, and only few will be analyzed here.

The price of methane, the heating fuel used by almost all residential buildings in Lombardy, has been oscillating in the past ten years with a peak in 2012 and a minimum in 2016, with a moderate overall increasing trend.

On the other side, the value of CO_2 emissions, at least as portraited by its price on the European emission market, had an increase of about 15 €/t, in the last five years (see: Fig.1). One can thus assume, for instance, that a possible scenario is a similar increase in the future that starts from the current value of about 25 €/t and reaches 70 €/t in 2035. In countries where an emission market does not exists, such as the US, the value of CO_2 emission can be estimated by looking at the social cost. US EPA (2016) used three integrated models to assess possible future values of CO_2 emission, They account for the foreseen consquences of climate change, including damages in terms of agricultural productivity, human health, and property from increased flood risk, and consider reduced costs for heating and increased costs for air conditioning. The value estimation for 2035 depends on the actualization rate adopted and varies between 55 and 78 \$/t for rates of 3% and 2.5%, respectively (Marten et al.; 2014). Other estimates (e.g., Ricke at al., 2018) suggest much higher values at global scale.
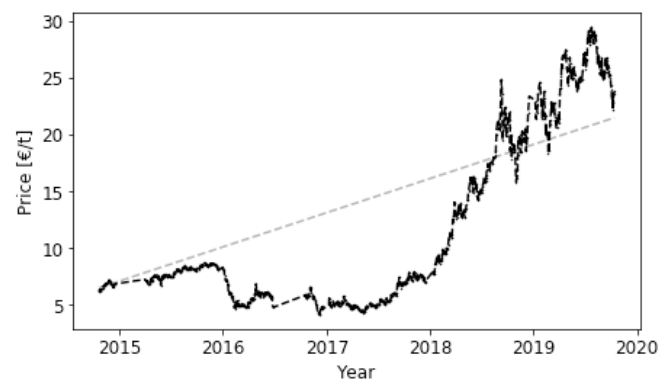

Fig. 1. CO_2 price (black line)on the Europen Emission Market, and linear trend (grey dashed line) (data from: https://markets.businessinsider.com) .

The efficiency of the energy-saving measures has not significantly changed in the last ten years, according to ENEA data, and assuming any modification is somewhat arbitrary. However, one may solve the inverse problem of determining what should the improvement in efficiency be to reach a certain energy or emission target.

Interestingly, both the increase of the price of fuels and of CO_2 point toward an earlier implementation of measures, since both trends favour a rapid adoption instead of a postponed one. We will thus analyse only two scenarios: a constant value of CO_2 (Scenario 0) and an increasing value (Scenario 1). In case of increasing prices of fuels, the differences between the two scenarios will be amplified.

2.3 Policy Implementation

The implementation of the energy-saving plan for residential buildings can follow different paths.

The one-shot policy, that we will adopt for comparison, is the full and contemporary adoption of all the measures necessary

to reach an efficient compromise between costs and energy reduction, with the consequent environmental effects. Such a policy is clearly the best from the environmental viewpoint, but would imply a very large expenditure at the beginning of the planning horizon and the possibility, for the competent authority, of defining exactly what measures to implement and where. This is probably not politically acceptable since it is well known that, even when imposing strict regulations, they cannot be too different among different groups of citizens. Furthermore, experience shows that the preferred instruments for policy implementation are incentives and promotional campaigns rather than ordinances.

The first option we will examine is to proceed for the next, say, 15 years in the same way adopted until now: the so-called "business as usual" or BAU policy, as emerging from ENEA data. This policy is determined by the presence of a tax reduction proportional to the expenses for measure adoption, but it is left to the individual choice of citizens which measure to implement. We can easily assume that such measures have a positive actual value for each house owner (otherwise, nobody would implement them), but they do not necessarily represent the most convenient choice for society. Additionally, measures are valued taking into account the tax reduction, which represents a simple transfer of money within the society, and without accounting for their effects in terms of local pollution and/or climate change.

The other group of policies we consider lies between the previous two. The authorities can foster (or impose) the adoption of specific measures in a progressive way (year-by-year), so to ease their implementation, avoiding a shock for the regional economy, even if it is economically and environmentally convenient. Policies in this group may differ in the amount of investment that should be actuated every year and in the target they address. For instance, it can be decided to first act in a certain area or on a certain category of buildings.

If an optimal one-shot policy exists, all the other paths would represent a less convenient option because they imply deferred benefits and costs, where the first are always greater than the second. The purpose of this study is to determine how large is the economic and environmental difference between these different policies, to support decisions about the effort that authorities should make to stimulate the adoption of the correct energy-saving actions.

2.4 The Planning Problem

The one-shot optimal policy can be determined by solving a mathematical programming problem formulated in the following way. Let n_{ij} be the number of buildings in each class i that adopt the measure j. These values constitute the decision variables of the problem (see: Guariso and Sangiorgio, 2019). The objective is to optimize the sum of measure implementation cost and of the savings due to energy and emission reductions. Implementation costs are assumed to be paid all at the beginning of the planning period, while savings last for the whole planning horizon and must be actualized with the classical formula of net present value (NPV). Thus:

$$\max_{\{n_{ij}\}} J = -\sum_{ij} c_{ij} \cdot n_{ij} + \sum_t \frac{\sum_{ij} b_{ij} \cdot n_{ij}}{(1+r)^t} \qquad (1)$$

Where c_{ij} is the investment cost and b_{ij} the annual (constant) benefit deriving from the adoption of action j on a building of class i; r is the actualization rate and the summation spans over the years t in the planning horizon, assumed equal to 15 years, i.e, 2021 to 2035. Benefits are due to both the fuel spared and the reduced GHG emission. Although it is widely used in economic analysis, it is well-known that the NPV approach is not able to deal with the uncertainty of future scenarios, as it has been pointed out by Verbruggen et al. (2011) and Menassa (2011). This is the reason why we have examined different price scenarios. However, such an uncertainty probably represents one of the main causes for the delayed application of economically convenient measures, or, saying it in different words, a purely economic approach is not fully representative of the complexity of the real decision process.

The decision variables of the planning problem are subject to a set of constraints, namely:

- The number of measures in each building class i cannot exceed a maximum value N_i

$$\sum_j n_{ij} \leq N_i \quad \forall i \qquad (2)$$

- The number of measures of a certain type j cannot exceed a maximum value M_j

$$\sum_i n_{ij} \leq M_j \quad \forall j \qquad (3)$$

besides being nonnegative values. These two upper limits are set on the basis of the CENED sample: a certain type of action is advisable only on a percentage of the buildings of a given class. The constraint of n_{ij} being integer is disregarded since it makes the solution of the problem much harder and represents a negligible approximation (of the order of less than one building over thousands). Once determined the optimal number of measures for each class of buildings, one can obtain several interesting outputs. For instance, we can compute the emissions of critical pollutants, such as PM10 and NOx, in terms of their spatial distribution. The number of buildings of each class j and the emission of pollutants in each municipality of the region are known and allow the computation of the reduced emissions, once the fuel reduction is defined.

The implementation of the step-by-step policies (including BAU), requires a different definition. The number of implemented measures becomes a function of time, namely $n_{ij}(t)$, and the objective J_y to be evaluated, becomes:

$$J_y = -\sum_t \frac{\sum_{ij} c_{ij} \cdot n_{ij}(t)}{(1+r)^t} + \left[f_{ij}\left(n_{ij}(t)\right) + \sum_t \frac{\sum_{ij} b_{ij} \cdot n_{ij}(t)}{(1+r)^t} \right] \qquad (4)$$

Where $f_{ij}(n_{ij}(t))$ is the final value of the energy-saving investments at the end of the planning period, and the summations extends to the end of the horizon.

Such an objective is simply simulated when the BAU policy is adopted: $n_{ij}(t)$ are substituted by the historical number of measures in each building class, with the consequent costs and savings. When assuming an intermediate policy, where the regional government can push for the adoption of efficient measures, J_y is maximized with the additional constraint:

$$\sum_{ij}[n_{ij}(t+1) - n_{ij}(t)] \le K \quad \forall t. \tag{5}$$

K represents the maximum number of implementations of each year and, in this study, is set to the current number of actions registered in the recent past. In principle, one should also impose that

$$n_{ij}(t+1) \ni n_{ij}(t) \, \forall t \tag{6}$$

meaning that what is implemented in year t remains in place for the following years. However, this is not necessary since the problem is linear, and thus, the most efficient choices in one year remain the most efficient also in the following period.

3. RESULTS

Table 1 summarizes the results of this study for the two different scenarios and the two step-by-step policies in comparison with the optimal one-shot solution.

Table 1. NPV [M€] of energy-saving policies over a 15-year horizon

Policy	Scenario 0 (constant CO₂ price)	Scenario 1 (increasing CO₂ price)
BAU	-700	100
Year-by-year	4,050	5,550
One-shot	5,700	7,500

As it immediately appears, the current trend of application is ineffective since it has a negative regional NPV, despite the convenience of measures for the individual owners. The individual decisions benefit from the tax discount, which is proportional to the measure implementation cost and not to its efficiency. It must be noted that the assumption of continuing exactly the BAU policy for the next 15 years is rather unrealistic since the number of actions foreseen on some building class exceeds the numerosity of the class itself. Nevertheless, these numbers are illustrative of the importance, for the regional government, to accurately direct the renovation efforts. Indeed, the year-by-year policy that concerns the same number of buildings as BAU, but where the actions can be better directed, shows positive and quite different values. In all cases, the NPV values in scenario 1 are higher, despite the CO_2 price increase is partly compensated by the actualization factor, and the optimized policies can better exploit the evolution of CO_2 price.

Needless to say that the one-shot solution dominates the others and is quite effective from the economic viewpoint (all the benefits fall within the planning horizon); even more when considering the increase in CO_2 price. Its drawback is that it is unrealistic since it would require expenditures for almost 30 G€ in a single year, i.e., 8% of the regional GDP.

As already pointed out, each solution (i.e., number and type of restructured buildings) corresponds to a decreased use of fuel and thus to a reduction of pollutant emission, in comparison to the current situation as portraited by the INEMAR emission inventory. Figure 2, for instance, depicts the differences between the policies during the next 15 years in Scenario 1 in terms of NOx emission of the region. The one-shot solution corresponds to an immediate reduction close to 30% of the initial value, while the two progressive policies decrease the emission in time in a linear way. Given that the year-by-year policy optimizes the choices every year, it corresponds to a faster reduction that does not reach the value of the best policy simply because the current yearly number of interventions is below that needed to achieve the one-shot result. The BAU policy also reduces NOx emissions every year, but it covers only about 75% of the possible reduction at the end of the planning horizon.
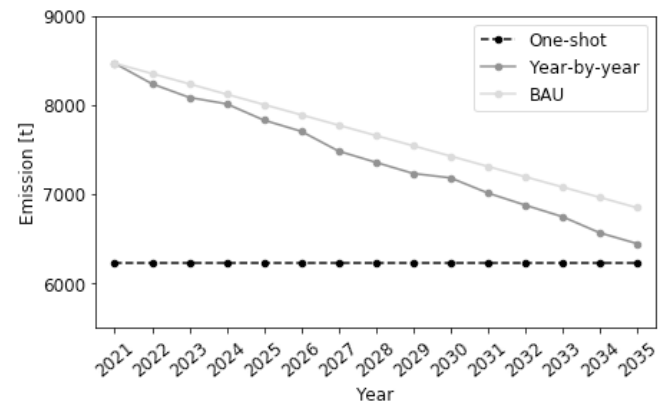

Fig. 2. NOx emission trend for the planning horizon.

Finally, Fig. 3 presents a spatial view of the results, showing where a policy suggests acting more resolutely with respect to another. Precisely, the figure shows where the BAU and year-by-year policies differ after 15 years, in Scenario 1. Values are normalized by the number of inhabitants of each municipality to avoid biases due to the quite different sizes. In the most crowded central area of the region, where most of the energy and emission are concentrated, the two policies are quite similar, i.e., efficient choices have already been actuated in the urban areas and this will continue in the future. On the contrary, the optimized year-by-year policy suggests a stronger action in the upper and lower parts of the region, where small one and two dwellings building are located, particularly if they were built before the '90s when energy legislation was much looser.

As an additional result, we have computed the average increase in efficiency required from new technologies to make the BAU policy perform as the one-shot one. One of the main justification to delay action is in fact that new, more efficient technologies will become available in the future and thus it not worthwhile investing in the present ones. The average efficiency improvement needed to equal the NPV of the BAU and one-shot policy is around 35% in Scenario 0, and even more in Scenario 1, while past data show only a small efficiency increase of some of the measures in the past 10 years. A jump of this size cannot be achieved in a single year and should better represent a continuous improvement. To reach such a performance starting from the current situation, the measures adopted toward the end of the planning horizon should achieve an energy reduction of the order of 70-80%. It seems quite an improbable occurrence.
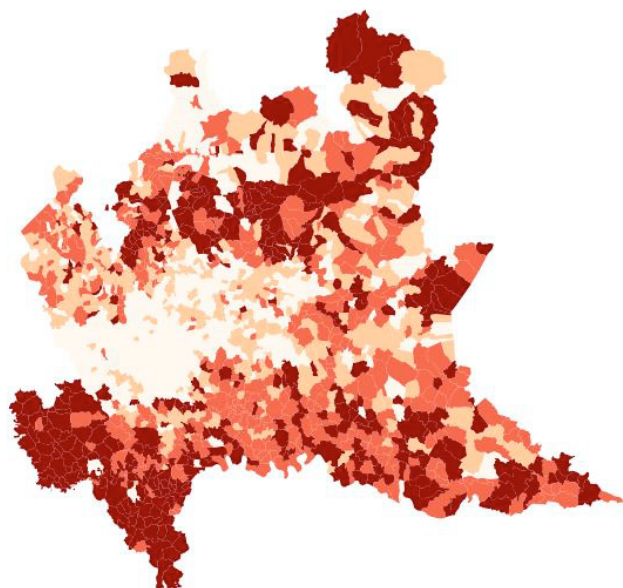
Fig. 3. Difference of CO_2 emissions per capita between BAU and year-by-year policy at municipal level (the lighter the hue, the smaller the difference).

4. CONCLUSIONS

Under an economic viewpoint, it is quite apparent that "the sooner, the better". The one-shot solution is economically very convenient and also good for the environment. It is rather robust since its performances do not vary much in various plausible future scenarios. Data from the CENED reports also show that implementing many energy-saving measures are economically convenient and many of the suggested measures have return-time, of less than 10 years, even considering just fuel reduction. Such return times are clearly shorter when considering the present uniform tax reduction.

It is thus difficult to understand why the adoption of these measures proceeds at a much slower pace than needed. Possibly, the few thousand euros that are necessary for some of these measures constitute, in many cases, an insurmountable entry barrier. This may become more and more a problem in the future with the aging of the population living in small villages and small private houses that do not see the interest in investing in something that will become profitable only at a distance of ten years or so. Finally, the uncertainty about the future situation, particularly the fear it will worsen, discourage whatever investment. These considerations are not depicted by the NPV approach that summarizes all the expectations about the future in a simple discount factor. Another minor aspect not considered in the present study is the energy and pollution of the restructuring operations themselves. For energy, it seems an acceptable assumption to considered it included in the implementation cost, while this is generally not true for pollution, that does not have a generalized economic market. The assumption made here is that the direct environmental impact of the construction sites can be disregarded, given its limited duration (few months) in comparison to the 15 years planning horizon considered.

Working with a different perspective with respect to individual citizens, a regional authority should look at these longer horizons and promote the adoptions of energy-saving measures in residential buildings, that have positive effects under many viewpoints. The present study allows the quantification of what the authority and/or the society at large should invest in reducing the delay of adoption of such measures as much as possible.

REFERENCES

Bosetti, V., Carraro, C., Sgobbi, A., and Tavoni, M. (2009a). Delayed action and uncertain stabilization targets. How much will the delay cost?. *Climatic Change*, 96 (3), 299-312.

Bosetti, V., Carraro, C., and Tavoni, M. (2009b). Climate change mitigation strategies in fast-growing countries: The benefits of early action. *Energy Economics*, 31, S144-S151.

Caserini, S., Giani, P., Cacciamani, C., Ozgen, S., and Lonati, G. (2017). Influence of climate change on the frequency of daytime temperature inversions and stagnation events in the Po Valley: historical trend and future projections. *Atmospheric Research*, 184, 15-23.

Friedman, C., Becker, N., and Erell, E. (2014). Energy retrofit of residential building envelopes in Israel: A cost-benefit analysis. *Energy*, 77, 183-193.

Chen, Y., Liu, A., and Cheng, X. (2020). Quantifying economic impacts of climate change under nine future emission scenarios within CMIP6. *Science of The Total Environment*, 703, 134950.

Cho, K., and Yoon, Y. (2015). Decision support model for determining cost-effective renovation time. *Journal of Management in Engineering*, 32 (3), 04015051.

Desideri, F. and Asdrubali, U. (eds.) (2019). *Handbook of Energy Efficiency in Buildings: A Life Cycle Approach*. Elsevier, Oxfird, UK.

European Parliament (2009). P6_TA-PROV(2009)0278 - Energy performance of buildings (recast) ***I, European Parliament legislative resolution of 23 April 2009 on the proposal for a directive of the European Parliament and of the Council on the energy performance of buildings, 2009.

Guariso, G., and Sangiorgio, M. (2018). Integrating Economy, Energy, Air Pollution in Building Renovation Plans. *IFAC-PapersOnLine,* 51 (5), 102-107.

Guariso, G., and Sangiorgio, M. (2019). Multi-objective planning of building stock renovation. *Energy Policy,* 130, 101-110.

Hermelink, A. H. (2009). How deep to go: remarks on how to find the cost-optimal level for building renovation. Report Commissioned by European Council for an Energy Efficient Economy; Ecofys GmbH, Köln, Germany.

Jakob, M., Luderer, G., Steckel, J., Tavoni, M., and Monjon, S. (2012). Time to act now? Assessing the costs of delaying climate measures and benefits of early action. *Climatic Change*, 114 (1), 79-99.

Krey, V., and Riahi, K. (2009). Implications of delayed participation and technology failure for the feasibility, costs, and likelihood of staying below temperature targets-

Greenhouse gas mitigation scenarios for the 21st century. *Energy Economics*, 31, S94-S106.

Kumbaroğlu, G., and Madlener, R. (2012). Evaluation of economically optimal retrofit investment options for energy savings in buildings. *Energy and Buildings*, 49, 327-334.

Kurnitski, J., Kuusk, K., Tark, T., Uutar, A., Kalamees, T., and Pikas, E. (2014). Energy and investment intensity of integrated renovation and 2030 cost optimal savings. *Energy and Buildings*, 75, 51-59.

Lechtenböhmer, S., and Schüring, A. (2011). The potential for large-scale savings from insulating residential buildings in the EU. *Energy efficiency*, 4 (2), 257-270.

Luderer, G., Pietzcker, R. C., Bertram, C., Kriegler, E., Meinshausen, M., and Edenhofer, O. (2013). Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environmental Research Letters*, 8 (3), 034033.

Marten, A.L., Kopits, E.A., Griffiths, C.W., Newbold, S.C., and Wolverton, A. (2015). Incremental CH4 and N2O mitigation benefits consistent with the US Government's SC-CO2 estimates, *Climate Policy*, 15 (2), 272-298,

Matschoss, K., Heiskanen, E., Atanasiu, B., and Kranzl, L. (2013). Energy renovations of EU multifamily buildings: do current policies target the real problems. Rethink, renew, restart. In Proceedings of the eceee 2013 Summer Study (pp. 1485–1496). Eceee.

Menassa, C. C. (2011). Evaluating sustainable retrofits in existing buildings under uncertainty. *Energy and Buildings*, 43 (12), 3576-3583.

OECD (2012). OECD Environmental Outlook to 2050: The Consequences of Inaction, ISBN 978-92-64-122161, OECD (available at: *http://oecd.org*)

Ricke, K., Drouet, L., Caldeira, K., and Tavoni, M. (2018). Country-level social cost of carbon. *Nature Climate Change*, 8, 895–900.

Semprini, G., Gulli, R., and Ferrante, A. (2017). Deep regeneration vs shallow renovation to achieve nearly Zero Energy in existing buildings Energy saving and economic impact of design solutions in the housing stock of Bologna. *Energy and Buildings*, 156, 327-342.

Tokimatsu, K,, Dupuy, L., and Hanley, N. (2018), Using Genuine Savings for Climate Policy Evaluation with an Integrated Assessment Model. *Environmental and Resource Economics,* 72, 281–307.

US EPA (2016). Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis. Interagency Working Group on Social Cost of Greenhouse Gases, United States Government (available at: *https://19january2017snapshot.epa.gov/sites/production/ files/2016-12/documents/sc_co2_tsd_august_2016.pdf*).

van Vliet, J., den Elzen, M. G., and van Vuuren, D. P. (2009). Meeting radiative forcing targets under delayed participation. *Energy Economics*, 31, S152-S162.

Vecchi, R., Marcazzan, G., Valli, G., Ceriani, M., and Antoniazzi, C. (2004). The role of atmospheric dispersion in the seasonal variation of PM1 and PM2. 5 concentration and composition in the urban area of Milan (Italy). *Atmospheric Environment*, 38 (27), 4437-4446.

Vecchi, R., Marcazzan, G., and Valli, G. (2007). A study on nighttime–daytime PM10 concentration and elemental composition in relation to atmospheric dispersion in the urban area of Milan (Italy). *Atmospheric Environment*, 41 (10), 2136-2144.

Verbruggen, A., Al Marchohi, M., and Janssens, B. (2011). The anatomy of investing in energy efficient buildings. *Energy and buildings*, 43 (4), 905-914.

Yang, X., Zhang, S., and Xu, W. (2019). Impact of zero energy buildings on medium-to-long term building energy consumption in China. *Energy Policy*. 129, 574-586.