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From cost-optimal to nearly Zero Energy Buildings' renovation: Life Cycle Cost comparisons under alternative macroeconomic scenarios

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A B S T R A C T

Policies and financial framework aiming to encourage energy efficient building renovations should contribute to "fill" the existing investment gap between Cost-Optimal (CO) solutions, that are more economically convenient, and nearly Zero Energy (nZE) solutions, which have the lower energy consumption, in order to make more convenient to the investors to choose the more energy efficient options.

This investment gap depends on the long-term expected value and volatility of several interdependent macroeconomic variables. However, standardized LCC methods used for CO assessments disregard the long-term uncertainty and interdependence affecting these variables and, consequently, misrepresent the impact of the associated risk on the economic convenience.

The present work aims to model alternative macro-economic scenarios where to carry out a "stochastic" LCC of predetermined building renovation solutions, in order to provide a useful and effective decision tool for building LCC, and especially to evaluate whether and how much the future macroeconomic scenario could influence the investment gap between a CO and a nZE refurbishment solution.

At this aim, we estimated the Vector AutoRegressive (VAR) models of four alternative macro-economic scenarios, ranging from a "regular growth" case to more extreme conditions as experienced by major western economies in the last decades, based on real data, i.e. observed time series.

The scenarios modelling and its relation to the stochastic LCC is the main result and novelty of the work compared to the conventional approach adopted in most of the literature and suggested by international regulations and standards. The method is illustrated through a case study, which demonstrates the potential of the developed methodology in providing interesting and informative results on the nature of the investment gap between CO and nZE solutions, that the policy should contribute to fill in order to address the environmental challenge in the building sector, and on how much this gap may vary depending on the volatility of the macro-economic context.

The novelty of the work mainly lies on the possibility to highlight in which specific macroeconomic conditions the convenience of taking an investment decision under risk-aversion may be jeopardised (augmented), thus requiring a stronger (weaker) compensating public support.

1. Introduction

Saving energy is one of the most important objectives of the European Union (EU) environmental and energy policies, to help the transition towards climate-neutral Europe by 2050 (European Commission (EC), 2018). To this respect, energy efficiency improvements in the building sector are essential, given its major impact on climate. Buildings are in fact responsible for approximately 40% of final energy consumption and 36% of carbon dioxide (CO_2) emissions in the EU, moreover, 84% of buildings' energy demand is still generated from fossil fuels ("Energy Efficiency," 2020). About 45% of the EU's buildings have been constructed before nineties and almost 75% of the building stock is in need of an energy efficiency upgrade (European Commission (EC), 2016), which should entail deep renovation measures on the building envelope

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and technical systems to reach substantial energy efficiency improvements. Thus, during the last decade, the sector has been interested by several policy interventions aimed at setting targets for the energy performance of buildings.

In particular, the EU Energy Performance of Buildings Directive - EPBD (Directive 2010/31/EU) (European Parliament, 2010), revised in 2018 (European Parliament, 2018) has strengthened the policy and financial framework to stimulate the refurbishment of existing building stocks towards the so-called “nearly Zero Energy” (nZE) levels. Member States (MSs) shall then “*develop policies and take measures such as the setting of targets in order to stimulate the transformation of buildings that are refurbished into nearly zero-energy buildings*” (nZEBs) (European Commission (EC), 2012a).

To identify the “minimum” energy performance requirements contained in national building codes, the EPBD imposes to MSs to adopt an approach that identifies the level of building energy performance, obtained through the combination of several design measures, which leads to the lowest cost during the estimated lifecycle of the building. The Directive designates this approach as the cost-optimal (CO) approach. The CO calculation framework set at EU level allows to evaluate the impact of different Energy Efficiency Measures (EEMs) and Renewable Energy Sources (RES) applied to reference buildings. It is based on the Life Cycle Costing (LCC) procedures, used to determine the whole costs associated to energy efficiency measures during a specific time period. The LCC approach has then recently become familiar to building professionals, interested in comparing the economic performance of design alternatives, and is increasingly used by public administrations to evaluate the affordability of energy efficiency investments and define future incentives and policies pushing buildings construction and renovation projects.

The CO energy renovation for existing buildings is not as close to nZE as it would be needed to obtain greater energy savings, given the higher costs of investment for nZE renovation solutions. Thus, there is very often a divergence between the CO and the nZE solution. We refer to this gap as the “investment gap” as it is identified by the difference occurring between the life cycle costs associated to the two solutions. This gap has evident environmental and policy implications. Policies aiming to encourage energy efficient building renovations should contribute to fill the investment gap between CO and nZE. Namely, the estimated investment gap, calculated by LCC, defines the level of incentive that would be needed to make the investment in nZE convenient to private investors, compared to the CO solution.

But there is a major complication in designing policies in this direction. The investment gap obviously depends on the different investment costs to implement alternative energy technologies. In turn, the life cycle cost is function of few interdependent macroeconomic variables whose long-term expected value and volatility strongly affect the decision-making process of public or private investors (Hamdy et al., 2017). The macroeconomic environment is what eventually defines this interdependence, expectation and volatility. Particularly in the case of long-life investments, however, standardized LCC methods[1] disregard the long-term uncertainty and interdependence affecting these macroeconomic variables and, consequently, misrepresent the impact of the associated risk on the economic convenience for risk-averse economic agents.

Recent contributions (Baldoni et al., 2019; Burhenne et al., 2013; Fregonara et al., 2018) have put forward solutions to make the stochastic nature of macroeconomic variables explicit in LCC calculations. Among these, Baldoni et al. (2019) propose a LCC approach that not only admits stochastic macroeconomic variables, but make the respective stochastic data generation processes time-interdependent, that is, expression of a specific macroeconomic environment. For this reason, however, the approach proposed by the authors has the limitation to generate results that only apply to the specific macroeconomic context for which variables' interdependent expected values and volatility have been estimated. Although this macroeconomic context can be considered normal (i.e. regular or prevalent), it still fails to consider how LCC outcome, thus investment decisions, may vary in different macroeconomic contexts. More importantly, it fails to capture the impact on LCC outcome and related investment decisions of an expected change in the macroeconomic context during the whole investment life.

The objective of the present work, therefore, is to contribute to this literature on stochastic LCC by noticeably improving the approach in Baldoni et al. (2019) to make it work under alternative macroeconomic scenarios, in order to evaluate whether and how much these influence the LCC outcomes, and especially the investment gap between a CO and a nZE refurbishment solution. In this respect, the paper develops Vector AutoRegressive (VAR) models of four alternative macroeconomic scenarios based on real data (i.e., observed time series) ranging from “regular growth” to more extreme macroeconomic conditions, as experienced by major western economies in the last decades.

The work moves in the direction indicated by the recent literature in the field (Sibilla and Kurul, 2020) of developing a transdisciplinary integrated approach that combines economic and technical aspects. In this regard, the novelty of the work is twofold. Firstly, it gives more flexibility to LCC as it allows the user to decide, among other things, under which macroeconomic scenario the LCC calculation should be performed. Secondly, it significantly expands the policy implications of the approach. In fact, it may highlight in which specific macroeconomic conditions the convenience of taking an investment decision under risk-aversion may be jeopardised (augmented), thus requiring a stronger (weaker) compensating public support.

The potential of the stochastic LCC approach integrating alternative macroeconomic scenarios is illustrated in this paper through the presentation of a case-study: the assessment of the global costs of several predetermined Renovation Solutions (RSs) for an existing building towards the target nZE, focusing on the comparison among the four macroeconomic scenarios and their impact on the investment gap between the CO and the nZE solutions. A sensitivity analysis is performed to illustrate how the output variance depends on the stochastic nature of the different scenarios.

The rest of the paper is structured as follows. Section 2 briefly overviews the recent developments in the literature on the macroeconomic drivers of LCC assessments in the building sector and explains the rationale of the work. Section 3 presents the adopted methodological approach by overviewing the stochastic LCC calculation and detailing the construction of alternative macroeconomic scenarios. Section 4 presents and discusses the results of the application of the approach to the energy renovation of the building case-study. Section 5 concludes by stressing how the proposed approach could be used to develop proper and effective environmental policies and by discussing possible future developments of the proposed method. The nomenclature is reported in Table A.1 of Annex 1.

2. Overview of the literature and rationale of the work

The economic evaluation of the CO methodology set by Directive 2010/31/EU, the delegated Regulation 244/2012 and its Guidelines

[1] Standardized LCC methods usually refer to the main international standards as ISO 15686–5:2017 (ISO - International Organization for Standardization, 2017) and the European EN 15459–1:2017 (CEN European Commitee for Standardization, 2017).

(European Commission (EC), 2012a; 2012b), is performed according to the global costs calculation included in standard EN 15459 (originally the 2007 version, then updated in 2017 (CEN European Commitee for Standardization, 2017).[2] In a recent review, Ferrara et al. (2018)) analyzed 88 papers reporting 105 case studies of the CO procedure application since the EPBD recast entered into force. This review suggests that the introduction of the CO methodology has given a strong impulse to research in the field of cost-effective feasibility of nZEBs, carried out either by academic researchers or by national bodies.

According to this methodology, a net present value of all energy-related costs of a building project, occurring during a defined calculation period, is obtained based on assumptions concerning future inflation, interest rates and the evolution of energy and products prices. The CO procedure results in a graph where the horizontal axis represents the building primary energy need and the vertical axis reports the global cost (henceforth, C-E space). Fig. 1 displays this graph adapted from Atanasiu and Kouloumpi (2013, p. 16).

Each point in the graph identifies a hypothetical combination of EEMs with the consequent costs and energy need. Among these potentially very numerous combinations, a cost curve can be drawn (the orange line in Fig. 1) in order to identify the set of cases implying the minimum cost given the level of energy need. In principle, the point with the minimum cost along this curve identifies the CO level. As a matter of fact, however, "*the cost-optimum is rarely found as a single package of measures applied to a reference building, but rather as a set of more or less equally valid or cost-optimal solutions that can be considered as a cost-optimal range*" (Atanasiu and Kouloumpi, 2013, p. 11, 75) or Cost-Optimal area.[3] In general terms, when investigating CO levels only this range or area should be considered. As consequence, given a predetermined set of EEMs combinations, the analysis should disregard all cases not falling within this area.[4]

Nonetheless, a flat-enough cost curve could be legitimately considered as a good approximation of a CO curve for two main reasons that are at the core of the present study. First of all, because the delimitation of the CO area depends on the macroeconomic scenario assumed for the LCC calculation. Secondly, because risk-averse investors might define as optimal an option which is sub-optimal in terms of expected costs but is significantly less risky because of the lower cost variance. Therefore, an appropriate LCC approach should be able to identify the options falling in the CO area taking also into account that this area depends on the macroeconomic context and that it should also incorporate the different variability of costs.

Beside the CO level, Fig. 1 also shows the nZE target and the actual law requirements. From these levels it is possible to graphically display the ideal investment and energy gaps to be intended as the global cost and energy difference, respectively, between the CO level and the nZE solution and the actual requirement. The investment gap obviously depends on the different investment costs to implement the different energy technologies and these costs are, in turn, strongly dependent on the macroeconomic parameters considered in the LCC assessment (see section 3.1). *Ceteris paribus*, global costs decrease when discount rates increase as the current value of future costs decreases. Since nZE solutions imply higher initial investment costs and future energy savings, high discount rates may make them not economically convenient.

Copiello (2019) recently performed a review on 65 studies in the field of LCC of building energy efficiency solutions. Nearly 70% of these studies are quite recent as they concentrate in the 2014–2018 period. He eventually concluded that these studies are mainly organized around two main research strands. One focuses on the relationship between energy prices and the convenience of energy efficiency investments; the other on the central role of the discount rate on this convenience. In practice, most studies concentrate on only one economic variable, while only few cases consider the combined effects of economic variables and of their dynamics. However, a report of the Buildings Performance Institute Europe highlighted that the choice of LCC input factors (discount rate, energy price development) has a key influence on the results if two input factors are changed simultaneously in the same direction, e.g. a combination of a low (1%) discount rate and a high energy price development (Atanasiu and Kouloumpi, 2013).

Therefore, even though the recent literature clearly stresses how LCC and CO results are sensitive to input data, and especially to economic variables (Ferrara et al, 2014, 2018), only in few LCC studies the uncertainty associated to these variables is explicitly considered and a sensitivity analysis performed. Eventually, all these applications to building renovation point out to the strong limits of deterministic LCC assessments. At the same time, however, they also show how including the uncertainty associated to key macroeconomic variables may be challenging. Some of these works admit uncertainty in the form of subjectively pre-determined (pessimistic and optimistic) scenarios (Basinska et al., 2015; D'Agostino et al., 2017; La Fleur et al., 2019; Li et al., 2020; Mata et al., 2015; Moore and Morrissey, 2014; Morrissey and Horne, 2011; Yuan et al., 2019). In other cases, uncertainty enters in the form of macroeconomic variables drawn from some statistical distribution (Copiello et al., 2017; Hamdy et al., 2017; Kumbaroglu and Madlener, 2012; Zheng et al., 2019). However, not only these distributions are arbitrarily assumed ex-ante, but also with independent macroeconomic variables. Therefore, as acknowledged by Copiello et al. (2017), this literature misses to represent the key feature of the uncertainty associated to these macroeconomic variables: they reciprocally influence each other and this influence is itself the consequence of the specific macroeconomic environment generating them.

Few recent works have attempted to propose an actual stochastic LCC approach where all the variables entering calculations are not only stochastic but, at least in the case of macroeconomic variables, interdependent (Baldoni et al., 2019; Burhenne et al., 2013; Fregonara et al., 2018). Baldoni et al. (2019)in particular, propose an approach where macroeconomic variables are stochastic and drawn from a multivariate generation process that not only makes them interdependent, but that is estimated by real time series within a Vector AutoRegressive (VAR) model. So, the stochastic properties are not assumed ex ante but econometrically estimated from real data. This approach eventually reveals that the uncertainty associated to a LCC calculation is, in fact, made of two levels. The first level, which the authors investigate, concerns the

[2] The CO methodology was applied in 2013 by Member States to review their national minimum building energy performance requirements, thus resulting in the "EU countries' 2013 cost-optimal reports" (EU countries' 2013 cost-optimal reports). EU MSs perform and update their cost-optimality calculation every five years, to update their minimum energy performance thresholds to the cost-optimal energy performance levels and to provide incentives to meet the energy performance thresholds for nZEBs.

[3] It is worth reminding that this study uses the term "Cost-Optimality" in order to be consistent with the methodological framework, the nomenclature and the terminology widely used on this topic in the literature and in the European Policies, especially the EPBD Directive 31/2010.

[4] The cost curve in Fig. 1 thus behaves as a CO curve only in this CO area. Nonetheless, neither the cost curve nor the CO curve has to be intended as a Pareto frontier, that is, as the Pareto optimal set in a multi-objective space (cost and energy need, in the present case). Not only because the logic behind the CO curve is single-objective (cost minimization), but also because this frontier would evidently imply a monotone (decreasing) cost curve. The approach here proposed thus aims to position a set of N predetermined options on a C-E space in order to identify the CO area, and not to draw the C-E Pareto frontier among all possible options.

stochastic process simultaneously generating the variables entering the LCC within a specific macroeconomic environment. The second level deals with the most appropriate macroeconomic environment from which this stochastic process can be estimated. In Baldoni et al. (2019), however, results only apply to the specific macroeconomic context for which variables' interdependent expected values and volatility have been estimated. Therefore, this level of uncertainty is neglected. In fact, the macroeconomic environment cannot be intended as stochastic since it is unreliable and unfeasible to figure out a stochastic process generating alternative environments. History is this generating process and can be used to detect these alternative macroeconomic environments (or scenarios) eventually generating different interdependent stochastic macroeconomic variables.

The present paper significantly improves the approach of Baldoni et al. (2019) by making it perform under alternative macroeconomic scenarios. This improvement is expected to provide a useful LCC tool to assess whether and how macroeconomic scenarios affect the convenience of taking an investment decision and, thus, the investment gap between a CO and a nZE refurbishment solution.

3. Materials and methods

3.1. The stochastic LCC calculation model

The LCC calculation proposed here is a valuable improvement of the approach proposed by Baldoni et al. (2019). It is based on the modelling of the stochastic nature of all LCC input variables. The statistical distribution of these variables enters as input of the calculation of the Global Cost (GC) of the retrofitting investment, through a Monte-Carlo analysis. This makes the GC itself stochastic. In this respect, the main focus and novelty of the present approach, and of the present paper, concerns the stochastic nature of the macroeconomic variables and how this nature affects the GC Monte-Carlo simulations.

The proposed LCC method is based on the procedure of European Standard EN 15459–1:2017. The GC of the building's RSs, obtained combining all the j-th EEM(s), at the end of the Calculation Period (CP) but referred to the starting year (t = 0) (i.e., $GC_{RS,0}$), is calculated as follows:

$$GC_{RS,0} = \sum_{j=1}^{N}\left[CI_j + \sum_{t=1}^{CP}\left[\times \left(CM_{j,t} + CS_{j,t}\right)R_t^{disc}R_t^{L} + CE_{RS}R_t^{disc}R_t^{E}\right] - Val_{j,CP}\right] \quad (1)$$

Where: CI_j are the initial investment costs, CM_{jt} the annual maintenance costs assumed constant, CE_{RS} the building annual energy costs assumed constant, R_t^{disc} the discount factor, R_t^L and R_t^E the price development rates (respectively for human operation and for energy), $CS_{j,t}$ the replacement costs assumed equal to the discounted investment costs whose frequency depends on the j-th EEM Service Life, $Val_{j,CP}$ is the residual value of the j-th EEM at the end of the CP, calculated based on a straight-line depreciation of the initial investment or replacement cost of the measure until the end of the calculation, discounted at the beginning of the evaluation period. The building annual energy costs CE_{RS} are calculated multiplying the building annual energy consumption for the energy tariff related to the specific energy carrier.

The discount factor R_t^{disc} depends on the discount rate. Following the EN 15459–1, the LCC equation is specified in real terms. The discount rate d_t thus expresses the real interest rate as:

$$d_t = \frac{i_t - \pi_t}{1 + \pi_t} \quad (2)$$

where π_t indicates the inflation rate and i_t the nominal interest rate. The LCC calculation here performed is "dynamic" in the sense that π_t and i_t vary over time t. Therefore, the discount factor R_t^{disc} is itself time variant as it is computed as:

$$R_t^{disc} = \prod\nolimits_{s=1}^{t} \frac{1}{1+d_s} = \frac{1}{1+d_1}\,\frac{1}{1+d_2}\cdots\frac{1}{1+d_t} \quad (3)$$

Accordingly, price development rates R_t^L and R_t^E vary over time. R_t^L expresses the price development rate of labour (L) (i.e., the wage development rate) and, as clear in (1), it applies to maintenance and replacement costs. R_t^E expresses the price development rate of energy (E) and applies to energy costs.

3.2. VAR modelling under alternative macroeconomic scenarios

The LCC calculation described above includes four macroeconomic variables: the inflation rate (as expressed by the growth rate of the consumer price indices), the real interest rate, the real GDP growth rate, the oil price growth rate. In the formula of GC (1), these variables enter as follows: the real GDP growth rate proxies the growth rate of wages in real terms thus is used as escalation factor of the prices for human operation (labour cost), e_t^L; the oil price growth rate is used as the escalation factor of the prices for energy, e_t^E; the combination of the inflation rate and the real interest rate defines the discount rate, d_t.

The dynamics of these macroeconomic variables are the main source of uncertainty within the stochastic LCC. In the proposed method, they are drawn from a parametric model estimated on observed time series in order to capture the actual stochastic processes generating them. Out-of-sample projections of this estimated model are then generated to have predictions of the individual macroeconomic variables entering the stochastic LCC. Macroeconomic theory suggests that these variables are the expression of the formation of complex macroeconomic equilibria. Nonetheless, since the seminal work of Sims (1980), the empirical investigation of these equilibria has progressively overcome the complexity (and the controversies) of the macroeconomic theoretical models, by specifying and estimating systems of simultaneous dynamic reduced-form equations, where any endogenous macroeconomic variable is determined by its lagged values and by the lagged values of all other macroeconomic variables of interest. These are called Vector AutoRegressive (VAR) models (Christiano

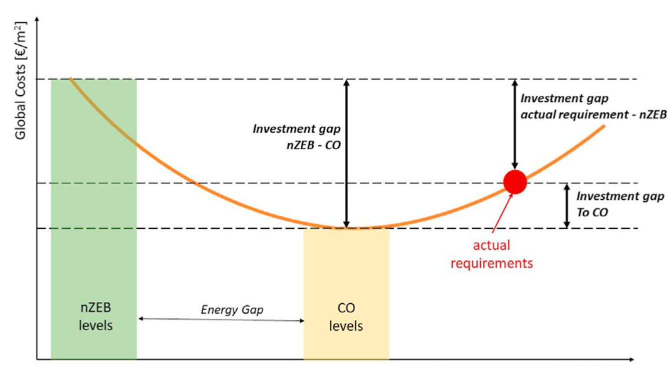

Fig. 1. Investment and energy gaps among the CO level, the actual law requirements, and the nZE target.

et al., 2006).

Even though the variables under consideration here are typically included in macroeconomic VAR models (Sims, 1980; Smets and Wouters, 2003), it is not possible to formulate univocal ex-ante expectations on the linkages among them. In fact, by empirically expressing the formation of the underlying macroeconomic equilibria, VAR models are able to capture the specificity of these equilibria in time and space, thus adapting to the specific macroeconomic context and environment under investigation.

Within the VAR model, the macroeconomic variables are time dependent but also interdependent. In practice, they are time-interdependent. This means that any variable's distribution is conditional on the distribution of the other variables and, therefore, due to time dependency, on the lagged distributions of the other economic variables. The VAR model estimation allows to recover this time interdependence from the past, that is, looking at real time series. Simultaneous projections of macroeconomic variables can be thus generated from multivariate relationships estimated on these observed time series, rather than relying on individual and static statistical distributions assumed ex ante. Then, rather that NxT independent draws (where N is the number of variables) the approach draws a sequence of T values of a Nx1 vector.

A VAR model with exogenous variables (VARX) assumes that the behaviour of N endogenous economic series can be represented by a discrete multivariate stochastic process as follows (Lütkepohl, 2005):

$$\mathbf{\Pi}(L)\mathbf{Y}_t = \mathbf{c} + \boldsymbol{\beta}'\mathbf{X}_{t-q} + \mathbf{u}_t, \quad t = 1, \ldots, T \tag{4}$$

$\mathbf{\Pi}(L) = \mathbf{I}_N - \mathbf{\Pi}_1 L - \ldots - \mathbf{\Pi}_p L^p$ is the lag polynomial where $\mathbf{\Pi}_p$ are NxN coefficient matrices. $\mathbf{Y}_t$ is the Nx1 vector of the endogenous economic series observed at time t (i.e., inflation rate, interest rate, GDP growth), $\mathbf{c}$ is the Nx1 vector of constant terms, $\mathbf{X}_{t-q}$ is the Mx1 vector of the exogenous variables observed at time t-q (possibly with q = 0); here, the only exogenous variable included in $\mathbf{X}_t$ is the oil price.[5] $\boldsymbol{\beta}$ is the MxN matrix of unknown coefficients. It is assumed that oil price directly influences only the inflation rate while the other two variables in $\mathbf{Y}$ are affected only indirectly via $\mathbf{\Pi}(L)$. Consequently, the only non-zero terms admitted in $\boldsymbol{\beta}$ are those concerning the inflation rate. Finally, $\mathbf{u}_t$ is the Nx1 vector of i.i.d. disturbance terms distributed as N(0,$\mathbf{\Omega}$) with $\mathbf{\Omega}$ indicating the variance-covariance.[6]

Provided that the N series in $\mathbf{Y}$ and the M series in $\mathbf{X}$ are stationary (i.e., I(0)),[7] the unknown coefficients in (4), included the terms in $\mathbf{\Omega}$, can be consistently estimated and the respective relationship among the variables can be thus projected outside the observed sample. In the present study, projections up to 2050 are generated.[8]

As anticipated, a VAR model like (4) is estimated on the basis of real data, i.e. observed time series. Different historical experiences might be considered in this respect possibly leading to different interdependence between the macroeconomic variables involved and, thus, to different VAR estimates. In practice, the VAR estimation and the consequent LCC simulation exercise can be performed on alternative macroeconomic climates or scenarios. Four alternative macroeconomic scenarios are here considered, and four different VAR estimations performed. Consequently, the LCC results are obtained, and then compared, under these four alternative cases.

The four scenarios characterized are: a baseline scenario of *regular growth*; an *intense growth* scenario; a *stagflation* scenario; a *deflation* scenario. For each of them, a VAR(p,q) model is specified and estimated. The number of lags p and q is selected by looking for the best fitting model according to the usual information criteria (the Akaike Information Criterion, AIC, is here adopted). These scenarios are characterized as follows.

3.2.1. Regular growth scenario (baseline)

The first macroeconomic scenario here considered aims to express a sort of regular (or baseline) case, a balanced growth path of the economy with an inflation rate around 2% and mild Gross Domestic Product (GDP) growth and long-term real interest rates. The evolution of the Western European countries during the 1980–2005 period is here assumed as the reference for this baseline scenario. By Western European countries here we intend the EU-19 aggregate. For this aggregate, however, data are not available prior to 1990. Therefore, for the period 1980–1989, West Germany data have been used. The iterative procedure based on the AIC selects a VAR(4,1) as the best model specification.

3.2.2. Intense growth scenario

This scenario is characterized by a robust growth of the real GDP and an inflation rate and interest rate higher than in the baseline case. Such conditions are met during the period 1990–2007 in the USA. Due to the higher inflation rate, also the oil price is expected to show a slightly higher growth. According to the AIC, the best fitting model for this scenario is a VAR(4,1) specification.

3.2.3. Stagflation scenario

In stagflation the economy is characterized by low growth of GDP, high inflation and higher oil price. At the same time, a higher interest rate might not be enough to compensate inflation and to drive the economy to a more balanced growth path. A situation in which high inflation and stagnation coexisted is represented by the period 1968–1974 in the USA. The best VAR specification to fit these data is a VAR(1,1) model.

3.2.4. Deflation scenario

The main features of this scenario are low GDP growth and very low (possibly negative for short periods) inflation that justifies a lower oil price dynamic. As a case study of deflation, macroeconomists typically use the Japan economy between 1991 and 2010. Of this period, we selected the subperiod 1990–2005 to run the statistical analysis and generate the multivariate model. The best-fitting VAR specification for this scenario is found to be a VAR(1,1) model.

Table 1 summarizes the four macroeconomic scenarios here considered. Table 2 reports the reference country and historical data and sources of (macro)economic variables used for the quantitative expression of the scenarios. Table 3 summarizes the descriptive statistics of the annualised predictions of the fours model variables under the alternative macroeconomic scenarios.[9]

These alternative scenarios allow to perform the calculation of

[5] The underlying assumption is that the macroeconomic equilibrium under analysis is unable to affect global oil price formation, but it is still affected by it. This assumption is also called Small Open Country assumption (Vu and Nakata, 2018).

[6] Given the normality assumption on the disturbance terms, estimation is here performed via Maximum Likelihood estimation.

[7] Unit root tests (Augmented Dickey-Fuller test) have been carried out for each variable clearly indicate that under all scenarios all variables in $\mathbf{Y}$ behave like I(0) series while the oil price is I(1). Therefore, this latter variable enters (1) as first difference (i.e., the change of oil price from t-1 to t). Unit-root test specifications and results are available upon request.

[8] Unlike the three endogenous variables, VAR projections cannot be generated for the exogenous oil price. Therefore, the Energy Information Administration (EIA) oil price 2017–2050 forecast is used for the all the scenarios. Nonetheless, as VAR specification and parameters are scenario-specific, the relationship between oil price growth and the other macroeconomic variables is itself scenario-specific.

[9] The whole set of statistical tests, estimation results and projections up to 2050 for these scenarios are available upon request.

Table 1
Characterization of alternative macroeconomic scenarios.

Scenario:	Variable:		
	Inflation rate (π)	Interest rate (i)	GDP
Regular growth *(Baseline)*	=	=	=
Intense growth	↑	↑	↑
Stagflation	↑	↑	↓
Deflation	↓	↓	↓

The Regular growth scenario's long-term expected values (indicated with " = ") serve as reference for the alternative scenarios; ↑ means higher than the baseline; ↓ means lower than the baseline.

Table 3
Summary statistics of the annualised 2050 predictions, in % (SD = standard deviation).

Scenario:	Variable:					
	Inflation rate (π)		Interest rate (i)		GDP	
	Mean	SD	Mean	SD	Mean	SD
Regular growth *(Baseline)*	2.25	0.97	2.77	0.78	2.54	1.64
Intense growth	2.55	0.63	3.45	0.73	3.31	1.19
Stagflation	8.41	3.35	4.81	0.32	0.34	3.21
Deflation	0.46	1.11	1.50	0.63	1.34	1.62

Table 2
Reference country and data used for the definition of the alternative macroeconomic scenarios and respective VAR model estimation.

Scenario: (reference country)	Variable: (data source and frequency)			
	Inflation rate (π)	Interest rate (i)	GDP	Oil price
Regular growth *(Baseline)*: EU, 1980−2005[a]	OECD Financial Statistics, Quarterly	OECD Financial Statistics, Quarterly	OECD National Accounts, Quarterly	USA EIA, Annual
Intense growth: USA, 1990−2007	Federal Reserve Economic Data, Quarterly	OECD Financial Statistics, Quarterly	OECD National Accounts, Quarterly	USA EIA, Annual
Stagflation: USA, 1968−1974	Federal Reserve Economic Data, Quarterly	OECD Financial Statistics, Quarterly	OECD National Accounts, Quarterly	USA EIA, Annual
Deflation: Japan, 1990−2005	Japan - Statistics Bureau, Quarterly	OECD Financial Statistics, Quarterly	OECD National Accounts, Quarterly	USA EIA, Annual

[a] West Germany when EU data not available (i.e. for GDP growth rate 1980−1989).

the stochastic LCC economic indicators considering different economic contexts and compare the related results' robustness and variations (Section 4). The event of an economy falling in one of these conditions is largely unpredictable. The choice among scenarios, therefore, should be made by the user according to other orders of arguments: political relevance, ethical concerns, attitude towards risk, etc. The calculation of these LCC indicators is based on the predictions generated up to 2050 from the respective VAR estimates. As the three endogenous variables used for the estimations are at quarterly frequency (Table 2), while the LCC calculations are performed with annual frequency, they are annualised using quarterly projections as follows:

$$annual\ rate = \prod_{i=1}^{4}(1 + quarterly\ rate_i) - 1 \qquad (5)$$

Fig. 2. The building case-study.

3.3. The building case study

In order to illustrate how the results of a global cost assessment can vary under these alternative macroeconomic scenarios, the stochastic LCC is applied to a case study, consisting of an energy renovation project of a real building.

The application follows the Cost-Optimal calculation framework defined in the EPBD recast and following regulation, including the main phases: (i) identification of different sets of EEMs to be applied to the building in order to reach increasing levels of energy performance towards the nZE target; (ii) evaluation of related investment and maintenance costs and service lives; (iii) calculation of related building heating energy performance; (iv) assessment of associated Global Costs in the alternative macroeconomic scenarios through the stochastic LCC.

The building case-study is a single-family detached house, built in 1935 in Cattolica, a town in the central eastern cost of Italy (Fig. 2). At present (situation prior to the energy renovation), the building walls are in plastered brick masonry, the floors and pitched roof consist of a wooden structure, the terrace floor consists of a concrete slab covered by tiles, the windows are all made by a wooden frame with a single glass. The building's heating system is realized with a conventional gas boiler and cast-iron radiators mainly placed under the windows. The regulation system consists of a zone thermostat with ON/OFF operation.

For the building renovation, focused in reducing heating and domestic hot water (DHW) consumptions, EEMs were selected addressing the three main categories: opaque building envelope,

Table 4
The EEMs designed on the building case study. Concerning building envelope, PL 0 matches with the unrenovated building.

	PL 0		PL 1		PL 2	
Opaque building envelope	**Typology**	**U (W/m^{2}K)**	**Typology**	**U (W/m^{2}K)**	**Typology**	**U (W/m^{2}K)**
Plastered brick masonry, 29 cm thick (main building)	Uninsulated	1.76	MW insulation, 4 cm thick	0.55	MW insulation, 12 cm thick	0.24
			CaSi insulation, 7.5 cm thick	0.51	CaSi insulation, 17.5 cm thick	0.26
Plastered brick masonry, 16 cm thick (minor building)	Uninsulated	2.58	MW insulation, 4 cm thick	0.61	MW insulation, 12 cm thick	0.26
			CaSi insulation, 7.5 cm thick	0.56	CaSi insulation, 17.5 cm thick	0.27
Ground floor (main volume)	Uninsulated	0.61	XPS insulation, 3 cm thick	0.25	XPS insulation, 5 cm thick	0.19
Ground floor (minor volume)	Uninsulated	0.72	XPS insulation, 3 cm thick	0.34	XPS insulation, 5 cm thick	0.25
Pitched roof	Uninsulated	1.09	XPS insulation, 11 cm thick	0.25	XPS insulation, 20 cm thick	0.15
Terrace	Uninsulated	1.72	XPS insulation, 11 cm thick	0.25	XPS insulation, 15 cm thick	0.20
Transparent building envelope	**Typology**	**U (W/m^{2}K)**	**Typology**	**U (W/m^{2}K)**	**Typology**	**U (W/m^{2}K)**
Window (1.75 × 0.90 m)	Single Glass 4 mm, Wood frame	5.17	Double glazing 4-16-4, wood/all. Frame	1.55	Triple glazing 4-12-4-12-4, wood-all. frame	1.14
			Double glazing 4-16-4, PVC frame	1.60	Triple glazing 4-12-4-12-4, PVC frame	1.18
Window (1.45 × 0.90 m)	Single Glass 4 mm, Wood frame	5.13	Double glazing 4-16-4, wood-all. Frame	1.56	Triple glazing 4-12-4-12-4, wood-all. frame	1.15
			Double glazing 4-16-4, PVC frame	1.61	Triple glazing 4-12-4-12-4, PVC frame	1.20
Window (0.60 × 0.40 m)	Single Glass 4 mm, Wood frame	4.46	Double glazing 4-16-4, wood-all. Frame	1.73	Triple glazing 4-12-4-12-4, wood-all. frame	1.41
			Double glazing 4-16-4, PVC frame	1.82	Triple glazing 4-12-4-12-4, PVC frame	1.51
Heating System	**Typology**	**η**	**Typology**	**η**	**Typology**	**η**
Generation	standard boiler 24 KW	0.93	Condensing boiler 32 KW	0.98	Heat pump + water storage tank	4.70 (COP)
Emission	Radiators	0.97	Radiators	0.97	Radiant floor panels	0.99
Distribution	Uninsulated pipeline	0.93	Insulated pipeline	0.99	Insulated pipeline	0.99
Regulation	Local, ON/OFF control	0.93	Local, proportional control (1 °C), outdoor temperature probe	0.97	Each room, proportional control (1 °C), outdoor temperature probe	0.98

transparent building envelope and heating and DHW equipment. The EEMs were chosen according to technical feasibility and suitability, considering three progressive Performance Levels (PL: 0, 1, 2) (Table 4). Then, the EEMs were combined with each other, giving rise to 17 Renovation Solutions (RSs) with progressively increasing energy performances up to the nZE target. In general, as the RS progresses, the PL of the EEM considered grows (Table 5).[10] The online Supplementary Material provides more details about the case-study and the rationale for the selection of the proposed EEMs and the consequent RSs.

The building energy performance in each RS is calculated according to EN ISO 13790 (CEN European Commitee for Standardization, 2008) and the compliance with minimum energy and the nZEB requirements verified according to the Italian legislation. As a result of the energy assessments, the building heating consumption mean values are the amount of consumed energy sources included in each RS, i.e. electricity energy (kWh) and gas (m^3). The online Supplementary Material provides more information on the energy assessments and on the LCC input data.

Beside the macroeconomic variables (whose stochastic modelling is reported in Section 3.2), also the other LCC input data were considered stochastic and characterized by a uniform distribution within a variation range of ±10%, to take into account possible uncertainty due to design and application variants and contingencies. Concerning investment and maintenance costs, the mean values are assumed based on the Italian regional prices lists. Concerning gas and electricity tariffs, the mean value was established based on the actual tariff in the Italian regulated market, while the tariff's variability is that observed in the free market in Italy. All tariffs include taxes.

[10] It is worth stressing that, as discussed in section 2, the objective here is not to put forward some optimization algorithm working over the large set of all hypothetical EEM combinations. The objective is rather to apply the proposed LCC approach to a limited set of feasible and realistically prevalent technical solutions, also considering that the case study concerns a historic building. This logic to select the relevant EEMs, also known as "manual approach", is quite common in the literature. In fact, in their review of studies on the Cost-Optimal Analysis for Nearly Zero Energy Buildings, Ferrara et al. (2018) found that most of the 88 reviewed papers (61%) use a "manual approach" to define EEMs on which calculate and compare the Global Costs, while only 35% use an automated approach (based on computer-based optimization algorithms).

Table 5
RSs and related sub-levels generated by the combination of the EEMs. RS have an increasing energy performance from 0 to 4 (nZEB) and sub-levels from A to C. "x" identifies the EEMs including MW insulation and PVC windows frames, while "y" those containing CaSi and wooden-aluminium frames.

Renovation Solution (RS)	Sub-level	PL walls	PL floors	PL windows	PL Heating System	Investment Cost (€/m^2)	Annual Maintenance Cost (€/m^2)
RS 0	A	0	0	0	0	17.40	0.33
	Bx	0 MW	1 XPS	1 PVC		81.24	0.34
	By	0 CaSi	1 XPS	1 W/A		100.88	0.34
	Cx	1 MW	1 XPS	2 PVC		153.46	0.36
	Cy	1 CaSi	1 XPS	2 W/A		360.09	0.36
RS 1	Ax	1 MW	1 XPS	1 PVC	1	293.11	2.53
	Ay	1 CaSi	1 XPS	1 W/A		500.04	2.53
	Bx	2 MW	2 XPS	2 PVC		338.36	2.68
	By	2 CaSi	2 XPS	2 W/A		722.89	2.71
RS 2	Cx	As RS 1Bx + ST				379.30	3.29
	Cy	As RS 1By + ST				764.23	3.33
RS 3	Ax	1 MW	1 XPS	1 PVC	2	307.17	3.73
	Ay	1 CaSi	1 XPS	1 W/A		514.13	3.74
	Bx	2 MW	2 XPS	2 PVC		353.28	3.96
	By	2 CaSi	2 XPS	2 W/A		737.96	3.99
RS 4 ("nZEB")	Cx	As RS 3Bx + ST + PV + MVHR				473.38	6.31
	Cy	As RS 3By + ST + PV + MVHR				859.22	6.31

The stochastic LCC couples Monte-Carlo simulations to the Global Cost calculation, thus in each iteration, values are selected from the input PDFs and inserted into the output equation in (1).[11] A study period of 30 years is assumed.

68 simulation cases have been obtained from the assessment of the 17 RSs under 4 macroeconomic scenarios. For each case, 20 000 iterations were run, after preliminary tests on the results accuracy.

The statistical distributions of the resulting LCC output *(GC)* are obtained and a Sensitivity Analysis (SA) is performed on these results, through the variance-based decomposition method known as Sobol method (Sobol, 2001). The Sobol method is used to calculate, for any stochastic input of the LCC calculation, the *total order sensitivity index* (STi), which measures the contribution to the output variance due to each input, including all variance caused by its interactions with any other input variables (Saltelli et al., 2008).[12]

4. Results and discussion

4.1. Stochastic LCC results of different scenarios in a C-E space

The LCC application to the case study, considering the RSs and macroeconomic scenarios discussed above, is summarised by the computed *GC* under the different circumstances. To be consistent with the discussion of section 2, these results are displayed in a C-E space, that is in a graph where the energy performance (EP_{nren}, non-renewable primary energy need for winter heating and DHW) is reported in the horizontal axis and the associated *GC* is reported in the vertical axis. Any *GC* result concerns a specific RS (i.e. a combination of EEMs) under a macroeconomic scenario. Therefore, many different cases may be obtained and compared in a C-E space. Moreover, for any case, the stochastic LCC returns not only the mean *GC* but also the respective standard deviation. In order to also represent the uncertainty of the cost performance, any case is displayed in the C-E space in the form of a "bubble", whose centre identifies the mean *GC* while the diameter expresses the *GC* standard deviation.

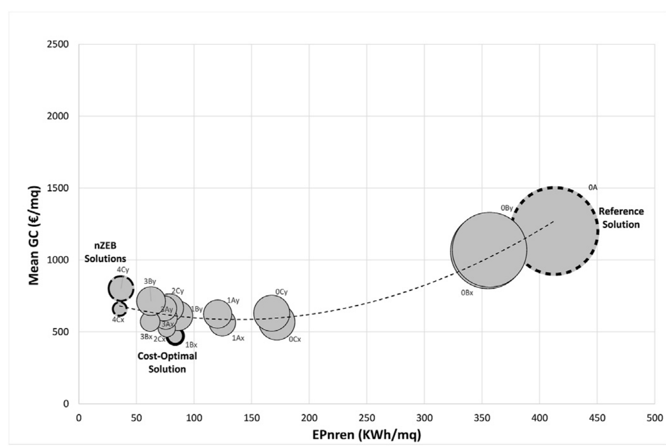

Fig. 3. Positioning of LCC results of each RS sub-level in the C-E space under the Regular Growth macroeconomic scenario (EP_{nren} indicates the non-renewable primary energy needs for winter heating and DHW. Global Costs are represented by "bubbles" where the centre is the mean value while the diameter the standard deviation. The dotted contours of the bubbles identify the nZE, the CO and the reference solutions).

Fig. 3 shows these results for the different RSs under the

[11] In this work, Sobol's sequences have been used as a quasi-random sampling technique in order to generate samples as uniformly as possible from inputs PDFs. Data analysis software "R" has been used for both sample generation and uncertainty propagation (The R Project for Statistical Computing, 2020).

[12] The Sobol method allows the calculation of another index called *first order sensitivity index* that indicates the main contribution of each input factor to the variance of the output. For the sake of space limitation, the results of this further index are not reported here but are available upon request.

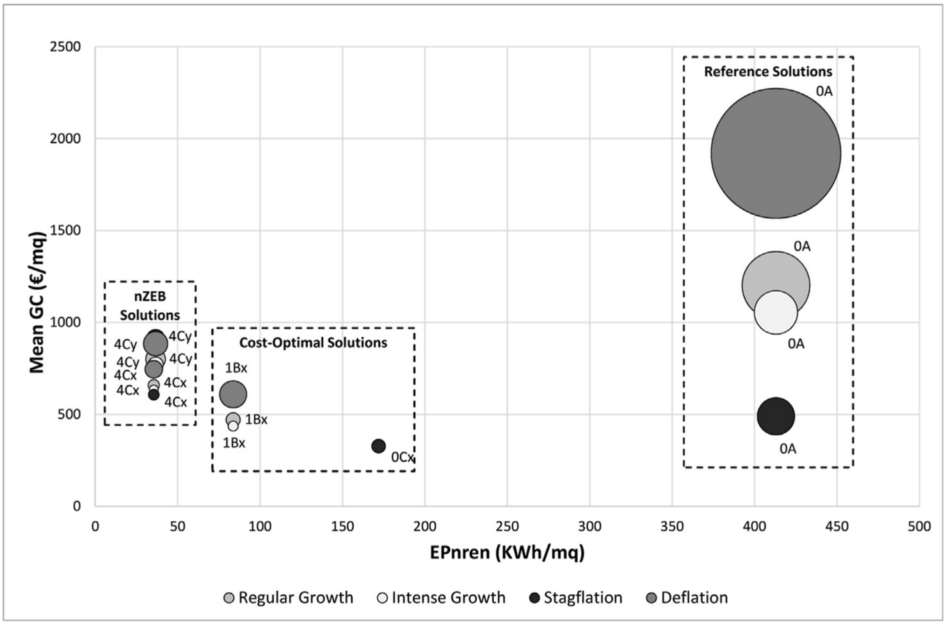

Fig. 4. Positioning of LCC results of selected RSs in the C-E space under all macroeconomic scenarios. For better understanding, only the reference case, the nZE and the CO solutions are reported.

macroeconomic baseline scenario. In order to facilitate its interpretation, among the 17 RSs, Fig. 3 (and Fig. 4) highlights three specific cases: the Reference Solution, the CO Solution (that with the lower mean *GC*), the nZE Solutions (those with the lower energy consumption and defined as nZEB according to the Italian legislation). It emerges that the energy requirement of the various RSs ranges from a minimum of 35 kWh/m^2 (nZE solutions) to a maximum of 413 kWh/m^2 (RS 0A, which only implies the simple replacement of the existing heat generator with a standard boiler). Moving within the graph from the right to the left we move from the RSs with higher energy requirement towards those progressively approaching the nZE standard. The energy saving obtained from this progressive combination of highly efficient EEMs is huge: the nZE solutions (RS 4Cx,y) reduce the energy consumption by about 92% compared to the RS 0A, by about 90% compared to all RS 0B and RS 0C cases and by at least 40% compared to all other RSs.

But the decision taken by risk-averse investors do not pursue the largest energy saving, but the economic convenience, of which energy saving is just a arguably relevant component. The mean *GC*, as well as their variability, are expected to express this overall convenience. Fig. 3 shows that the lowest mean *GC* is achieved by RS 1Bx and corresponds to about 470 €/m^2. This is the CO solution for this case study in the regular growth scenario but, at the same time, it shows an energy requirement which is higher than the nZEB solutions by almost 130%. A noticeable investment gap thus emerges. Among the two energy-equivalent nZE RS, the most expensive is RS 4Cy (mean *GC* about 800 €/m^2) for which the investment gap with respect to the CO RS is almost 70%. The mean *GC* of the other nZE RS (4Cx), however, imply a much lower investment gap (about 40%), due to the cheaper measures adopted for the envelope and equipment renovation. It remains true that this investment gap is expected to orient investors towards the CO solution, but this is largely inconsistent with a nZE policy, as both nZE solutions reduce consumption by about 60% compared to the CO solution. In addition, though not optimal from an economic perspective, both nZE RSs still show a much lower *GC* than RS 0A, whose mean *GC* exceeds 1200 €/m^2. Eventually, as widely stressed within this literature, nZEB solutions imply high *GC* due to the larger initial investment and higher operating (maintenance and replacement) costs of the heating system and renewable energy production.

Following the discussion in section 2 (Fig. 1), in Fig. 3 the CO area should be limited to those few RSs showing an energy need between 50 and 100 and a GC between 500 and 600. All the other RSs should be therefore handled as irrelevant solutions by a method looking for CO cases. But the proposed stochastic approach shows how the delimitation of this CO area is not so univocal for two main reasons.

On the one hand, Fig. 3 exhibits another essential information provided by the proposed stochastic LCC approach. As discussed, the uncertainty expressed by *GC* variability (i.e, standard deviation) also matters as, for a given mean *GC*, risk-averse investors are expected to opt for the solution with the lowest variability. The size of the RS "bubble" largely varies across RS with the coefficient of variation (i.e., the ratio between the standard deviation and the mean) ranging from a maximum of about 0.1 for RS 0A,B,C to a minimum of about 0.05 for RS 3 and 4. Therefore, *GC* uncertainty gradually decreases moving towards more energy-efficient solutions revealing that energy price is the main source of uncertainty. Between the two nZE RS, RS 4Cx shows about half the variability of RS 4Cy and it is also appreciably less uncertain than the CO RS.

On the other hand, the major novelty of the present study concerns the comparison across the alternative macroeconomic scenarios: a solution falling in the CO area under a specific scenario could fall outside the area under an alternative scenario. Fig. 4 reports, in the C-E space, the stochastic LCC results obtained under the four macroeconomic scenarios for the reference, nZE and CO RSs.[13] Four major aspects are worth noticing.

First of all, it clearly emerges that in the reference case (RS 0A), the computed *GC* is greatly influenced by the macroeconomic scenario. Compared to the regular growth case, the mean *GC* increases by about 60% in the deflation scenario (more than 1900

[13] Results obtained for all RSs under all macroeconomic scenarios are available upon request.

Table 6
Mean *GC* across macroeconomic scenarios: nZE and reference solutions compared to the CO RS.

Macroeconomic Scenario	Cost-Optimal Solution	nZEB Solution "4C"		Reference Solution "0A"
		"x" (MW on external wall and PVC frame on windows)	"y" (CaSi on external wall and W/A frame on windows)	
Regular Growth	"1Bx" (470.96 €/m^2)	+40%	+70%	+155%
Intense Growth	"1Bx" (436.59 €/m^2)	+46%	+77%	+142%
Stagflation	"0Cx" (327.66 €/m^2)	+85%	+179%	+50%
Deflation	"1Bx" (609.47 €/m^2)	+22%	+45%	+215%

€/m^2), while in the case of stagflation it is lower by 60% (about 490 €/m^2). Only in the intense growth scenario, the *GC* show a mean value that is closer to what obtained under regular growth (between 1000 €/m^2 and 1500 €/m^2). Secondly, on the contrary, the nZE RSs show a mean *GC* that remain quite stable across the various economic scenarios. It varies in a range between 600 and 750 €/m^2 for the RS "x" and between 770 and 910 €/m^2 in the "y" case. Evidently, as for the variability observed within a given scenario, the *GC* variation between scenarios is mostly determined by the energy price that becomes less relevant in the nZE RS. This does not mean that the macroeconomic environment becomes irrelevant in the nZE cases. For all scenarios, the *GC* of the RS 4Cy case are higher than the respective RS 4Cx case and, within a given scenario, this difference may be appreciable. This seems particularly true in the stagflation scenario where the *GC* of the RS 4Cx case is almost 40% lower than the RS 4Cy case.

Thirdly, as regards the CO solution, it emerges that the change of the macroeconomic environment may eventually change the CO RS. While in the intense growth and deflation scenarios it remains the same of the regular growth scenario (RS 1Bx), under stagflation the CO case becomes RS 0Cx. This confirms that in the stagflation scenario, energy costs are less relevant in the determination of the *GC* and, therefore, the RSs with lower energy performance are paradoxically preferable, from an economic point of view, to the nZE solutions. In fact, this is the only scenario in which the reference RS shows lower *GC* than nZE solutions and close to the CO solutions. Interestingly, while in the deflation scenario the *GC* of the nZE solution is closer to the CO, in the stagflation scenario it is the reference solution to be closer to the CO.

Finally, Fig. 4 exhibits another major implication of the macroeconomic environment on LCC results and, therefore, one of the main original contribution of the proposed stochastic LCC approach. It clearly emerges that not only the mean *GC* of a given RS remarkably varies across scenarios. Somehow more surprisingly, also the *GC* variability strongly depends on the macroeconomic environment. The deflations scenario always shows the highest variability (about twice that of the reference growth scenario). This suggests that higher uncertainty is associated to low growth and, above all, low inflation. This is confirmed by the other two scenarios. Stagflation and intense growth both show, in all cases, similar variability slightly lower than the regular growth scenario.

In order to make the more significant results emerge in terms of investment gap, Table 6 summarizes the average *GC* values and the respective percentage differences of the reference and nZE solutions compared to the CO solution. Three aspects are worth commenting. First of all, compared to the regular growth scenario, the investment gap between CO and nZE RS slightly increases (from +40% to +46% and from +70% to +77% in the two nZE cases, respectively) under intense growth while more than doubles under stagflation (from +40% to +85% and from +70% to +179%, respectively). On the contrary, the investment gap almost halves under the deflation scenario (from +40% to +22% and from +70% to +45%, respectively).

Secondly, as already anticipated, the investment gap always significantly differs moving from the nZE RS 4Cx to the RS 4Cy case. In this latter case, the gap is always remarkably larger. It is a little lower than the double in the regular growth and intense growth scenarios, it is the double under deflation, while it becomes more than the double under stagflation. Thirdly, also the difference between nZE solutions and the reference solution in terms of investment gap noticeably depends on the underlying macroeconomic environment. Both nZE solutions show a much lower investment gap under deflation (+22% and 45% versus +215%, respectively) while the opposite occurs under stagflation (+85% and 179% versus +50%, respectively). Under the intense growth scenario values are closer to the reference growth with an investment gap that clearly rewards the nZE solutions compared to the reference case.

4.2. Macroeconomic scenario implications on costs shares and GC variability

To better highlight the main original contribution of the present approach, it seems informative to further investigate the comparison across scenarios. Two aspects deserve a more careful attention. Firstly, in order to better understand why different scenarios may imply different *GC* for the same RS, thus possibly altering the ranking among RSs, it is useful to investigate how they influence the three cost components (investment, maintenance and energy costs) during the calculation period (the time horizon considered for the LCC assessment). Fig. 5 shows the breakdown of these cost components on the *GC* for all the RSs under the four economic scenarios analyzed. Histograms are sorted by increasing energy performance (decreasing consumption), thus from the reference solutions to the nZE RSs. The difference in cost shares is huge across the RSs under the same scenario but also across the scenarios for a given RS. The share of the investment cost ranges from a minimum of less than 2% on *GC* for RS 0A under deflation to a maximum of about 82% for RS 2Cy under stagflation. The share of the maintenance cost ranges from a minimum of less than 1% for RS 0By under deflation to a maximum of about 29% for RS 4Cx under intense growth. The share of the energy cost reaches its minimum of about 6% for RS 4Cy under deflation and its maximum of about 98% for RS 0A under deflation.

Not only these cost shares clearly demonstrate how large can be the impact of the combination of the different RS and macroeconomic scenarios on *GC* amount and composition. It also gives a quantitative confirmation to the qualitative expectations about the

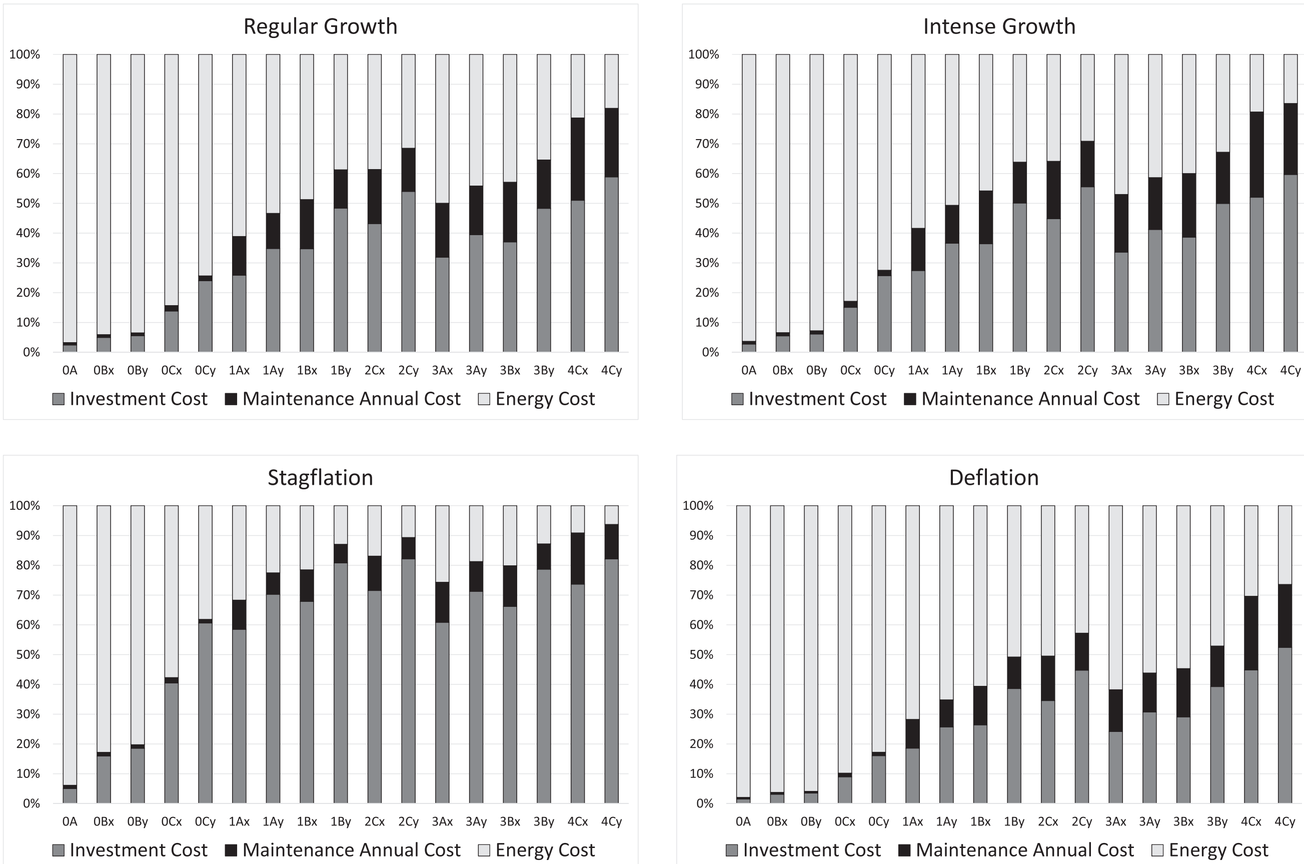

Fig. 5. *GC* shares of Investment, Maintenance and Energy costs for all RSs and macroeconomic scenarios.

direction of this impact. In particular, it demonstrates how dramatically the share of the investment cost increases under stagflation and to what extent the share of the energy cost is amplified under deflation regardless the RS. Therefore, stagflation penalizes the nZEB solutions in terms of economic convenience, while deflation makes the reference solution largely less convenient with respect to CO and nZEB RSs. It is also confirmed that also in terms of cost shares, the regular growth and the intense growth scenario tend to provide a similar LCC outcome.

In order to better show how the adopted approach is able to identify both the investment gap and the different cost structure between the CO and the nZE solutions, Table 7 selectively reports these cost shares only for these cases and the reference RS. It emerges that, as expected due to increase of energy performance, moving from the reference and the CO solutions to the nZE cases the investment and maintenance cost shares increase (due to the greater number of components with an increasing level of sophistication) while the energy cost share declines. This obviously occurs regardless the macroeconomic environment scenarios. In particular, under all macroeconomic scenarios, in the reference case, the combined investment and maintenance cost shares are lower than 5% and, consequently, the energy cost share is always higher than 95%. In the CO RS, the energy cost share drops substantially ranging between 46% and 61% while investment raises always above 25%. This shift from energy to investment cost is reinforced in the nZE RSs where the latter are always above 40% and always above the energy cost that is, in turn, always below 30%.

Differences between CO and nZE solutions, however, also emerge across scenarios. In particular, the largest difference between CO and nZE solutions is observed under the deflation

Table 7
GC shares of Investment (Inv.), Maintenance (Man.) and Energy (Ene.) costs for all CO, nZE and reference solutions under all macroeconomic scenarios.

Macro -economic Scenario	Cost-Optimal Solution			nZEB Solution “4C”						Reference Solution “0A”		
				“x” (MW on external wall and PVC frame on windows)			“y” (CaSi on external wall and W/A frame on windows)					
	Inv. (%)	Man. (%)	Ene. (%)	Inv. (%)	Man. (%)	Ene. (%)	Inv. (%)	Man. (%)	Ene. (%)	Inv. (%)	Man. (%)	Ene. (%)
Regular Growth	34.75	16.51	48.74	51.04	27.66	21.30	58.89	23.01	18.10	2.44	0.80	96.76
Intense Growth	36.44	17.74	45.82	52.04	28.63	19.32	59.69	23.86	16.45	2.76	0.90	96.34
Stagflation	40.48	1.80	57.72	73.69	17.19	9.13	82.12	11.59	6.29	5.01	1.12	93.86
Deflation	26.41	12.97	60.62	44.84	24.75	30.42	52.44	21.12	26.44	1.55	0.51	97.94

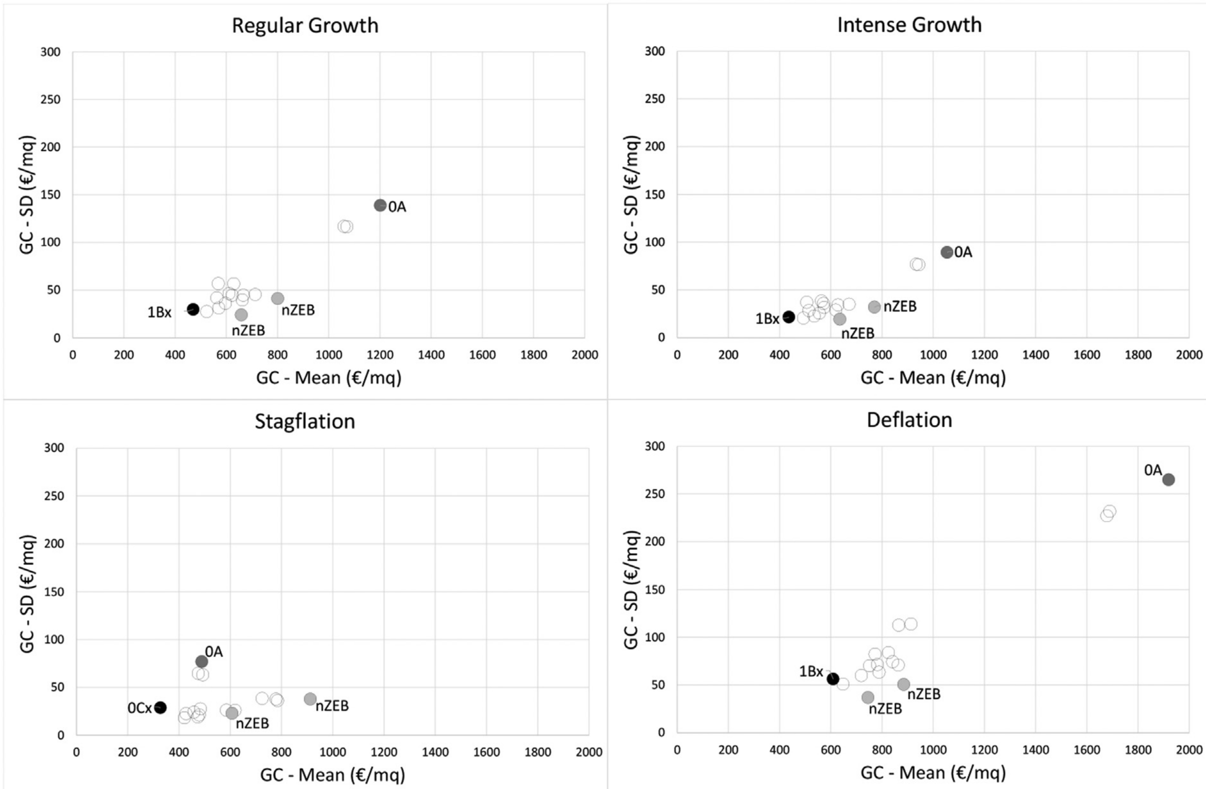

Fig. 6. RSs comparison within the *GC* mean - standard deviation space under alternative macroeconomic scenarios.

scenario. On the contrary, cost shares are the closest in the case of intense growth. This further confirms that what really matters in shaping the amount and composition of the *GC* emerging from the LCC calculation, is not the value of the growth and inflation rate separately, but their combination.

The second aspect to investigate further about the role of the macroeconomic environment concerns how the different scenarios can affect risk-averse decision makers due to the different *GC* variability they bring about. As already discussed, by influencing the shares of the different cost component of any RS, the macroeconomic scenario influences the investors' economic convenience, not only by affecting the respective *GC* but also their variability, thus riskiness. Eventually, investment decision makers look for the best combination between low *GC* and low *GC* variability. Thus, investment options can be ordered on a mean-variance space under the assumption that for risk averse investors the generic j-th RS is always preferred to the i-th RS (j-th RS dominates i-th RS) if $E(GCj) < E(GCi)$ and $VAR(GCj) < VAR(GCi)$, where $E(GCj)$ and $VAR(GCj)$ indicates the mean and the variance of the GC of the j-th RS (Bodie et al., 2018).

Fig. 6 juxtaposes the results obtained for all RS and under all scenarios within a mean - standard deviation space. RSs are positioned in this space with dots and only the reference, nZE and CO RSs are labelled. It clearly emerges that some scenarios show a larger standard deviation (SD) differential among RSs (Regular Growth and, above all, Deflation) while for the other cases SD is almost equal for all RSs thus turning out to be irrelevant in decision making (Intense Growth and, above all, Stagflation). Regardless the scenario, however, some general results still emerge.

First of all, the reference solution (RS 0A) always shows a higher *GC* variability and this makes it dominated in all macroeconomic scenarios but stagflation. This confirms that in no circumstance this solution can be considered economically rational. Secondly, in all scenarios there is at least one nZE whose *GC* standard deviation is lower than the CO solution. Thirdly, this nZE always is RS 4Cx that, consequently, always dominates the other nZE solution (RS 4Cy). In particular, RS 4Cx shows a *GC* whose standard deviation is always lower than 50 and a coefficient of variation always lower than 0.05 but in deflation scenario where it is slightly below 0.1.

Fig. 6 eventually demonstrates that in no macroeconomic scenarios it is possible to identify a dominant RS. At the same time, however, for a reasonable risk aversion degree, in three scenarios the preferred RS is always the CO case, thus behaving as the almost-dominant solution. Only under deflation case the nZE RSs can become preferable for some non-zero degree of risk aversion. This can be interpreted as a further confirmation that an investment gap between CO and nZE solutions not only exists, but it also occurs in terms of a higher *GC* uncertainty associated to the nZE cases. This evidently reinforces the need of policy instruments and measures filling this gap.

4.3. Sensitivity analysis

The stochastic LCC approach here adopted presents the main advantage to provide LCC outcomes in terms of both expected *GC* and its variability as a consequence of the stochastic nature of the macroeconomic variables entering the LCC calculation. However, this stochastic approach does not tell anything, by itself, on

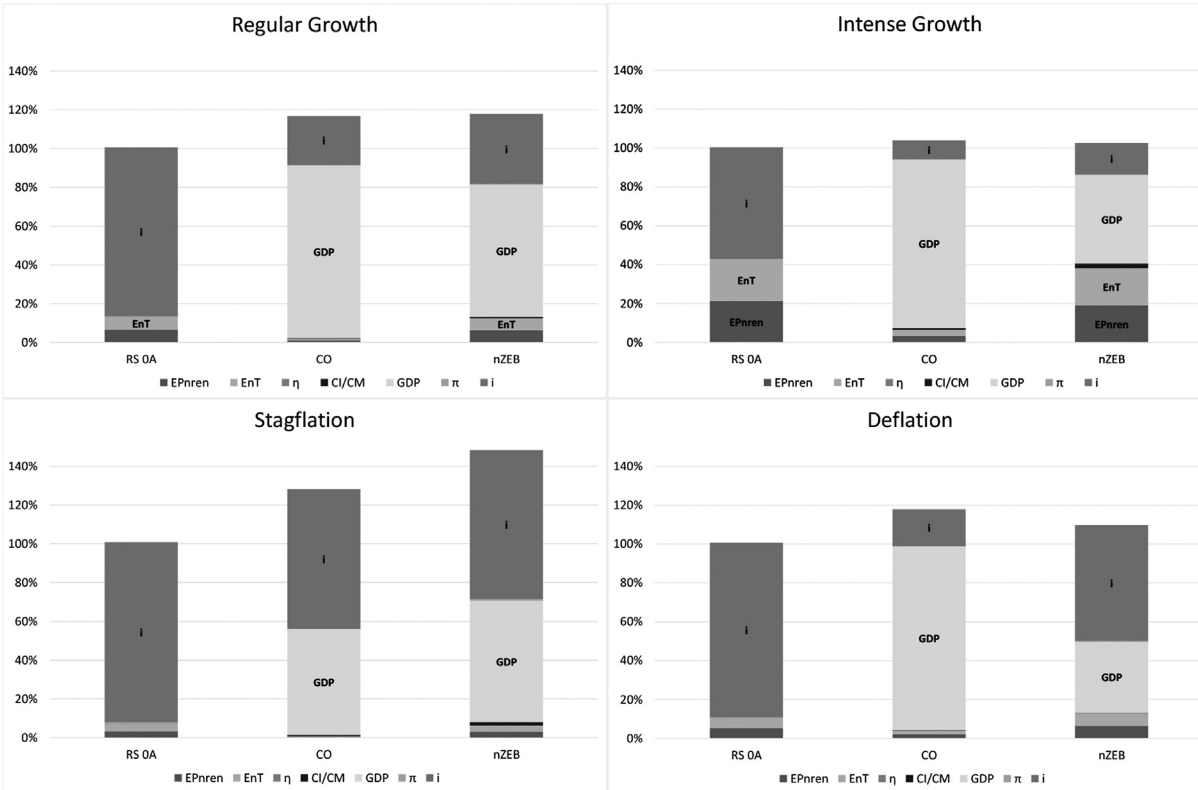

Fig. 7. Sensitivity Total Order Indices (STi) of the LCC inputs[a] under the four macroeconomic scenarios for the reference, CO and nZE RSs.
[a] Legend: EPnren = Non-renewable primary energy needs for winter heating and DHW; EnT = Energy tariff of the energy source considered; η = Heating system efficiency; CI/CM=Investment and Maintenance Costs; GDP = nominal GDP growth rate; π = inflation rate; i = nominal interest rate.

robustness of the LCC results, that is, to what extent *GC* mean and variance varies whenever the dataset entering the LCC calculation changes. Assessing such robustness seems critical for any proposed method in this field as it expresses the reliability and generalizability of its results and of the conclusions being drawn.

Here this robustness check is performed computing the *total order sensitivity index* (STi) with the Sobol method. The higher the value of the sensitivity indices, the most influential the respective input on the LCC outcome variance. By indicating which input is more influencing the output variance, the adopted SA indicates whether and to what extent LCC results remain robust under alternative cases (as expressed by different datasets entering the LCC calculation).

Fig. 7 displays the STi of the LCC input data under the four macroeconomic scenarios and for the three RSs of main interest here, that is, the reference (RS 0A), the CO and the nZEB (RS 4Cx) cases.

In all scenarios, for the reference case (RS 0A) the well-known tyranny of the interest rate ("tyranny of discounting" (Pearce et al., 2003)) is confirmed while for CO and, above all, for nZE the GDP growth rate is, at least, as important as the interest rate and often prevalent. With the only exclusion of the intense growth scenario, in all other cases, interest rate and GDP matters for more of 90% of the variability of LCC outcome. None of the other input, on the contrary, matters more than 6%. Therefore, the conclusion is that there is rather a combined tyranny of economic growth and interest rate not only in affecting the LCC outcome but also in determining its variability.

It also interesting to notice the SA results significantly varies across macroeconomic scenarios. Regular growth and deflation show quite similar indices, while stagflation and intense growth present differentiated patterns. Under stagflation, all three RSs show the higher index for the interest rate suggesting that in this macroeconomic environment this is the key variable to determine the LCC outcome variability. The intense growth scenario, on the contrary, represents the most peculiar case. Only in this circumstance, both EP_{nren} and EnT account for about 20% of variability in RS 0A and nZE cases, while the CO RS reaches the minimum index for the interest rate. In general term, under this macroeconomic environment, the interest rate significantly loses its relevance, while GDP growth and the technical characteristics of adopted solution becomes the key determinants of GC variability.

A final interesting evidence emerging from Fig. 7 concerns the sum of the individual STi. As this sum measures the contribution to the GC variance of any LCC input, including the variance caused by its interactions with other inputs, it may be > 1 (or >100%). In fact, it is = 1 only when the model is purely additive. It emerges that such interaction is minimum for the RS 0A case under all scenarios. On the contrary, both CO and nZE solutions show a significant interaction among inputs in all scenarios expect under intense growth. In particular, the sum of STi largely exceeds 100% (by 24% and 49%, respectively) in the stagflation case. This is a further confirmation that a macroeconomic environment showing boundary values of some variable (inflation rate, in this case) may affect the LCC outcome and its variability in those solutions showing a higher initial investment value and lower life-cycle costs.

5. Concluding remarks and policy implications

Improving energy savings towards climate-neutrality, particularly in the building construction sector, represents one of the crucial and most challenging targets of the EU energy and environmental policy. However, the most effective investment solutions to meet the abovementioned neutrality are not necessarily the most economically convenient and, therefore, are not those adopted by private or public decision makers. Covering this investment gap between the CO and the nZE renovation solutions for existing buildings should be the main purpose of policy instruments in this field.

The present paper aims to propose an original stochastic LCC approach to assess the determinants of this gap and, in particular, the technological characteristics of the interventions and the external macroeconomic environment as expressed by the key macroeconomic variables (GDP growth rate, discount rate, inflation rate, energy price) and their interdependence.

The application of this approach to a case-study building under several alternative renovation solutions and macroeconomic scenarios demonstrates the potential of the developed methodology in providing informative results on the nature of the investment gap between CO and nZEB solutions. It is confirmed that the cost-optimal solution tends to dominate the zero-energy solution. But results also reveal two often neglected aspects in this respect. Firstly, the cost-optimal solution may vary depending on the macroeconomic environment. In the present case, in particular, this occurs under stagflation. Secondly, there can be peculiar macroeconomic circumstances that can make the nZE solution competitive with the CO solution for risk averse investors, as the *GC* mean is just slightly higher but its variance significantly lower. This is observed under the deflation scenario. Eventually, the investment gap between cost-optimal and zero-energy solutions ranges between 22% and 85% with the highest value found under stagflation. Therefore, the proposed stochastic LCC approach is able to identify and quantify those macroeconomic scenarios when the gap eventually shrinks thus reducing the need of specific policy measures.

Results also suggest that the most conservative (and still the most frequently adopted) solutions are always dominated by both the CO and the nZE solutions. In this case, the investment gap with respect to the CO case may reach 215% and is higher than 100% in all scenarios with the only exception of stagflation where the gap is just 50%. Even more importantly from the perspective of a risk averse investor, these conservative solutions also show a larger *GC* variability in all macroeconomic scenarios. Again, however, variability is highly dependent on the macroeconomic context as it substantially shrinks under deflation. The proposed approach is thus able to demonstrate and quantify the relevance of the macroeconomic context under which risk averse investors make their decisions. In particular, it shows how under peculiar macroeconomic circumstances (like deflation and stagflation) the economic convenience of CO, nZE and conservative solutions may be affected to the point of altering investment choices themselves.

Performing a stochastic LCC calculation under alternative macroeconomic scenarios is also helpful to more deeply recognize when and why macroeconomic variables become critical in affecting the investment decision. In particular, under deflation, the energy costs always represent a major component of the *GC* (ranging from more than 95% for the conservative solution to about 30% in the nZE case). On the contrary, under stagflation, investment costs surface as a critical cost component reaching 80% of the *GC* for the nZE solutions. More generally, LCC results and the consequent sensitivity analysis show that the key determinants of the *GC* and of its variability (therefore, of investment decisions) should be not taken for granted. The same predominant role of the interest rate, often stressed by the literature on this topic, substantially depends on the characteristics of the intervention and on the macroeconomic context in which the investment is made.

The policy implications of the stochastic LCC results here presented seem remarkable. First of all, they suggest that the design of appropriate policy instruments should be conditioned on the specific macroeconomic environment in which they are going to be implemented. Secondly, and more importantly, as over the whole investment life this environment is unpredictable and variable, these policy instruments should be flexible enough in order to adapt to this changing external context, up to the extreme case of being activated/disactivated under specific macroeconomic conditions. How policy design should be adapted in order to achieve the abovementioned flexibility remains an open issue and requires further research in this field.

Given the relevance of these implication, it has also to be emphasized that the results here presented only concern a specific case study and mostly aim to illustrate the method's novelty and potential. Therefore, these results should be carefully validated and generalized by applying the approach to other case-studies, technical solutions, or possible macroeconomic conditions. In addition, the approach itself could be improved further. A possible research direction, in this respect, consists in extending the stochastic LCC calculation with an optimization algorithm automatically exploring over a larger set of non-predetermined EEM combinations. This would allow to simultaneously identify the cost-energy need Pareto frontier and compute the respective investment gap under alternative macro-economic scenarios. However, the present study makes clear that performing such a computer-based multi-objective optimization within the proposed stochastic LCC calculation is going to be very challenging for the arguably dramatic increase of computational requirements.

CRediT authorship contribution statement

Authors are listed in alphabetic order. The individual contribution may be identified as follows. **Edoardo Baldoni:** Data curation, Software, Validation, Writing - original draft, Writing - review & editing. **Silvia Coderoni:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Marco D'Orazio:** Conceptualization, Supervision. **Elisa Di Giuseppe:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Roberto Esposti:** Conceptualization, Supervision, Methodology, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.125606.

Annex 1

Table A.1
Nomenclature

Acronym	Definition
CaSi	Calcium silicate panels
C-E	Cost - Energy
CEN	European Committee for Standardization
CE_{RS}	Building annual energy costs
CI	Initial investment costs
CM	Annual maintenance costs
CO	Cost-Optimal
CO_2	Carbon dioxide
CP	Calculation Period
CS	Replacement costs
d	Discount rate
DHW	Domestic Hot Water
EEMs	Energy Efficiency Measures
EIA	Energy Information Administration
EP_{nren}	Non-renewable primary energy needs for winter heating and DHW
EPBD	Energy Performance of Buildings Directive
EU	European Union
GC	Global Cost
GDP	Gross Domestic Product
HDD	Heating Degree-Days
i	Interest rate
ISO	International Organization for Standardization
LCC	Life Cycle Costing
MSs	Member States
MVHR	Mechanical Heat Recovery Ventilation
MW	Mineral wool
nZE	nearly Zero Energy
nZEB	nearly Zero Energy Building
OECD	Organization for Economic Cooperation and Development
PL	Performance Level
PV	Photovoltaic system
PVC	Polyvinyl chloride
${R_t}^E$	Price development rates for energy
R_t^{disc}	Discount factor
${R_t}^L$	Price development rates human operation
PDFs	Probability Density Functions
RES	Renewable Energy Sources
RS	Renovation Solution
RSs	Renovation Solutions
SA	Sensitivity Analysis
STi	Sensitivity Total Order Indices
ST	Solar Thermal
SD	Standard Deviation
U	Thermal transmittance
USA	United States of America
x	EEMs including MW insulation and PVC windows frames
XPS	Insulation with extruded polystyrene
y	EEMs containing CaSi and wooden-aluminium frames
VAR	Vector AutoRegressive
VARX	Vector AutoRegressive with exogenous variables
VAR(x)	Variance of x
W/A	Wood/Aluminium
η	Heating system efficiency
π	Inflation rate

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