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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 methodology for energy retrofit of buildings is introduced, geared towards 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 methodology is developed, featuring a real options investment appraisal. The methodological advancements introduced are applied to an office building, illustrating the model's performance. The case study results indicate that energy price changes significantly affect the profitability of retrofit investments, and that increased price volatility creates a substantial value of waiting, making it more rational to postpone the investment. Further insight is gained on various aspects of economic decision-making concerning energy retrofit of buildings.

Keywords: Building energy efficiency, Energy conservation, Net present value, Real options

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 due to the often 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.

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 methodology 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 methodology is presented, elaborating details of the economic evaluation and introducing a sequential real options investment appraisal methodology to evaluate the value of waiting under uncertainty. In Section 4, a case study building is introduced on which the economic analysis methodology is employed. Results from the application arereported, 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 [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 methodology emerges.

Another example of a decision-making tool is the one developed by Chidiac et al. [6] as a screening methodology for cost-effective energy retrofit measures in Canadian office buildings. The methodology 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 in this study, 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 methodology.

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 exogenously fed into the model and are, obviously, based on deterministic assumptions and thus ignore the implicit uncertainty.

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.

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 ignorance of irreversibility and preclusion of other applied studies is highlighted as an essential weakness.

Overall, the literature review reveals the lack of a comprehensive techno-economic evaluation methodology and negligence of crucial factors and uncertainty in the economic analysis of retrofit alternatives.

3. Methodology

The methodology 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 methodology 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 ($I_{r,t=0}$), annual interest payments ($IP_{r,t}$) for externally financed capital, and annual operating costs ($OC_{r,t}$), are discounted to the present value of costs, PVC_r:

$$PVC_r = I_{r,t=0} \cdot (1+tc) + \sum_{t=1}^{T} \frac{IP_{r,t}+OC_{r,t}}{(1+i)^t}, \tag{1}$$

where *tc* denotes the transaction cost, defined as a percentage of $I_{r,t=0}$, i represents the real interest rate, t stands for the time period, and T is the planning horizon. Obviously, the first cost component in (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 costs and interest payments. The interest payments for annuity loans are computed as follows (cf. [12]):

$$IP_{r,t} = \begin{cases} I_{r,t=0} \cdot i_l & \text{for } t \leq T_{gp} \\ I_{r,t=0} \cdot i_l \cdot \frac{(1+i_l)^{T_l - T_{gp}} - (1+i_l)^{t - T_{gp}}}{(1+i_l)^{T_l - T_{gp}} - 1} & \text{for } T_{gp} < t \leq T_l \,, \end{cases} \tag{2}$$

where i_l is the real interest rate of the loan, T_l the duration of the loan, and T_{gp} the grace period. During the grace period only interest but no redemption of the credit is paid to the bank. Once T_{gp} is over, the annual interest payments diminish in line with the remainder of the debt.

Note that the above definition of cost is the same for both user/owner situations, i.e. it does not matter whether the building is used by the owner or let to a tenant. This is because operating costs do not include energy costs but define the additional costs arising from maintenance, inspection, and repair of the installed energy-efficient devices. The change in energy cost is accounted for in the calculation of benefits, where the owner/user situation plays a crucial role.

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”, a situation that induces an energy efficiency gap (e.g. [13]). Split incentives arise in energy retrofit investments because the user benefits from the energy conservation of a retrofit, whereas the investor pays for the cost of it. The impact of the two cases (building used by the owner, building let to a tenant) on the computation of benefits is explicitly considered in the following.

(i) 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.

$$B_{r,s,t} = EC_{s,t}^{base} - EC_{r,s,t}^{new}, \tag{3}$$

where $EC_{s,t}^{base}$ and $EC_{r,s,t}^{new}$, for a given energy price scenario *s*, denote the building's energy cost at time *t* in the two cases "base" (prior to retrofit) and "new" (after retrofit), respectively. Equation (4) can be written in more explicit form as

$$B_{r,s,t} = \sum_q \left(Q_{q,t}^{base} - Q_{q,r,t}^{new}\right) \cdot p_{q,s} \cdot \left(\dot{p}_{q,s}\right)^t, \tag{4}$$

where $Q_{q,t}^{base}$ denotes the final consumption of energy carrier type *q* at time *t* that would occur in the case where no retrofit investment is undertaken. $Q_{q,r,t}^{new}$ denotes the final consumption of energy carrier type *q* at time *t* that is expected in the case where retrofit investment *r* is undertaken. The unit price of energy carrier *q* in scenario *s* is represented by $p_{q,s}$; $\dot{p}_{q,s}$ 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)* is calculated as

$$PVB_{r,s} = S_{r,t=0} + \sum_{t=1}^{T} \frac{B_{r,s,t}}{(1+i)^t}, \tag{5}$$

where $S_{r,t=0}$ defines possible subsidies for building installations that use renewable energy sources, such as pellet boilers or heat pumps, 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.

(ii) 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. In Germany, for example, since 2011 landlords have been entitled to increase the rent by 11% of the retrofit investment costs according to Law §559 of the German Civil Code (BGB).[1] 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

$$B_{r,t} = y \cdot \left(I_{r,t=0} - S_{r,t=0}\right), \tag{6}$$

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

Hence, the present value of benefits does not depend on energy price scenario assumptions and is calculated as

$$PVB_r = S_{r,t=0} + \sum_{t=1}^{T} \frac{B_{r,t}}{(1+i)^t} \ . \tag{7}$$

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.

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[1] 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].

i) Building used by the owner

$$
\begin{aligned}
NPV_{r,s} &= PVB_{r,s} - PVC_r \\
&= S_{r,t=0} + \sum_{t=1}^{T} \frac{\sum_q \left(Q_{q,t}^{base} - Q_{q,r,t}^{new}\right) \cdot p_{q,s} \cdot \left(\dot{p}_{q,s}\right)^t}{(1+i)^t} \\
&- \left(I_{r,t=0} \cdot (1+tc) + \sum_{t=1}^{T} \frac{IP_{r,t} + OC_{r,t}}{(1+i)^t}\right). \qquad (8)
\end{aligned}
$$

In (8), $IP_{r,t}$ is determined as given by (2). 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 a NPV at least at the level of $\overline{NPV_{r,s}}$, are determined. The expected NPV is then calculated for each investment alternative as

$$E(NPV_r) = \left(\sum_s pr_{r,s} \, \overline{NPV_{r,s}}\right) \qquad (9)$$

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.

ii) Building let to a tenant

As 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

$$\begin{aligned} NPV_r &= PVB_r - PVC_r \\ &= S_{r,t=0} + \sum_{t=1}^{T} \frac{B_{r,t}}{(1+i)^t} \\ &- \left(I_{r,t=0} \cdot (1+tc) + \sum_{t=1}^{T} \frac{IP_{r,t}+OC_{r,t}}{(1+i)^t}\right), \end{aligned} \qquad (10)$$

where $IP_{r,t}$ is determined according to (2).

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.

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 [11].[2] $NPV_{r,s,t}$ 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

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[2] 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. $NPV_{r,s=GBM,t} = E(NPV_{r,s=GBM,t})$.

resolved), and the next period's projections are added to historical data so as to compute new NPVs for the succeeding period:

$$E\left(NPV_{r,s,t+1}\right) = NPV_{r,s,t} \cdot pr\left\{NPV_{r,s,t+1} > NPV_{r,s,t}\right\}. \tag{11}$$

The decision criterion to wait / invest is then defined as indicated by inequality (12). If the next period's expected NPV is greater than the preceding period's NPV, the investor is recommended to wait.

$$NPV_{r,s,t} \overset{?}{\leq} \frac{1}{1+i} \cdot E\left(NPV_{r,s,t+1}\right) \tag{12}$$

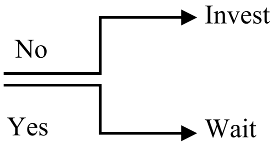

Figure 1 provides an illustration of the sequential decision framework. An immediate investment occurs at *t*=0 if $NPV_{r,s,t}$ is positive and $NPV_{r,s,t} > \frac{1}{1+i} \cdot E\left(NPV_{r,s,t+1}\right)$. Otherwise, the investor waits up to the next period and meanwhile some uncertainty dissolves. In this case, the same decision loop continues in the succeeding period, as $NPV_{r,s,t+1}$ is compared 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 $E\left(NPV_{r,s,t+3}\right)$ etc.

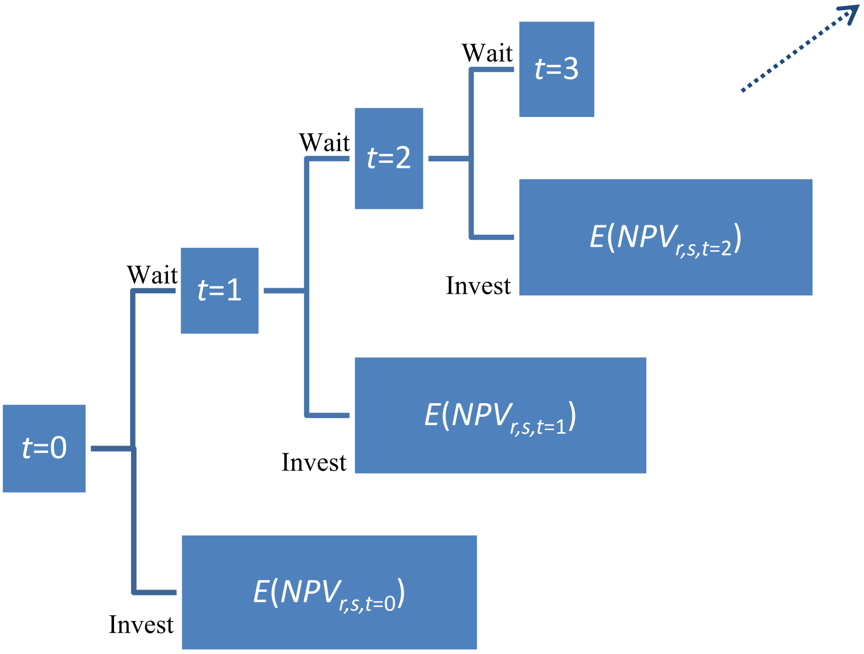

Figure 1. Sequential decision framework for real options investment appraisal

4. Case Study

4.1. The case study building

The case study analyzes a public administration building constructed in 1900 in Aachen, Germany.[3] 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/m² and a total final consumption for heating of 539.5 kWh/m², 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 Figure 2.

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[3] Although the application is based on an office building due to ease of data availability, there is no restriction in the methodology specific to office buildings. Thus, the methodology is applicable to residential buildings as well.

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		539.50 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

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

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

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

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 forecasting methodologies for electricity is presented in [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 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. Geometric Brownian Motion for energy prices, implied stochastic variability in price change rates.

The implied price trajectories for fossil fuels and electric energy are shown in Figures 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.

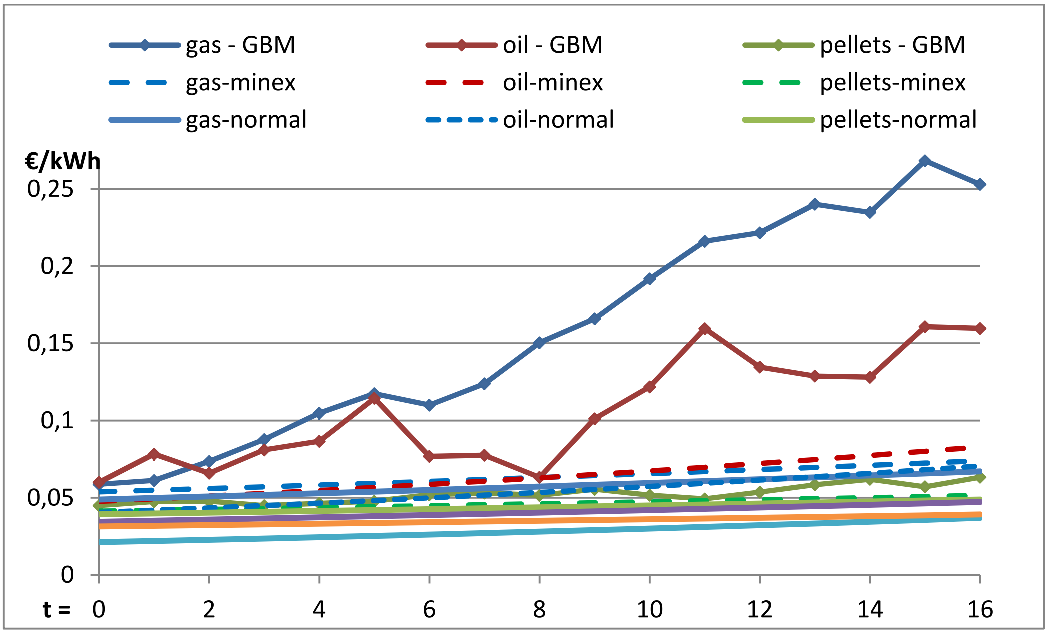

Figure 3. Fossil fuel price trajectories

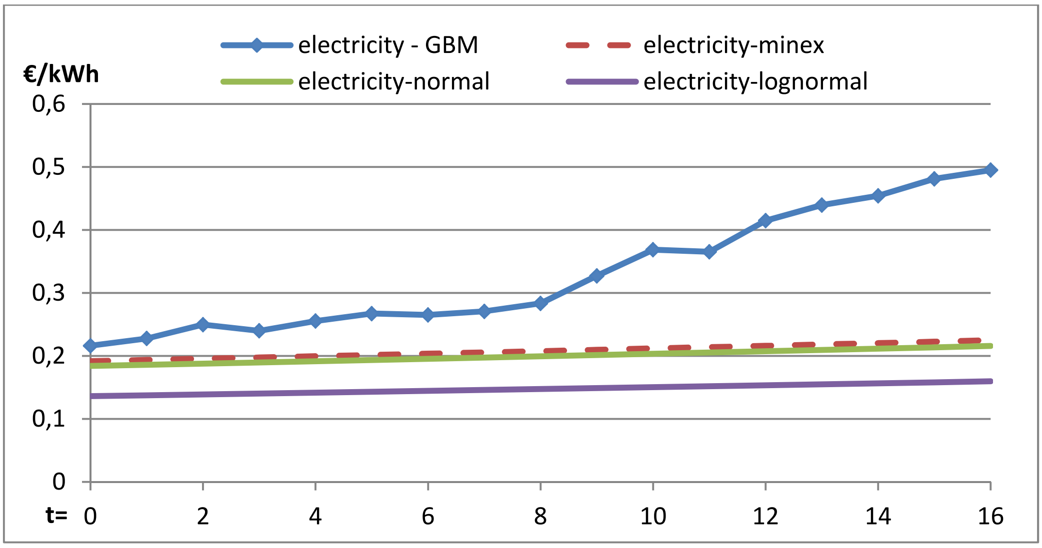

Figure 4. Electric energy price trajectories

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 – externally funded	***i***	2.25% - 5.00% 2.17% - 7.87%	4.22%
Renewable energy subsidy: - Electric brine-water heat pump ≤ 10 KW > 10 - 20 KW > 20 - 100 KW - Wood pellet boiler	$S_{r,t=0}$	€2,400 €2,400 + 120 €/kW 100 €/kW 36 €/kW (min. €2000)	With a required thermal input of 72 kW: €7200 €2592
Rent increase	***y***	0-11% of retrofit investment costs	11% of retrofit investment costs

Source: Milanowski [2], modified

4.2.4. 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 envelope and installation complete retrofit options; the coding of investment alternatives j can be found at the end of the article):

i) 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 C1 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 methodology section, and results are presented in section 4.2.5 below.

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

	Min. Extreme		Normal		Lognormal		GBM		Criteria	
	$\overline{NPV}_{r,s}$ (€)	$pr_{r,s}$	$\overline{NPV}_{r,s}$ (€)	$pr_{r,s}$	$\overline{NPV}_{r,s}$ (€)	$pr_{r,s}$	$\overline{NPV}_{r,s}$ (€)	$pr_{r,s}$	$\boldsymbol{Min\{\overline{NPV}_r\}}$ (€)	$\boldsymbol{E\{NPV_r\}}$ (€)
A1	2,661	38.4%	2,734	36.4%	2,810	35.5%	8,032	50.0%	2,661	4,386
A2	5,954	38.4%	6,367	36.4%	6,792	35.5%	36,034	50.0%	5,954	15,616
A3	13,382	38.4%	13,618	36.4%	13,861	35.5%	30,570	50.0%	13,382	18,902
A4	12,122	37.2%	11,783	37.8%	12,471	35.5%	36,491	50.0%	11,783	19,708
A5	33,778	38.4%	34,840	36.4%	35,935	35.5%	111,127	50.0%	33,778	58,623
B1	-24,413	69.4%	29,056	41.9%	28,451	45.4%	70,561	50.0%	-24,413	21,019
B2	18,843	53.8%	25,243	41.9%	24,602	46.4%	13,670	50.0%	13,670	20,283
B3	-72,817	54.4%	-100,301	61.5%	-103,349	69.0%	105,339	50.0%	-103,349	-51,062
B4	-33,349	44.9%	34,757	42.5%	35,606	39.9%	100,202	50.0%	-33,349	36,172
C1	24,347	47.9%	40,380	37.0%	41,305	34.9%	76,982	50.0%	24,347	**46,819**
C2	34,766	36.9%	37,620	37.0%	38,535	41.1%	61,325	50.0%	**34,766**	44,397
C3	-12,188	42.7%	-64,777	100.0%	-18,580	38.8%	97,329	50.0%	-64,777	-12,322
C4	-15,792	44.1%	4,339	41.5%	5,672	40.6%	105,796	50.0%	-15,792	28,394

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

ii) Building let to a tenant

In this case, the investment appraisal is 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 owner on economic grounds.

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	- 706	B1	- 437	C1	- 11,622
A2	- 5,966	B2	- 747	C2	- 11,933
A3	- 1,164	B3	- 3,172	C3	- 14,358
A4	- 3,350	B4	- 4,267	C4	- 15,453
A5	- 11,186				

4.2.5. 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 (2) is then applied to the matrices, yielding the results shown in Table 5.

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	W	W	W	I	I	W	W	W	W	W	I
C4	W	W	W	I	I	I	I	I	I	W	W	I

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.

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 techno-economic evaluation methodology is introduced, where all these highly relevant issues are tackled. Energy price uncertainty is addressed through a Monte Carlo simulation under various distributional assumptions. Both a conventional (static) and sequential (dynamic) evaluation methodology are introduced and applied to a case study building. The case study results reveal that:

- energy price changes indeed significantly affect the profitability of retrofit investments;
- a legally allowed rent increase of 11% does not justify an energy retrofit investment for building owners;
- 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 and rapidly increasing prices, waiting becomes a more profitable option.

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Nomenclature

$B_{r,s,t}$	annual benefits of retrofit investment
$EC_{s,t}^{base}$	energy cost prior to retrofit
$EC_{r,s,t}^{new}$	energy cost after retrofit
i	real interest (discount) rate
i_l	real interest rate of the loan
$I_{r,t}$	initial investment expenditures
$IP_{r,t}$	annual interest payments
NPV	net present value
$OC_{r,t}$	annual operating costs
$p_{q,s}$	energy prices
$\dot{p}_{q,s}$	annual price change rate
$pr_{r,s}$	probability of achieving a higher NPV
PVB	present value of benefits
PVC	present value of costs
q	type of energy carrier
$Q_{q,t}^{base}$	final energy consumption w/o retrofit
$Q_{q,r,t}^{new}$	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
T	planning horizon
T_l	duration of the loan
T_{gp}	grace period
y	percentage of the rent increase allowed in the case of an energy retrofit

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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