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Evaluation of economically optimal retrofit investment options for energy savings in buildings

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ABSTRACT

In this study, a techno-economic evaluation method for the energy retrofit of buildings is introduced, geared toward finding the economically optimal set of retrofit measures. Split incentives of building owners and users are considered explicitly in a conventional (static) evaluation to identify the investment alternatives maximizing the net present value (NPV). Energy price uncertainty for various distributional assumptions of the stochastic variables is addressed through Monte Carlo simulation. Results from the simulation are used to compute probabilities and expected NPVs. Based on this, a sequential (dynamic) evaluation method is developed, featuring a real options investment appraisal. The real options approach is introduced as an advancement in the practice of economic evaluation of building retrofit investment options. The new method is applied to an office building in Germany, illustrating its performance. The case study results indicate that energy price changes significantly affect the profitability of retrofit investments, and that high price volatility creates a substantial value of waiting, making it more rational to postpone the investment.

1. Introduction

Energy efficiency is at the heart of the European Union's "Europe 2020" strategy to become a smart, sustainable, and inclusive economy that is resource-efficient. In March 2011, the European Commission adopted the Communication "Energy Efficiency Plan 2011" [1]. It starts with the recognition that the EU is on course to achieving only half of its objective of reducing energy consumption by 20% through energy efficiency improvements. Noting that nearly 40% of final energy consumption in Europe is in buildings, the plan recognizes that the largest energy-saving potential lies in the building sector and hence focuses on instruments to increase the energy efficiency in buildings. Overcoming energy performance contracting problems, expanding access of Energy Service Companies (ESCOs) to innovative project-based financing, and requiring public authorities to refurbish at least 3% (by floor area) of their buildings, are some of the measures put forward in the plan.

Since the turnover of the building stock is low, the challenge to successfully reduce the energy consumption in the building sector over the next decades is to find effective strategies for retrofitting existing buildings [2]. Fortunately, recent technological advances offer promising retrofit solutions to increase the energy efficiency of buildings. Improving the thermal properties of a building's envelope (roof, external walls, windows, doors, and floors) is typically one of the most economical ways to reduce its energy needs under constant operating conditions. There are, however, numerous technically feasible retrofit alternatives with varying costs and different energy-saving potentials available to the building stock owners. An improvement in energy performance is therefore often the result of an optimization process of choosing from a selection of technically favorable and cost-effective measures. The selection of an economically optimal set of retrofit measures requires a preceding detailed technical evaluation of the building envelope, energy supply systems for heating and cooling, and external and indoor climate properties, so that feasible retrofit options are identified and their energy-saving potentials are computed accurately. Once all techno-economic parameters have been identified, economically optimal choices can be determined by comparing the investment expenditures with expected cost savings from energy conservation using standard methods from engineering-economics. There is, however, a great deal of uncertainty involved in the accounting of future cost savings often due to high volatility in energy prices. Since energy retrofit investments are typically of an irreversible nature, it is very important to adopt realistic assumptions about the uncertain future and to consider the option of postponing the investment expenditure if uncertainty has a significant impact on the economics of the retrofit options, implying a high value of waiting.

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Nomenclature

$B_{r,s,t}$	annual benefits of retrofit investment
$C_{r,t=0}$	investment costs
$C_{r,t\neq 0}$	annual operating costs
$CE_{s,t}^{base}$	cost of energy prior to retrofit
$CE_{r,s,t}^{new}$	cost of energy after retrofit
f	type of fuel
i	real interest rate (discount rate)
i_l	real interest rate of the loan
NPV	net present value
$p_{f,s}$	energy prices
$\dot{p}_{f,s}$	annual price change rate
$pr_{r,s}$	probability of achieving a higher NPV
PVB	present value of benefits
PVC	present value of costs
$Q_{f,t}^{base}$	final energy consumption w/o retrofit
$Q_{f,r,t}^{new}$	final energy consumption after retrofit
r	retrofit alternative
s	energy price scenario
$S_{r,t}$	subsidies for building installations that use renewable energy sources
t	time
tc	transaction costs (% of investment costs)
T	planning horizon
y	percentage of the rent increase allowed in the case of an energy retrofit

This study is based on Milanowski [2], extending her investment appraisal into an application with several distributional assumptions, scenarios, and decision criteria within a new method. The aim is to find the optimal set of retrofit measures, and introducing a real options analysis to evaluate the possibility of delaying the retrofit investment.

The paper is organized as follows. In Section 2, a literature survey is carried out, reviewing decision-making tools for energy retrofit of buildings, with a focus on their inherent economic analyses. In Section 3, the new method is presented, elaborating details of the economic evaluation and introducing a sequential real options investment appraisal to evaluate the option value of waiting under uncertainty. In Section 4, a case study building is introduced on which the new method is applied. Results from the application are reported, yielding valuable insights into the economics of alternative energy retrofit options under varying assumptions. Section 5 concludes.

2. Literature review

Various decision aid tools were developed to support and advise building stock owners with respect to retrofitting decisions for energy conservation. However, available tools mostly focus on the technical aspects of energy efficiency measures and, as a consequence, address economic aspects either insufficiently or inaccurately. An assessment of existing tools for energy retrofit can be found in Milanowski [2], the enriched version of which is summarized below.

The TOBUS software, which was developed in Switzerland during a 2-year European research project funded by the European Commission, provides an interactive aid tool for diagnosis and decision-making regarding office building retrofits [3]. It includes seven modules that address different aspects of the retrofit analysis and also includes investment costs but disregards future cash flows [4]. Accordingly, it neglects the possibility that retrofit options, which typically require high investment costs up-front but feature significant energy savings in subsequent years, might be more cost-effective than less expensive alternatives. Having evaluated a bundle of measures to reduce energy demand and to increase the occupants' level of comfort for various office building types in Switzerland, Jakob [5] highlights the benefits of concepts of juridical combinations of highly efficient technologies in terms of high energy efficiency (electricity and fuels), low discomfort, and low total annual costs. Thus, the importance of a comprehensive techno-economic evaluation method emerges.

Another example of a decision-making tool is the one developed by Chidiac et al. [6] as a screening method for cost-effective energy retrofit measures in Canadian office buildings. The method assesses the profitability of an energy efficiency measure with the discounted payback period rule (i.e. accounting for the time value of money). Although the cost analysis is preferable to a static comparison of initial costs, as conducted in the TOBUS tool, it remains inaccurate due to fixed assumptions for interest rates, inflation, and, most importantly, for energy prices, and the rates of change of these variables. Historical data of energy prices show high fluctuations and sometimes even reversals in trends, thus indicating that a linear development is only a rough approximation at best. Aside from the imprecision, maintenance costs of the improved devices have been neglected completely by Chidiac et al., despite the fact that most building installations cause considerable annual costs due to maintenance, inspection, and repair [7].

A review of residential energy analysis tools is provided by Mills [8]. Having evaluated 50 web-based and 15 disk-based residential tools, the author finds that few tools offer substantial decision-support content. It is noted that many tools provide estimates of baseline energy bills but no recommendations or estimates of potential savings, and still fewer of them address cost-effectiveness. Moreover, it is found that tremendous fragmentation and redundancy as well as inconsistency prevail among the tools in use, revealing the importance of applying a sound methodological framework.

Doukas et al. [9] present a decision-support model for the identification of the need for intervention and further evaluation of energy-saving measures in an existing building, based on the systematic incorporation of building energy management system data. As a result, the building's energy efficiency status is identified and energy-saving measures are proposed, including various retrofit options. The proposed options are inserted into a financial evaluation, where net present value (NPV), internal rate of return, and payback period are computed. Economic parameters, such as interest rates, fuel prices, etc., are based on deterministic assumptions and thus uncertainty is ignored.

Diakaki et al. [10] investigate the feasibility of the application of multi-objective optimization techniques to the problem of improving energy efficiency of buildings, in such a way that the maximum possible number of alternative solutions and energy efficiency measures may be considered. However, they find that no optimal solution exists for this problem due to the competition between the incommensurable decision criteria involved. In other words, the decision-maker has to take into account environmental, energy, financial, and social factors in order to reach the best possible and feasible solution. As the objectives are competitive, a feasible intermediary solution is aimed for. The issue of uncertainty is yet another concern that complicates the decision-making problem and that is not addressed by the multi-objective framework proposed.

A discussion of time, uncertainty, and irreversibility of energy retrofit investments is provided by Verbruggen et al. [11], who argue for the importance of a dynamic model of decision-making instead of the traditional static approach. The importance of a real options investment appraisal, employing a sequential decision framework, is documented. In this paper, with methodological focus, the ignoring of irreversibility and of preclusion by other applied studies is highlighted as an essential weakness.

Heo et al. [12] present a probabilistic method to support investments in energy retrofits of buildings while accounting for uncertainty. Arguing that nuances associated with the operation of buildings and their components are difficult to represent in building energy models, they present a new method that is based on Bayesian calibration of normative energy models. In a case study, they take into account uncertainty in physical properties, equipment performance, and investment costs. Economic performance, however, is evaluated in a case study that is based on the simple payback time criterion, and more detailed economic factors are ignored.

Overall, the brief literature review provided indicates various shortcomings in the way economic analysis of retrofit alternatives is conducted in different studies; typically, either energy price uncertainty is ignored or some other factors important for an economic evaluation are neglected.

3. Description of the new method

The new method used in this study includes four modules: (i) an energy management system data compilation module for buildings, which includes an interface to convert the energy data of different systems into a useable format; (ii) a tool to evaluate building energy performance based on the technical properties of the envelope, the energy supply systems for heating and cooling as well as the external climate conditions; (iii) a matrix of retrofit measures that includes all technically feasible alternative measures, their potential energy and CO_2 savings, investment and operating cost estimates, as well as additional descriptive information about special user demands and internal building ratings; and (iv) an economic evaluation module which is based on an NPV analysis that is done both conventionally (static) as well as sequentially (dynamic), featuring a real options investment appraisal. A distinction is made between two cases, where the building is either used by the owner or let to a tenant. Details of the economic evaluation procedure are provided in the following.

3.1. Definition of costs and benefits

3.1.1. Costs

For each retrofit alternative r, the initial investment expenditures ($C_{r,t=0}$) and annual operating and maintenance costs ($C_{r,t=1,\ldots,T}$), are discounted to the present value of costs (PVC_r):

$$\mathrm{PVC}_r = C_{r,t=0}(1+tc) + \sum\nolimits_{t=1}^{T} \frac{C_{r,t}}{(1+i)^t}, \tag{1}$$

where tc denotes the transaction costs, defined as a percentage of the initial investment $C_{r,t=0}$, i represents the real interest rate, t stands for the time period, and T is the planning horizon. Obviously, the first cost component in Eq. (1) only occurs at time $t = 0$ and consists of the total of additional investment costs for purchasing the considered retrofit package, and the transaction costs. The second component defines the discounted operating and maintenance costs.

3.1.2. Benefits

Agency Theory and Principal-Agent problems deal with asymmetric information that leads to moral hazard, adverse selection, and conflict of interest between two parties entering into a contract. The energy efficiency literature refers to this problem as the “investor/user dilemma”, one aspect that induces the “energy efficiency gap” (e.g. [13]), i.e. the paradox that seemingly cost-effective energy efficiency technologies only gradually penetrate the market. Split incentives arise in energy retrofit investments because it is mainly the user who benefits from the energy saving effect of a retrofit measure, whereas the investor pays for the cost of it. The impact of the two cases (building used by the owner vs. building let to a tenant) on the computation of benefits is explicitly considered in the following.

3.1.2.1. Building used by the owner. If the owner uses the building him-/herself, he/she will benefit from the energy conservation in future periods. In this case, obviously, energy prices play a crucial role in the computation of future energy cost savings. Accordingly, the benefits $B_{r,s,t}$ of retrofit alternative r at time t depend on the energy price scenario s as well.

$$B_{r,s,t} = CE_{s,t}^{\text{base}} - CE_{r,s,t}^{\text{new}}, \tag{2}$$

where $CE_{s,t}^{\text{base}}$ and $CE_{r,s,t}^{\text{new}}$, for a given energy price scenario s, denote the building’s cost of energy at time t in the two cases “base” (prior to retrofit) and “new” (after retrofit), respectively. Eq. (2) can be written in more explicit form as

$$B_{r,s,t} = \sum\nolimits_{f} (Q_{f,t}^{\text{base}} - Q_{f,r,t}^{\text{new}}) p_{f,s} (\dot{p}_{f,s})^t, \tag{3}$$

where $Q_{f,t}^{\text{base}}$ denotes the final consumption of fuel type f at time t that would occur in the case where no retrofit investment is undertaken. $Q_{f,r,t}^{\text{new}}$ denotes the final consumption of fuel type f at time t that is expected in the case where retrofit investment r is undertaken. The unit price of fuel type f in scenario s is represented by $p_{f,s}$; $\dot{p}_{f,s}$ denotes the annual price change rate (simulated through a Monte Carlo simulation under various energy price scenarios with different distributional assumptions).

The present value of benefits ($PVB_{r,s}$) is calculated as

$$PVB_{r,s} = S_{r,t=0} + \sum\nolimits_{t=1}^{T} \frac{B_{r,s,t}}{(1+i)^t}, \tag{4}$$

where $S_{r,t=0}$ defines possible subsidies for building installations, which is a non-recurring up-front benefit to the investor. Obviously, the second summand represents the discounted annual benefits of the retrofit path, which depends on the owner–user situation.

3.1.2.2. Building let to a tenant. In the case where the owner has let the building, he/she will not benefit from the energy cost savings. He/she may, however, profit from a rent increase if there is a legal provision.[1] In Germany, for example, since 2011 landlords have been entitled to increase the rent by 11% of the retrofit investment costs according to §559 of the German Civil Code (BGB).[2] Subsidies for the energy efficiency investment must be deducted from the expenditures. The benefit in each year is the same fixed percentage of investment costs net of subsidies. Hence

$$B_{r,t} = y(C_{r,t=0} - S_{r,t=0}), \tag{5}$$

where y denotes the percentage of net investment expenditures, which is allowed as a rent increase in case of an energy retrofit.

[1] It should be noted that there may be complex relations between energy performance and the value/higher rents of a building; e.g. when energy prices are low, tenants may not be willing to pay the higher prices resulting from formal allowances by governments to increase rents when buildings are more energy efficient.

[2] In contrast, the government of the United States provides landlord–tenant laws for rent control that vary in each state. The law in San Francisco, California, for example, limits annual rent increases due “to major capital improvement” to 10% of the yearly paid rent until the improvement has been paid off [14]. Major capital improvements are defined as work done that significantly adds to the worth of the property and/or prolongs the useful life of the building, e.g. replacing windows or the roof [15].

Accordingly, assuming that a legal rent increase (as in Germany) is possible and that market effects are negligible, the present value of benefits is calculated independently of energy price scenario assumptions as

$$PVB_r = S_{r,t=0} + \sum_{t=1}^{T} \frac{B_{r,t}}{(1+i)^t}. \tag{6}$$

3.2. Conventional (static) evaluation: invest now or never

The *NPV* is calculated as the sum of the discounted benefits and costs, depending on the owner's position, for each investment alternative *r* under each energy price scenario *s*, as follows.

3.2.1. Building used by the owner

$$NPV_{r,s} = PVB_{r,s} - PVC_r = S_{r,t=0} + \sum_{t=1}^{T} \frac{\sum_f (Q_{f,t}^{base} - Q_{f,r,t}^{new}) p_{f,s} (\dot{p}_{f,s})^t}{(1+i)^t} - \left(C_{r,t=0}(1+tc) + \sum_{t=1}^{T} \frac{C_{r,t}}{(1+i)^t} \right). \tag{7}$$

The energy price assumptions are embedded in the *NPV* formula, which is simulated by sampling random real energy prices and rates of energy price changes from the assumed probability distribution. Once the simulation has been completed, the mean value of the possible NPVs, $\overline{NPV}_{r,s}$, and the probability $pr_{r,s}$ of achieving an NPV at least at the level of $\overline{NPV}_{r,s}$, are determined. The expected *NPV* is then calculated for each investment alternative as

$$E(NPV_r) = \left(\sum_s pr_{r,s} \overline{NPV}_{r,s} \right) \tag{8}$$

That is, the $pr_{r,s}$ are normalized as $\left(pr_{r,s}/\sum_s pr_{r,s}\right)$ and used as an approximation of the probability to achieve NPV_r within the energy price scenario *s*. As no other likelihood can be assigned to the energy price scenarios, there is no other weighting and these are assumed to occur equally likely. Since $pr_{r,s}$ represents the probability to achieve an *NPV at least* at the level of $\overline{NPV}_{r,s}$, this is a rather conservative approach. Another conservative decision criterion, the maximin approach to maximize the minimum *NPV*, is also used. Hence, there are two conservative decision criteria:

1. Maximizing the minimum *NPV* of the different energy price scenarios, i.e. making the best of the worst that could happen;
2. maximizing the expected *NPV*, where probabilities are based on a conservative estimate resulting from the simulation as described above.

3.2.2. Building let to a tenant

Based on the assumption that energy prices have no impact on the *NPV* when the building is let to a tenant, there is no energy price scenario and the *NPV* of each investment alternative is computed as

$$NPV_r = PVB_r - PVC_r = S_{r,t=0} + \sum_{t=1}^{T} \frac{B_{r,t}}{(1+i)^t} - \left(C_{r,t=0}(1+tc) + \sum_{t=1}^{T} \frac{C_{r,t}}{(1+i)^t} \right). \tag{9}$$

3.3. Sequential (dynamic) evaluation: real options investment appraisal

Rising energy prices may turn a non-profitable retrofit alternative into a profitable one if the savings from energy conservation start to outweigh the costs in due time. If, on the other hand, an energy price increase turns out to be smaller than anticipated, an alternative evaluated initially as profitable may turn out to be non-profitable. Recognizing this potential and considering the possibility of delaying the investment (if feasible), in order to wait and see how energy prices develop, and to decide accordingly, may prevent some poor decision-making.

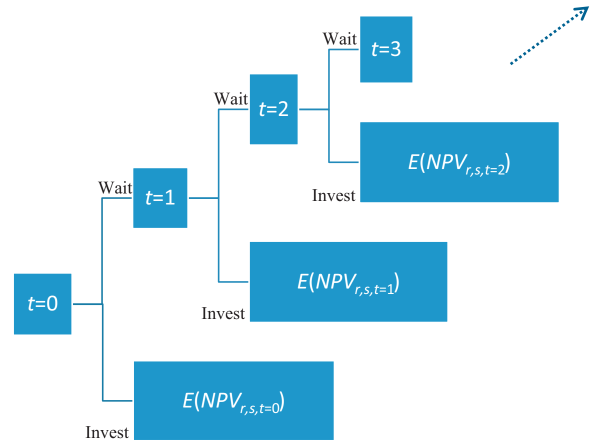

Fig. 1. Sequential decision framework for the real options investment appraisal.

The possibility of delaying the investment is considered on a sequential basis, period by period. In each period, an independent Bernoulli trial (a single experiment that can have one of two possible outcomes) is performed, where the investor invests with probability $(1 - pr)$ or waits with probability *pr*. The probability *pr* is determined from the frequency of achieving a higher NPV in the following period and used in computing the succeeding period's expected *NPV*, as shown in Eq. (10).[3] $NPV_{r,s,t}$ and $NPV_{r,s,t+1}$ both result from a Monte Carlo simulation, with the difference being the progress of a period. In this respect, it is assumed that energy prices have evolved, as was projected in the scenarios (implying that some uncertainty is resolved), and the next period's projections are added to historical data so as to compute new *NPVs* for the succeeding period:

$$E(NPV_{r,s,t+1}) = NPV_{r,s,t}\, pr\{NPV_{r,s,t+1} > NPV_{r,s,t}\} \tag{10}$$

The decision criterion to wait/invest is then defined as indicated by inequality (11). If the next period's expected NPV is greater than the preceding period's *NPV*, the investor is recommended to wait.

$$NPV_{r,s,t} \overset{?}{\leq} \frac{1}{1+i} \cdot E(NPVr_{,s,t+1}) \begin{cases} \text{No} \rightarrow \text{Invest} \\ \text{Yes} \rightarrow \text{Wait} \end{cases} \tag{11}$$

Fig. 1 provides an illustration of the sequential decision framework. An immediate investment occurs at $t = 0$ if $NPV_{r,s,t}$ is positive and $NPV_{r,s,t} > (1/1+i)E(NPV_{r,s,t+1})$.

Otherwise, the investor waits up to the next period and meanwhile some uncertainty dissolves. In this case, the same decision loop continues in the succeeding period, as $NPV_{r,s,t+1}$ is compared

[3] For the case of a GBM process, where no probability estimates are available, the computed *NPVs* for each period are assumed to be equal to the expected values, i.e. $NPV_{r,s=GBM,t} = E(NPV_{r,s=GBM,t})$.

Table 1
Descriptive data of the case study building.

General description		
Building use		Office and administration
Year of construction		1900
Number of floors		3
Net volume		978 m^2
Gross volume		1450 m^2
Heated floor space		400 m^2
Total final consumption		539.5 kWh/(m^2 a)
Primary energy demand		605.4 kWh/(m^2 a)
Building installation technology		
Model year		1982
Type		Central gas-fired boiler
Nominal heat output		72 kW
Building components		
Basement		Unheated
	Area	117 m^2 (ceiling)
Exterior wall	Type	Massive construction
	Area	327 m^2
Windows	Type	Wooden frame, single-glazed
	Area	54 m^2
Attic		Fully developed
Roof	Shape	Gabled roof, 45° pitch
	Type	Wood construction
	Area	168 m^2

Data source: Meyer [17], own compilation.

Energy retrofit measures		Area (m²)	Specific additional costs (€/m²)	Total additional costs (€)
Basement	Insulation below basement ceiling	117	21.00	2,457.00
Exterior wall	Exterior insulation on outside wall	327	63.50	20,764.50
Window	Complete replacement of windows	54	75.00	4,050.00
Roof	Insulation to gabled roof	168	69.40	11,659.20
Building installation	Condensing oil-fired boiler		1,520.00	1,520.00
	Condensing gas-fired boiler		2,600.00	2,600.00
	Wood pellet boiler		12,100.00	12,100.00
	Brine-water heat pump		17,797.00	17,797.00

Fig. 2. Additional costs of retrofit measures applied in the case study.
Data source: Meyer [17].

with $E(NPV_{r,s,t+2})$ to decide whether to invest at $t = 1$ or wait until $t = 2$. If the investor is recommended to wait, $NPV_{r,s,t+2}$ is compared with $E(NPV_{r,s,t+3})$, etc.

4. Case study

4.1. The case study building

The case study analyzes a public administration building constructed in 1900 in Aachen, Germany.[4] Using such an old building increases potential energy and cost savings, and helps to reveal the economics of different alternatives in a more pronounced manner. It is a non-air-conditioned, three-storey office building with a solid construction that is protected by law as a historic monument. Therefore, the range of possible energy efficiency measures is restricted by architectural and aesthetic aspects relevant for national heritage considerations. The building is heated with a central gas-fired boiler, which dates back to 1982 and thus has outlived its average expected lifetime of 20 years. With a primary annual energy demand of 605.4 kWh/m^2 and a total final consumption for heating of 539.5 kWh/m^2, the energy demand of the building exceeds roughly three times the reference values for old buildings stipulated in the 2009 German Energy Savings Regulation [16]. Further information on the building's installation technology and components can be found in Table 1.

The technical aspects, including energy efficiency improvement potentials, were analyzed in detail in Meyer [17], yielding a set of technically feasible and energetically reasonable retrofit options. For the building envelope, these include insulation of the gabled roof, exterior insulation of the outside walls, insulation of the basement ceiling, and the replacement of windows. For the building installation, four different alternative heating systems are considered: (i) a condensing oil-fired boiler, (ii) a condensing gas-fired boiler, (iii) an electric brine-water heat pump, and (iv) a wood pellet boiler. An overview of these measures, with a listing of the *additional cost of energy retrofit* for each measure, is provided in Fig. 2.

The additional cost of the energy retrofit excludes the basic expenditures needed for a non-energy retrofit, assuming that the energy retrofit will be done additionally to a non-energy retrofit. For example, the maintenance of exterior walls on average necessitates painting every 30 years. For the painting, scaffolding needs to be put up. If the decision of an energy retrofit is given, some additional costs in excess of the scaffolding arise, which are defined as additional costs of the energy retrofit. It should be noted that in many cases it may be that energy retrofits are only accepted when standard renovation works are planned, or energy retrofits alone may be too expensive when not linked to standard retrofitting. Therefore, building renovations should be planned so as to reduce energy use while increasing indoor comfort and improving the architectural appearance of the facades. The combined undertaking of energy and non-energy retrofits may affect the sequential decision-making as conflicting priorities can arise: an energy retrofit that appears to be economically more advantageous to delay, for example, may conflict with the desire to carry out the non-energy retrofit immediately in order to enhance the indoor comfort level or the outside appearance as soon as possible.

If there is no necessity of a non-energy retrofit, then the full cost of carrying out the energy retrofit is taken into account.

4.2. Economic analysis

4.2.1. Energy price uncertainty

There exists a significant debate over how energy prices should be modeled. Despite a large body of empirical literature, there is no consensus yet as to the best way to capture the true dynamics of energy price changes [18]. In our study, the variability in energy prices is considered through a Monte Carlo simulation with 100,000 trials. Historical time series of real energy prices and price change rates for fuel oil, natural gas, electricity, and wood pellets were evaluated to fit an appropriate probability distribution. However, due to the random price swings of the energy carriers, there exists no matching stochastic distribution. An overview of different price

[4] Although the application is based on an office building due to ease of data availability, there is no restriction of the method specific to office buildings. Thus, the new approach suggested is applicable to residential buildings as well.

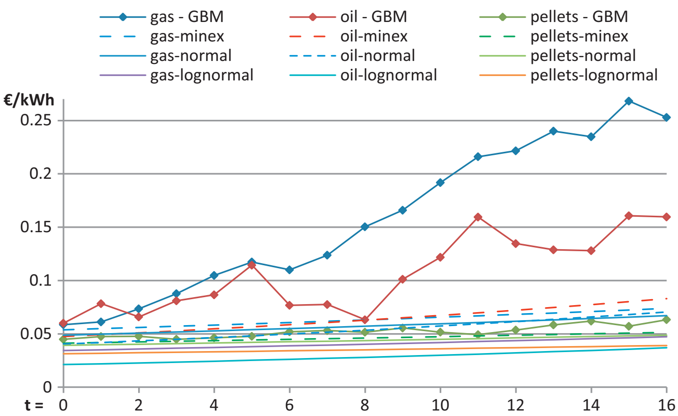

Fig. 3. Fossil fuel price trajectories.

forecasting methodologies for electricity is presented in Aggarwal et al. [19]. The study reveals no superiority of one approach over another on a consistent basis, bringing out the importance of testing various assumptions. In our study, the minimum extreme, normal, and lognormal distributional assumptions are employed for the initial price, with a logistic probability distribution for price growth rates (which represents the best fit according to historical data). Furthermore, a Geometric Brownian Motion (GBM) is employed for the energy prices, which introduces stochastic variability in the price change rates. The parameters of the GBM are estimated based on historical data for 1999–2010. Accordingly, the following four price scenarios were defined:

1. minimum extreme distribution for energy prices and Logistic Probability Distribution (LPD) for price growth rates;
2. normal distribution for energy prices and LPD for the rate of the price change;
3. lognormal distribution for energy prices and LPD for the rate of the price change;
4. GBM for energy prices, which implies stochastic variability in price change rates.

The implied price trajectories for fossil fuels and electric energy are shown in Figs. 3 and 4, respectively. Other parameter value assumptions are shown in Table 2, together with typical value ranges and the values used in our case study.

4.2.2. Conventional (static) evaluation: invest now or never

Results of the economic analysis are presented in the following (A_j denotes building envelope retrofit options; B_j represents building installation retrofit options and C_j stands for complete envelope and installations retrofit options; the coding of investment alternatives j can be found at the end of the article).

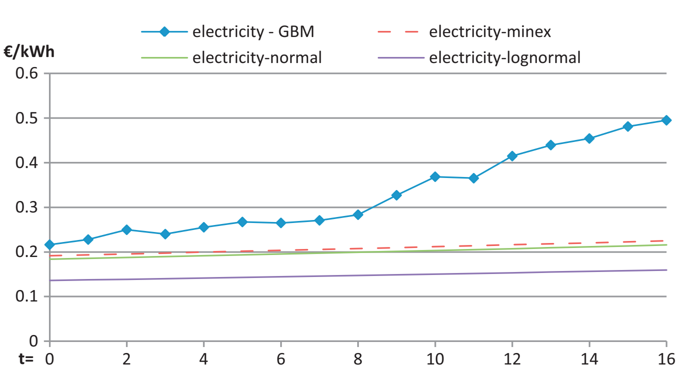

Fig. 4. Electric energy price trajectories.

4.2.2.1. Building used by the owner. Table 3 summarizes the mean NPV results for the various distributions (on which the energy price scenarios are based) and retrofit options. The two decision criteria, minimum mean *NPVs* and expected *NPVs*, are indicated in the rightmost column for all technically feasible retrofit options. It can be seen that all outcomes for the building envelope retrofit yield a positive *NPV*, whereas some of the building installation retrofit alternatives have a negative *NPV*, depending on the distributional assumption. The fact that the same retrofit option has both a positive and negative *NPV* under different energy price trajectories (e.g. B3 is negative for all energy price scenarios except GBM; B4 is positive for all energy price scenarios except min. extreme, etc.) indicates the significant impact of energy price developments on the profitability of investment decisions, and a need for the kind of modeling proposed. The final decision with respect to the two decision criteria is not obvious: the maximum of the minimum mean *NPVs* yields C2 as the favorable choice, whereas the maximum of the expected *NPVs* indicates A5 as the most favored one. Delaying the investment decision might be a further option worthy of consideration. The possibility of a sequential decision-making is explored through a real options investment appraisal, as introduced in the section describing the new method, and results are presented in Section 4.2.3 below.

4.2.2.2. Building let to a tenant. In this case, the investment appraisal is assumed to be independent of energy prices and, therefore, does not contain an uncertain component of energy costs. Accordingly, there is no need for an energy price simulation and only a single deterministic NPV is computed for each retrofit alternative. The results obtained are shown in Table 4. All NPVs are negative, which shows that the legally allowed rent increase of 11% does not justify any energy retrofit investment for the building's owner on economic grounds.

4.2.3. Sequential (dynamic) evaluation: real options investment appraisal

In the sequential decision-making application, two-year time steps are used to define the length of a period. Thus, in comparison to annual time increments, the computational burden is reduced and energy price effects can be better observed, since the price difference between two successive periods is higher. The dynamic evaluation is made for four periods: $t=0, 2, 4, 6$. For each period, results are computed in the form of an *NPV* matrix (as depicted in Table 3 for the static case), accompanied by probabilities of achieving a higher NPV in the following period (as determined from the simulation results). The sequential decision framework is then applied to the matrices, yielding the results shown in Table 5.

It can be seen from Table 5 that "waiting" is more profitable in the GBM energy price scenario for all retrofit alternatives. This is because of the high volatility and rapid increase inherent in the GBM price trajectories. In the case of rather smooth and moderate energy price changes, as implied by the other energy price scenarios, the value of waiting is limited and case-specific. It is found that a value of waiting arises under moderate and smooth energy price changes, particularly when there is a fuel switch. This can be observed from the results for retrofit options B3 (pellet boiler), B4 (heat pump), C3 (complete envelope retrofit + pellet boiler) and C4 (complete envelope retrofit + heat pump). Clearly, there is no value of waiting for a building envelope retrofit, unless significant energy price fluctuations are expected.

Table 2
Parameter assumptions employed in the case study.

Parameter		Typical value ranges	Values used in the case study
Transaction costs	tc	3.00–8.00%	7.00%
Discount rate – self-funded retrofit	i	2.25–5.00%	4.22%
Discount rate – externally funded retrofit		2.17–7.87%	
Renewable energy subsidy:	$S_{r,t=0}$		
Electric brine-water heat pump			
≤10 kW		€2400	With a required thermal input of
>10–20 kW		€2400 + 120 €/kW	72 kW: €7200
>20–100 kW		100 €/kW	
Wood pellet boiler		36 €/kW (min. €2000)	€2592
Rent increase	y	0–11% of retrofit investment costs	11% of retrofit investment costs

Source: Milanowski [2], modified.

Table 3
NPV simulation results for Case I: building used by the owner.

	Min. extreme		Normal		Lognormal		GBM		Criteria	
	$\overline{NPV}_{r,s}$ (€)	$pr_{r,s}$	$\overline{NPV}_{r,s}$ (€)	$pr_{r,s}$	$\overline{NPV}_{r,s}$ (€)	$pr_{r,s}$	$\overline{NPV}_{r,s}$ (€)	$pr_{r,s}$	Min{$\overline{NPV}_r$} (€)	$E\{NPV_r\}$ (€)
A1	3190	38.4%	3269	36.4%	3348	35.5%	8540	50.0%	3190	4912
A2	10,369	38.4%	10,812	36.4%	11,255	35.5%	40,330	50.0%	10,369	20,011
A3	14,288	38.4%	14,541	36.4%	14,794	35.5%	31,408	50.0%	14,288	19,797
A4	14,292	37.2%	14,657	37.8%	15,020	35.5%	38,903	50.0%	14,292	22,206
A5	42,139	38.4%	43,279	36.4%	44,418	35.5%	119,182	50.0%	42,139	66,933
B1	−23,872	69.4%	29,457	41.9%	29,199	45.4%	71,165	50.0%	−23,872	21,584
B2	19,832	53.8%	25,861	41.9%	25,570	46.4%	13,132	50.0%	13,132	20,789
B3	−67,695	54.4%	−96,168	61.5%	−98,541	69.0%	103,372	50.0%	−98,541	−47,798
B4	−23,669	44.9%	44,542	42.5%	45,542	39.9%	98,009	50.0%	−23,669	42,571
C1	33,086	47.9%	49,158	37.0%	50,224	34.9%	68,870	50.0%	33,086	50,648
C2	43,791	36.9%	46,619	37.0%	47,676	41.1%	52,732	50.0%	43,791	48,102
C3	890	42.7%	−5942	100.0%	−5468	38.8%	87,306	50.0%	−5942	15,538
C4	2041	44.1%	22,281	41.5%	23,699	40.6%	95,548	50.0%	2041	38,333

Note: as the Geometric Brownian Motion (GBM) does not have such a probability, a conservative estimate of 50% has been used for $pr_{r,s=\mathrm{GBM}}$.

Table 4
NPV simulation results Case II: building let to a tenant.

Envelope retrofit	NPV_r (€)	Installation retrofit	NPV_r (€)	Complete retrofit	NPV_r (€)
A1	−461	B1	−285	C1	−7584
A2	−3893	B2	−487	C2	−7787
A3	−759	B3	−1964	C3	−9263
A4	−2186	B4	−2491	C4	−9790
A5	−7299				

Table 5
NPV simulation results with the possibility of delaying the investment: wait (W) or invest (I).

	Min. extreme			Normal			Lognormal			GBM		
	t = 0–2	t = 2–4	t = 4–6	t = 0–2	t = 2–4	t = 4–6	t = 0–2	t = 2–4	t = 4–6	t = 0–2	t = 2–4	t = 4–6
A1	I	I	I	I	I	I	I	I	I	W	W	I
A2	I	I	I	I	I	I	I	I	I	W	W	I
A3	I	I	I	I	I	I	I	I	I	W	W	I
A4	I	I	I	I	I	I	I	I	I	W	W	I
A5	I	I	I	I	I	I	I	I	I	W	W	I
B1	I	I	I	I	I	I	I	I	I	W	W	I
B2	I	I	I	I	I	I	I	I	I	W	W	I
B3	W	W	W	W	W	W	W	W	W	W	W	I
B4	W	W	W	I	I	I	I	I	I	W	W	I
C1	I	I	I	I	I	I	I	I	I	W	W	I
C2	I	I	I	I	I	I	I	I	I	W	W	I
C3	W	I	W	W	I	I	W	W	W	W	W	I
C4	W	I	W	I	I	I	I	I	I	W	W	I

5. Conclusions

Investments in building energy retrofits are subject to irreversibility, energy price uncertainty, and split incentives, which complicates the determination of optimal investment alternatives. In this paper, a new techno-economic evaluation method for (energy) retrofits of buildings is introduced, where these highly relevant issues are tackled. Energy price uncertainty is addressed through a Monte Carlo simulation under various distributional assumptions. Most NPV assessments are based on static decision-making, although a dynamic sequential approach is needed in the presence of uncertainty, which is the case in energy retrofit investments. In this paper, a real options investment appraisal method is introduced as an advancement in the economic evaluation of building retrofit investment alternatives. Applications of both a conventional (static) investment appraisal and the proposed sequential (dynamic) evaluation method featuring a real options analysis are presented on a case study office building in Aachen, Germany. To our knowledge, this is the first application of a real options approach to investment appraisal for energy retrofits of buildings. The case study results reveal that

- energy price changes indeed significantly affect the profitability of retrofit investments;
- the legally allowed rent increase of 11% in Germany alone does not justify an energy retrofit investment for owners of buildings;
- there is no value of waiting with regard to building envelope retrofit if energy price increases remain moderate and smooth;
- building installation retrofit may imply a value of waiting, especially if there is a change in energy carrier; and
- in the case of highly volatile prices waiting becomes a more profitable option.

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Appendix A. Indexation of the energy retrofit options for buildings considered

Building envelope:

A1: Insulation of basement ceiling
A2: Exterior insulation of outside wall
A3: Window replacement (incl. frames)
A4: Insulation of gabled roof
A5: Retrofit of complete building envelope (A1 + A2 + A3 + A4)

Building installations:

B1: Condensing boiler for fuel oil
B2: Condensing boiler for natural gas
B3: Pellet boiler
B4: Brine-water heat pump

Complete retrofit of building envelope and installations:

C1: A5 + B1
C2: A5 + B2
C3: A5 + B3
C4: A5 + B4

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