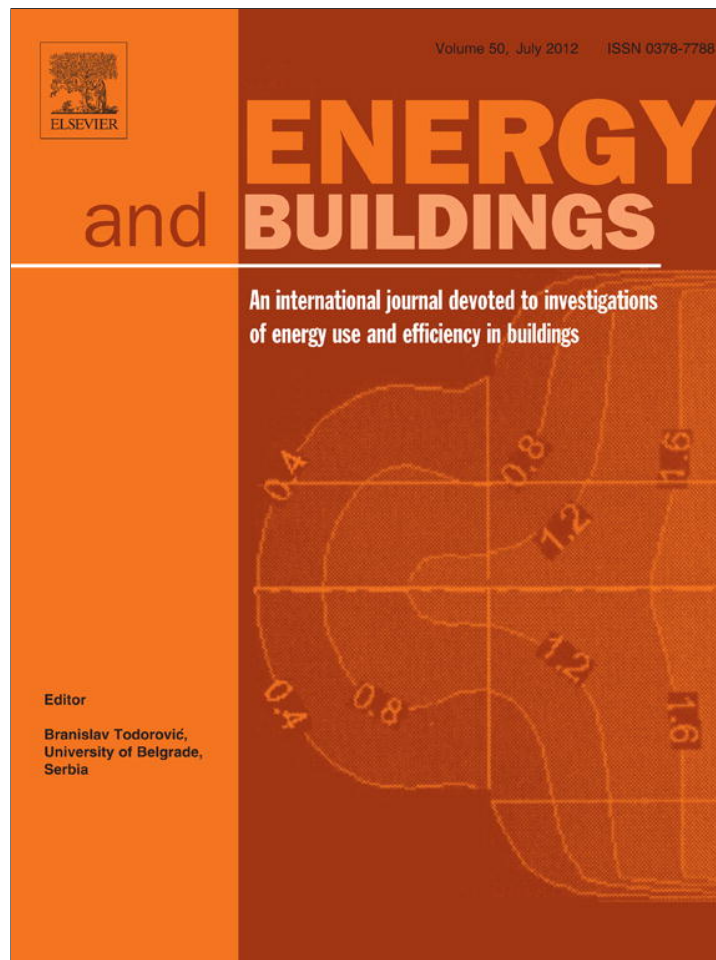


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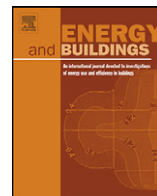


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Including fuel price elasticity of demand in net present value and payback time calculations of thermal retrofits: Case study of German dwellings

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ABSTRACT

In the domestic heating sector a number of different mathematical models are used to evaluate the economic viability of thermal retrofit measures. Currently, however, none of these models incorporate the effect of fuel price elasticity of demand. This paper offers a method for incorporating a factor for fuel price elasticity into models for assessing the net present value and payback time of thermal retrofits of existing homes. A set of working equations is developed, and empirically tested in a case study, a housing estate retrofit project in Ludwigshafen, Germany. The value used in these equations for year-on-year price elasticity, -0.476 , is derived from further empirical studies. The inclusion of price elasticity is found to lower the net present value by 14–24% and lengthen the payback time by 5 years in some cases, and hundreds of years in others. It also shows CO₂ saved over the technical lifetime of the retrofit measures to be 15–24% lower than anticipated. These findings have implications for government policy and investment decisions of businesses, private households and housing providers.

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1. Introduction

This paper explores how the inclusion of price elasticity of demand affects estimates of payback time and net present value of thermal upgrades of existing homes. A mathematical model is developed, and to illustrate its effect quantitatively it is applied to a particular set of empirical observations of a housing estate in Ludwigshafen. The fuel price elasticity value used in this illustration is also estimated from recent empirical studies.

The element of price elasticity is missing from models typically used to calculate the economic viability of thermal retrofit projects. In Germany, for example, simple algebraic models are offered by organisations such as the Passivhaus Institut¹ [1] and the Institut Wohnen und Umwelt² [2], none of which include price elasticity. This is also absent in models typically offered to estimate the economic viability of thermal upgrades in Switzerland [3,4], the United Kingdom [5], Japan [6], Greece [7], Denmark [8], South Africa [9], and Belgium [10].

More generally, the element of price elasticity of demand is absent from theoretical discussions of what is involved in estimating the economic viability of housing energy efficiency

measures [11–13], and often of energy efficiency measures in general [14].

However, this paper shows how existing NPV models can be modified to include a factor for price elasticity of demand, without changing their basic structure or putting them beyond the reach of people who are not professional economists.

This paper argues that without considering price elasticity, payback time models tend to overestimate the net present value and underestimate the payback time of thermal retrofit measures and thereby make them appear more economically efficient than they are in practice. They can also overestimate the CO₂ savings these measures can bring. This can lead to poorly informed investment decisions, and distort the allocation of resources for climate change mitigation.

Domestic space and water heating is a major consumer of non-renewable energy and is responsible, in Europe, for some 25% of greenhouse gas (GHG) emissions [15]. European governments are therefore demanding increasingly high thermal standards for new builds, with attempts to reach 'zero energy' or 'zero emission' home standard within the next decade [16]. However, most existing homes will still be standing in 2050, by which time GHG emissions are required to fall by 80%. Most of these homes are severely energy-inefficient. In Germany, for example, the average energy performance rating (EPR) of dwellings is around 225 kWh per square metre of living area per year (kWh/m² a), while the average EPR required for a new build is currently 70 kWh/m² a and incentives are offered for homes achieving even lower EPRs, while passive houses usually achieve an EPR of 15 kWh/m² a [17].

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Some caution is needed with these figures, however, as empirical studies show that the actual average level of consumption of heating energy in Germany is some 33% lower than the EPR, at around 150 kWh/m² a [18–20]. Nevertheless, this will still need to be considerably reduced if climate policy goals are to be met.

European governments and the EU Commission are promoting, incentivising and regulating for thermal refits of existing homes so as to bring down these buildings' heating energy demand significantly. Germany is one of the most advanced countries in this regard. Its home heating regulations, the *Energieeinsparverordnung* (EnEV), introduced in 2002, require homes to be thermally refitted whenever a portion of the building envelope is being repaired or renewed. The EnEV was upgraded in 2009, so that comprehensive refits now have to reach an EPR of 100 kWh/m² a or lower, while partial refits have to reach the new-build standard for each section refitted [20]. There are plans to tighten these standards by a further 30% in 2012.

A serious problem with thermal refits to such high standards is their cost. The cost of a comprehensive refit to current standards ranges from €250 to €1200 per m² of living area, depending on the size, substance and geometric form of the dwelling, and where it lies in relation to the sun [4,21]. The German government uses a three-pronged approach in its attempts to persuade homeowners to refit their properties: 'demand, incentivise, inform' (*fördern, fördern, informieren*) [22]. A major part of the last of these is promoting the idea that thermal refits to EnEV standards are 'economically viable' (*wirtschaftlich*), i.e. they pay back within the technical lifetime of the refit measures. In fact, the law that proscribes the parameters of the EnEV restricts these regulations to demanding only measures that meet this criterion of economic viability.

There are a number of methodologies for calculating the economic viability of energy efficiency measures in general and thermal refit measures in particular [12,13]. German government literature almost invariably uses a 'net present value' (NPV) methodology, and this was used in the expert reports that were commissioned to prove that the thermal standards demanded in the EnEV drafted for 2002 and 2009 were economically viable [1,23]. The dominance of this methodology can also be seen in its frequent use in other government-commissioned technical reports [24, 190ff], in promotional material from the German Energy Agency (*Deutsche Energie-Agentur* – DENA), and in pamphlets from the Housing Ministry (*Bundesministerium für Verkehr, Bau und Stadtentwicklung* – BMVBS). However, these often break from a pure NPV framework and also allude to the expected payback time of refit measures.

The basic approach of a NPV methodology is to compare the cost of the refit measures, with the value of the fuel saved long-term as a result of these, adjusted to current euro values (=NPV). If the latter is equal to or greater than the former, the refit measures are said to be economically viable.

The challenge with a NPV (or payback time) methodology is to include appropriate parameters, with appropriate values, in calculating the cumulative value of the fuel saved (or time to pay back) as a result of the retrofit. In most current models for thermal refits these parameters are: the expected technical lifetime of the refit measures; the expected annual fuel savings; the expected annual percentage increase in the price of heating fuel; and the discount rate. While the values assigned to these are highly contestable, the focus of this paper is on how they play out together when a further parameter, price elasticity of demand for heating fuel, is both omitted from, and included in, the mathematical models that bring these factors together. Discussion may be found elsewhere on the issues involved in setting values for the expected lifetime of the thermal refit measures [4], the future price of fuel [15, 29ff], and the discount rate [24–26].

Fuel price elasticity of demand has the effect of reducing the quantity of future purchases of fuel, both for retrofitted and non-retrofitted dwellings. While in percentage terms the reductions are the same for both, in absolute values they are greater for dwellings that do not retrofit, as these have higher energy demand. Hence, from a purely mathematical perspective, fuel price elasticity brings an extra net saving for refraining from retrofitting, compared to retrofitting. The challenge is to incorporate this factor into NPV and payback time models so that its effect can be quantified.

Whatever value we set for fuel price elasticity is contestable. An elasticity value can be based on empirical studies of past years, but assumptions have to be made as to how this will continue in the future. Further, a fall in consumption associated with a rise in fuel price does not necessarily prove that the latter caused the former, even if stochastic effects such as temperature swings are taken into account. There may also be other causes running in parallel with price rises, such as growing environmental concern, increasing skill in running heating systems efficiently, and social shifts in how rooms are used. Further, the impact of price elasticity on NPV and payback time depends crucially on the future price of fuel, which is itself a contestable value. However, since the modelling in this paper is based on straightforward equations, it is possible to see how various ranges of future fuel price rise affect the outcome.

This paper proceeds as follows. Section 2 outlines the basic elements of a NPV methodology and discusses how this would be affected by inclusion of price elasticity, formalising this with a set of equations. Section 3 establishes a value for fuel price elasticity of demand for domestic heating fuel in Germany, based on recent empirical studies. Section 4 applies the methodologies and empirical findings to a case study of a set of German dwellings refitted to four different thermal standards. Section 5 supplements this with equations for a payback time model, and uses this for purposes of comparison. Section 6 considers the implications of price elasticity for CO₂ savings. Conclusions are summarised and discussed in Section 7.

2. Developing the methodology

In this section we develop a set of basic equations for use in calculating NPV both with and without fuel price elasticity of demand.

2.1. Models without price elasticity

The NPV model we are considering calculates NPV using equations of the form:

$$V = Q_1 P_1 \frac{A^N - 1}{A - 1}, \quad (1)$$

where V is the NPV, i.e. the total value of all the fuel savings in N years, converted into year 1 values, Q_1 = quantity of fuel saved (kWh) in year 1, P_1 = price (€/kWh) of fuel in year 1, N = expected technical lifetime of the refit measures, in years, and A = annuity factor.

The annuity factor is a composite factor combining the fuel price increase and the discount rate:

$$A = \frac{1 + f/100}{1 + d/100},$$

where f = expected percentage annual increase in the price of fuel and d = percentage discount rate, i.e. the cost of finance, including bank interest rate, consumer price index, risk factor and opportunity costs factor.

The point of including a discount rate is that fuel price savings in, say, year 10, are decreased by the fact that the number of €s to be gained in 10 years time will be worth less than the same number

of €s gained today, i.e. they are decreased by the discount rate. For later reference we can simplify variables by setting:

$$F = 1 + f/100 \text{ and } D = 1 + d/100$$

The factor $(A^N - 1)/(A - 1)$ in Eq. [1] above is the sum of the geometric series:

$$A^0 + A^1 + A^2 + \dots + A^{(N-1)}.$$

It should be noted that there are variations on the way these variables are treated in various versions of this methodology. For example, Kah et al. [1] propose a 2-stage model, where the refit measures are presumed to be as good as new for the first 20 years, then deteriorate according to a formula for the next 30 years. Jakob [4] treats each type of refit measure (e.g., new windows, external wall insulation, new boiler) separately, giving each its own independent payback time and economic viability. Kumbaroğlu, and Madlener [11] include further factors, such as the maintenance costs of the refit measures. They also project possible refit scenarios into the future. However, the general mathematical form of the modelling is the same in all these. This paper uses the most basic form of the model so that the issues for including price elasticity are made as clear as possible.

It should also be noted that the variables in the equation are often expressed per square meter of living area, in which case Q is in kilowatt-hours per square metre per year (kWh/m² a), P is in euros per square metre (€/kW h) as before, and V is in euros per square metre (€/m²). These variables can alternatively be expressed in larger value units, such as total nationwide savings, or savings for a particular project.

2.2. Price elasticity of demand and its effect on quantity of fuel purchased

The price elasticity of demand, E , is defined as the percentage change in quantity of goods purchased for a one percent change in their price.

$$E = \frac{(Q_{n+1} - Q_n)/Q_n}{(P_{n+1} - P_n)/P_n},$$

where Q_n = quantity purchased at time n , and P_n = price at time n .

But $P_{n+1} = P_n \times F$, hence $(P_{n+1} - P_n)/P_n = F - 1$. Hence $E = [(Q_{n+1} - Q_n)/Q_n]/(F - 1)$.

Rearranging this we get:

$$Q_{n+1} = Q_n(EF - E + 1).$$

Let $B = EF - E + 1$.

Hence $Q_{n+1} = Q_n \cdot B$, or more generally,

$$Q_n = Q_1 B^{n-1}. \tag{2}$$

We note here that B is a composite variable made up of both the price elasticity of demand for fuel (established from past consumer behaviour), and the annual rate of increase in the price of the fuel (which is expected to occur in the future). B behaves as a modified annuity factor. It is constant over time – i.e. the same for each year – as long as the year-on-year price elasticity and the rate of increase in fuel price are constant. It is important to note, however, that the price elasticity for a change in price from year n to year $n + 1$ will be different from that for a change in price from year n to year $n + x$, where x is an integer other than 1. There are 3 reasons for this. Firstly, people may respond differently to large changes in price compared to small annual changes, and these responses can only be determined empirically. Secondly, the two factors being compared are asymmetrical: the change in price is measured relative to its lower beginning, while the change in quantity is measured relative to its higher beginning – or the opposite way around if prices

are falling and quantity is increasing. Thirdly, the function is exponential, not linear, so the factor $\Delta Q/\Delta P$ varies depending on the distance between its beginning and end points on the n -axis (see discussion in, e.g. [27]). However, combining the elasticity and the increase in annual fuel price into one variable, a modified annuity factor, enables us to incorporate it into long-run calculations using simple geometric sequences, as it models the phenomenon of each year's purchasing decision being considered as a function of the previous year's, with the effects accumulating over time. We must nevertheless bear in mind that human beings might have all sorts of reasons for breaking their annual patterns if, for example, the paucity of the amount to be purchased reaches some threshold of intolerance.

Using the formula for the sum of the geometric series we can now derive a formula for the total quantity of fuel, Q_T , purchased in N years:

$$Q_{TN} = Q_1 \frac{B^N - 1}{B - 1} \tag{3}$$

2.3. The cost of fuel purchased

Let C_n be the cost of fuel purchased in year n .

$$C_n = Q_n P_n = Q_1 B^{n-1} P_1 F^{n-1},$$

so

$$C_n = Q_1 P_1 (BF)^{n-1}. \tag{4}$$

Again using the formula for the sum of a geometric series we find C_{TN} , the total cost of fuel purchased over N years:

$$C_{TN} = Q_1 P_1 \frac{(BF)^N - 1}{BF - 1}. \tag{5}$$

This gives us the total number of euros spent on fuel in n years. However, since euros spent in future years are worth less than euros spent today, we need to discount future purchase costs to translate them into today's euro values.

2.4. The discounted cost of fuel purchased in future years

To find C_{Dn} , the discounted cost of fuel purchased in year n at discount rate $d\%$, we set $D = 1 + d/100$, and note that:

$$C_{Dn} = \frac{C_n}{D^{n-1}} = Q_1 P_1 \frac{(BF)^{n-1}}{D^{n-1}},$$

so

$$C_{Dn} = Q_1 P_1 \left(\frac{BF}{D} \right)^{n-1}. \tag{6}$$

Again using the formula for the sum of a geometric series we find C_{TDN} , the total discounted costs of N years' consumption:

$$C_{TDN} = Q_1 P_1 \frac{(BF/D)^N - 1}{(BF/D) - 1}. \tag{7}$$

We note that these equations apply to both a non-refitted home and a refitted home: in each case Eq. [7] gives us the NPV of all the fuel consumed over N years. Hence to calculate the NPV of the fuel saved through refitting, we could calculate both cases and subtract the result for the refitted home from that for the non-refitted home. More simply, we can substitute S_1 , the fuel saved in year 1, for Q_1 , and the answer will be the NPV of the fuel saved over N years, namely S_{TDN} :

$$S_{TDN} = S_1 P_1 \frac{(BF/D)^N - 1}{(BF/D) - 1}. \tag{8}$$

We now have all we need to calculate the NPV of a thermal refit, provided we know the year-on-year fuel price elasticity.

2.5. Translating long-run to year-on-year fuel price elasticity

Year-on-year price elasticity is most appropriate for considering household responses to fuel price changes, because the heating fuel billing for most German householders is set annually. Householders can then respond to the change in fuel price by attempting to adjust their consumption, on a year-by-year basis. However, empirical studies do not always give us year-by-year fuel price elasticity directly; instead they often give the fuel price elasticity between the two years they consider in their investigations (e.g. [28]). How this translates into a year-on-year value depends on fuel price changes during that period. This subsection therefore offers a way of translating long-run price elasticity into year-on-year price elasticity. Since this is intuitively difficult to grasp, the mathematics are presented here more fully.

Let G = long-run fuel price elasticity over n years (in the past). Using the definition of fuel price elasticity:

$$G = \frac{(Q_n - Q_1)/Q_1}{(P_n - P_1)/P_1}$$

Substituting for Q_n from Eq. [2] and noting that $P_n = P_1 F^{n-1}$

$$G = \frac{(Q_1 B^{n-1} - Q_1)/Q_1}{(P_1 F^{n-1} - P_1)/P_1} = \frac{B^{n-1} - 1}{F^{n-1} - 1}$$

Rearranging to make B the subject:

$$G(F^{n-1} - 1) = B^{n-1} - 1$$

$$B = \sqrt[n-1]{1 + G(F^{n-1} - 1)}$$

But

$$B = EF - E + 1 \quad (\text{see Section 2.2})$$

$$\text{Hence } E(F - 1) + 1 = \sqrt[n-1]{1 + G(F^{n-1} - 1)}$$

So

$$E = \frac{\sqrt[n-1]{1 + G(F^{n-1} - 1)} - 1}{F - 1} \quad (9)$$

Hence if we know the long-run elasticity, G , over n years, and the annual percentage fuel price increase during those years, f , where $F = 1 + f/100$, we can calculate the year-on-year fuel price elasticity (here F refers to the past years' fuel price increase, not that of future years). We now turn to empirical studies to obtain credible parameter values for case study sample calculations.

3. Determining fuel price elasticity empirically

Rehdanz [28] found the fuel price elasticity of German space heating consumption from 1998 to 2003 to lie between -0.63 and -0.44 . However, her sample included dwellings that had been thermally refitted during this five-year period. This has the effect of increasing the absolute value of fuel price elasticity, i.e. shifting it further into the negative range, since fuel consumption falls stepwise after a refit. Further, since Rehdanz [28] did not include water heating in her figures, this probably had the opposite effect, as intuitively we would expect hot water consumption to stay relatively constant even when householders become thriftier with space heating, and national statistics on domestic fuel use show that there was very little change in water heating consumption in the years 2000–2009 [29], despite large reductions in space heating fuel consumption.

National statistics enable us to produce a cautious estimate of the domestic heating fuel price elasticity of demand for

German dwellings that did not benefit from thermal upgrade measures between 1 July 2000 and 30 June 2009 (hereinafter called 2000–2009). For this we use temperature-adjusted national consumption totals from the Federal Statistics Office (*Statistisches Bundesamt Deutschland – Destatis*) [29] cross-checked with non-adjusted totals from the Federal Ministry of Economy and Technology (*Bundesministerium für Wirtschaft und Technologie – BMWi*) [30]. We use national totals of occupied dwellings and newly built dwellings from Destatis [29,31–33], from which we also calculate the net number of dwellings abandoned in 2000–2009. An estimate of the total equivalent living area that benefited from thermal refits is based on Friedrich et al. [15], Tschimpke [34] and a report from the German Energy Agency (*Deutsche Energie-Agentur – DENA*) [35], while the average percentage reduction in heating energy consumption achieved through thermal refits in Germany is drawn from empirical studies by Michelsen and Müller-Michelsen [36] and Schröder et al. [18]. Fuel price changes over the period are estimated from statistics given by the BMWi [30], Destatis [33] and Euroil [37], while the proportionate distribution of each fuel type through the housing stock is given by Schloman et al. [38] and Shell [39].

A more detailed account of these estimations is given in the authors' previous work [40]. For the purposes of this paper, we use the following estimates.

Total national domestic heating energy consumption (temperature-adjusted) in Germany in 2000 was 660 TW h. Of this, 17.5 TW h was consumed by dwellings that were later abandoned in 2000–2009, and a further 49.7 TW h by the equivalent living area of dwellings that benefited from thermal upgrades in 2000–2009. Hence the total consumed in 2000 by dwellings that were neither thermally upgraded or abandoned in 2000–2009 was 601.8 TW h.

Total domestic heating energy consumption (temperature-adjusted) in 2009 was 550 TW h. Of this, 33.1 TW h was consumed by dwellings newly built in 2000–2009, and a further 32.3 TW h by the equivalent living area of dwellings that had benefited from thermal upgrades in 2000–2009. Hence the total consumed in 2009 by dwellings that were not thermally upgraded or built new or abandoned in 2000–2009 was 484.6 TW h.

The domestic heating fuel price increase during this period, not adjusted for cost of living or inflation, but weighted according to the quantities of each type of fuel consumed by its relevant proportions of the housing stock, was 52.5%. For future reference we note that this is equivalent to a year-on-year fuel price increase of 4.8% ($\sqrt[9]{1.525} = 1.048$). Hence $f = 4.8$ and $F = 1.048$.

Hence the long-run (9-year) fuel price elasticity was:

$$G = \frac{(484.6 - 601.8)/601.8}{(1.525 - 1)/1} = -0.371$$

Substituting these figures for F and G in Eq. [9], we find the year-on-year price elasticity of demand, E :

$$E = \frac{\sqrt[n-1]{1 + G(F^{n-1} - 1)} - 1}{F - 1} = \frac{\sqrt[8]{1 + (-0.371)(1.048^8 - 1)} - 1}{1.048 - 1} = -0.476$$

This is the figure we will use in our empirical case study, below. We will use the same annual fuel price increase scenarios which the case study's original authors use.

4. Case study: a low energy home refit in Ludwigshafen

4.1. The case outlined

Enseling and Hinz [2] investigated the economic viability of thermal refits of employee housing belonging to the chemical firm BASF, in Ludwigshafen-am-Rhein. The dwellings had an EPR

of 275 kWh/m² a prior to the refitting, which aimed to produce renovated homes of 4 different EPRs: 150, 70, 40 and 30 kWh/m² a, based on living area. Metering post-refit revealed the average actual consumption of the four types to be 192, 70, 42 and 28 kWh/m² a.

The authors of the Ludwigshafen study used an NPV model, mathematically identical to that outlined in Section 2.1 above, to investigate the refits' economic viability. They assumed a 25-year technical lifetime for the refit measures; a pre-refit heating fuel consumption equal to the EPR of 275 kWh/m² a; a fuel price of €0.05/kWh in the first post-refit year; and a discount rate of 5%. They offered three scenarios for each dwelling type, based on future annual fuel price rises of 3%, 4% and 5%. Their cost and consumption figures are given per m² of living area.

It is important to note that the authors do not use the actual refit costs in their calculations of economic viability, but only the 'energiebedingte Mehrkosten', or 'additional thermal costs'. This is because they assumed all the buildings were ready for a comprehensive overhaul. The costs of substantial features that had to be undertaken to accommodate the thermal insulation – such as a new roof, new balcony, and scaffold to replace the render on the walls – were not included in the calculations. This makes their results most relevant to cases where comprehensive general refits are already planned, and a consequential investment decision has to be made as to what level of thermal quality to attempt to achieve. The discount rate these authors use, of 5%, is somewhat low, since, as they state, it allows for interest rate payments and inflation only, and nothing for risk or opportunity costs, but these are sufficient for the main point of this paper to estimate the effect of fuel price elasticity on NPV and payback time.

More significant is the assumption that the dwellings' actual pre-refit heating energy consumption was equal to the EPR, of 275 kWh/m² a. This is unlikely given recent studies of actual thermal performance of German dwellings. Loga et al. [41], using empirical studies of large datasets from 2010, found the average actual consumption of dwellings with an EPR 275 kWh/m² a to be 35% below their EPR, i.e. 180 kWh/m² a. Based on empirical studies of actual consumption in 2002 [38], and in 2010 [18,19], we note that average actual consumption at the time of the Ludwigshafen measurements was some 15% higher than in 2010. Hence we suggest that a credible value for the pre-refit consumption of the Ludwigshafen dwellings was around 210 kWh/m² a, i.e. 15% higher than the average 2002 figure of 180 kWh/m² a. This is the value we use in our sample calculations. The fact that this value is not known with certainty is often a factor in real upgrade scenarios.

Table 1 gives the additional thermal costs, in €/m², for each of the four refit types, alongside the post-refit fuel savings in the first post-refit year for both assessments of pre-refit consumption. The estimate of energy saved, in kWh/m² a, for each of the four upgrade levels (which achieved 28, 42, 70 and 192 kWh/m² a, respectively) is 182, 168, 140 and 18 kWh/m² a, while the additional thermal costs are 314, 187, 122 and 35 €/m², respectively.

In this constellation a refit would be deemed economically viable if the additional thermal cost per m² of living area is equal to or smaller than the NPV of energy saved per m² over the 25-year technical lifetime of the refit measures. In the next section we show how this works out, both without, and with, the inclusion of price elasticity of demand.

4.2. The calculations of economic viability

There are 12 possible cases to consider, as there are 4 different refit levels, each examined with 3 different estimates of future fuel price rise. We take 6 of these in order to explore the possible effects of excluding and including fuel price elasticity in the calculations

of NPV. Firstly, we show two sample calculations of NPV: for the second highest thermal standard with an annual fuel price increase of 4% (Case B in Table 2), with and without price elasticity. Here:

$$N = 25 \text{ years}; P_1 = 0.05 \text{ €/kWh}; S_1 = \text{€}168/\text{m}^2; d = 5\%, \\ \text{so } D = 1.05; f = 4\%, \text{ so } F = 1.04$$

For the case without elasticity:

$$A = \frac{1 + 4/100}{1 + 5/100} = 0.9905$$

Using Eq. [1]:

$$V = \text{€}168/\text{m}^2 \times 0.05 \frac{0.9905^{25} - 1}{0.9905 - 1} = \text{€}188/\text{m}^2.$$

The NPV was €188/m², and the additional thermal costs were €187/m². Hence this case can be deemed economically viable. Over the 25-year lifetime of the refit measures, it returns a profit of €1/m² of living area.

For the case including elasticity:

Recalling that

$$B = EF - E + 1, \\ B = -0.476 \times 1.04 - (-0.476) + 1 \\ = 0.98096$$

Now using Eq. [8], the NPV is:

$$S_{TDN} = S_1 P_1 \frac{(BF/D)^N - 1}{(BF/D) - 1} \\ S_{TDN} = 168 \times 0.05 \frac{(0.98096 \times 1.04/1.05)^{25}}{(0.98096 \times 1.04/1.05)} \\ = \text{€}152/\text{m}^2$$

In this case, the project would not be deemed to be economically viable, as the NPV of €152/m² is lower than the additional thermal costs, of €187/m². Including fuel price elasticity has reduced NPV by 19.1%.

The results for the 5 further cases, listed in Table 2 and displayed in Fig. 1, are as follows:

In case A (70 kWh/m² a post-refit, 3% annual fuel price rise) the NPV decreases from €140/m² to €120/m², or by 14.3%. Economic viability is lost, as the additional thermal costs were €122/m².

In case C (190 kWh/m² a post-refit, 4% annual fuel price rise) the NPV decreases from €20/m² to €16/m², or by 20.0%. The additional thermal costs were €36/m², this case is not economically viable in either scenario.

In case D (28 kWh/m² a post-refit, 4% annual fuel price rise) the NPV decreases from €203/m² to €165/m², or by 18.7%. With additional thermal costs of €314/m², this case is not economically viable in either scenario.

In case E (42 kWh/m² a post-refit, 5% annual fuel price rise) the NPV decreases from €210/m² to €160/m², or by 23.8%. As the additional thermal costs were €187/m², this loses economic viability when price elasticity is included.

In case F (70 kWh/m² a post-refit, 5% annual fuel price rise) the NPV decreases from €175/m² to €133/m², or by 24.0%. As the additional thermal costs were €122/m², this case is economically viable with or without price elasticity.

Hence it can be seen that the inclusion of price elasticity reduces NPV by 14–24% in these cases. This brings into question the economic viability of some refit cases, but not all. In cases that are not economically viable without the inclusion of price elasticity, its inclusion reduces NPV, though in practice this might not make any

Table 1
Parameters and values for economic viability calculations of Ludwigshafen thermal refit programme, from Enseling and Hinz [2], together with estimate of likely actual pre-refit consumption.

Pre-refit EPR (kW h/m ² a)	Assumed pre-refit actual consumption (kW h/m ² a)	Metered post-refit actual consumption (kW h/m ² a)	Energy saved based on EPR (kW h/m ² a)	Energy saved based on assumed pre-refit consumption (kW h/m ² a)	Additional thermal costs (€/m ²)
275	210	28	247	182	314
275	210	42	233	168	187
275	210	70	205	140	122
275	210	192	83	18	36

difference because these cases are less likely to have been embarked upon if they were already seen not to be economically viable.

In order to obtain a broader picture of the effect of price elasticity, it is worthwhile showing calculations using a methodology other than NPV. The following section shows how price elasticity can be incorporated into a payback time model, and offers sample calculations.

5. Price elasticity in a payback time model

The mathematical effect of price elasticity is identical, in payback time models, to its effect in NPV models. The difference is that the unknown variable is the number of years to reach a specified NPV, rather than the NPV achieved within a specified number of years. Hence we begin by specifying the NPV as being equal to the cost of the refit project.

Let J = the cost of the refit project (here in €/m²)

The project pays back when J is equal to the NPV of the fuel savings, i.e.:

$$J = S_1 P_1 \frac{(BF/D)^N - 1}{(BF/D) - 1} \text{ from Eq. (8).}$$

Rearranging and making N the subject, we get:

$$N = \frac{\log\{1 + [J/(S_1 P_1)] \times (BF/D - 1)\}}{\log(BF/D)} \tag{10}$$

To show a sample calculation we consider case D , the most energy efficient refit, with a 4% annual fuel price increase. Here:

$$J = 314 \text{ €/m}^2; S_1 = 182 \text{ kW h/m}^2; P_1 = 0.05 \text{ €/kW h};$$

$$B = 0.98096; F = 1.04; D = 1.05$$

So

$$N = \frac{\log\{1 + [314/(182 \times 0.05)] \times (0.98096 \times 1.04/1.05 - 1)\}}{\log(0.98096 \times 1.04/1.05)}$$

$$N = 134.8 \text{ years}$$

Excluding price elasticity from the calculations (i.e. setting $B = 1$) would have resulted in a payback time of 41.6 years. Hence the inclusion of price elasticity has lengthened the payback time by 93.2 years, or 224%.

Further results are listed in Table 2 and displayed in Fig. 2.

The lowest percentage increase in payback time is in case A (70 kW h/m² a post-refit, 3% annual fuel price rise), from 21 to 25.5 years, or 21.4%. This takes its payback time marginally over the 25-year lifetime of the refit measures. The largest increase is for case C (190 kW h/m² a post-refit, 4% annual fuel price rise), from 50 years without price elasticity to an infinite length of time when elasticity is included. In practice this means the refit would never pay back, even if the technical lifetime of the refit measures were itself infinite. This counter-intuitive result arises because the NPV of future years' fuel savings is the sum of a convergent geometric series if the term $B \times F/D$ is less than 1, which it will be if D is large (because of a high discount rate), F is small (because of a low annual fuel price rise, and B is small (because the absolute value of the price elasticity is high). In such a geometric series the sum of all its terms (of which there is an infinite number) is a finite quantity. If this quantity is less than the cost of the project, it can never pay back. Galvin [24] discusses cases where payback time is infinite even without price elasticity, noting that the annual savings will be a convergent series whenever $F/D < 1$.

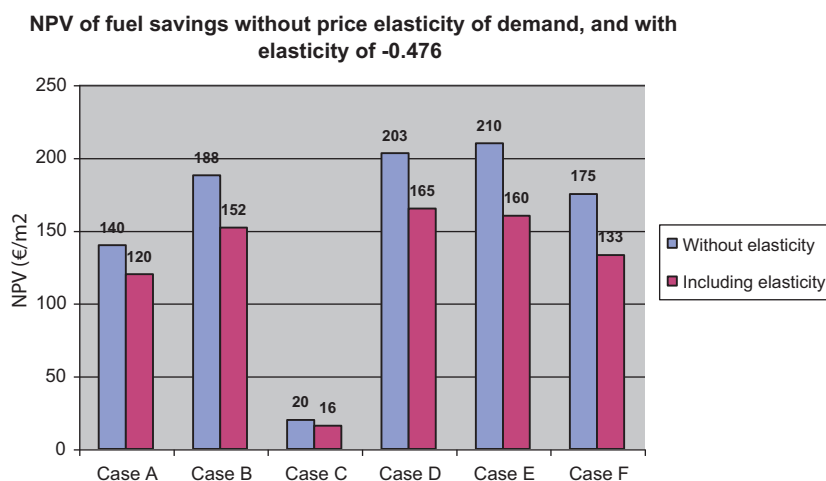


Fig. 1. Net present value, calculated without fuel price elasticity of demand, and with elasticity of -0.476 , for thermal upgrades of homes in Ludwigshafen, Germany. See Table 2 for Case descriptions.
Data source: Enseling and Hinz [2]; own analysis.

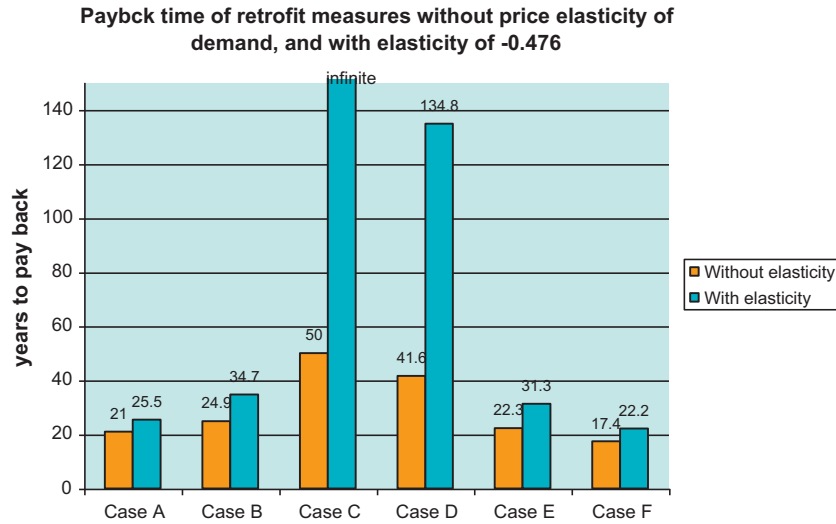


Fig. 2. Payback time, calculated without fuel price elasticity of demand, and with elasticity of -0.476 , for thermal upgrades of homes in Ludwigshafen, Germany. In case C the payback time with elasticity is infinite. See Table 2 for Case descriptions. Data source: Enseling and Hinz [2]; own analysis.

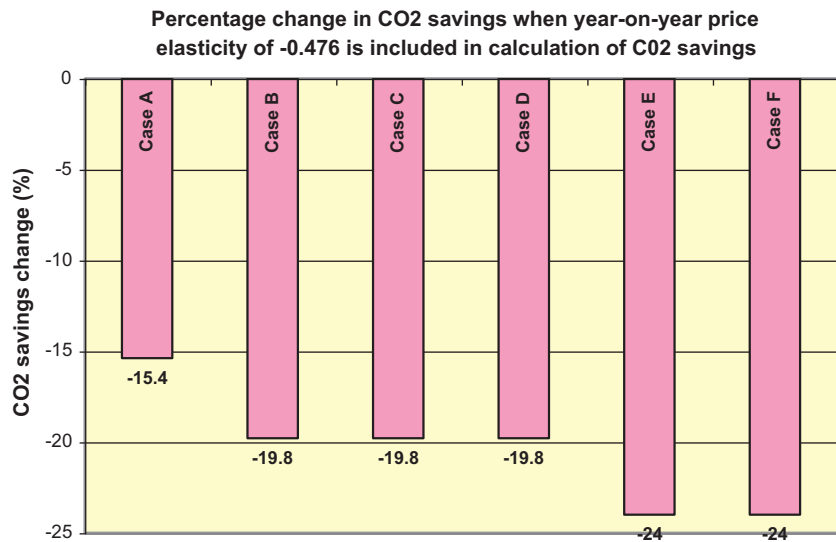


Fig. 3. Change in CO₂ savings when fuel price elasticity of demand of -0.476 is included in calculations of future performance, for thermal upgrades of homes in Ludwigshafen, Germany. See Table 2 for Case descriptions. Data source: Enseling and Hinz [2]; own analysis.

6. Carbon savings and fuel price elasticity of demand

The carbon saved through thermal refits is reduced by the effect of fuel price elasticity of demand, since the annual fuel saving reduces as prices rise. The degree of reduction depends on the elasticity and the future annual percentage fuel price rise (since these two interact to produce year-by-year reductions in consumption), but not on the discount rate, the initial fuel price, or the savings in the first year. Consider Eq. [8]:

$$S_{TDN} = S_1 P_1 \frac{(B \cdot F/D)^N - 1}{(B \cdot F/D) - 1}$$

The term B determines the year-on-year reducing quantity of fuel consumed. This directly affects the amount of CO₂ saved. The term F/D determines the year-on-year change in price per unit of fuel consumed. This does not affect the amount of CO₂ saved. Hence we set F and D to 1.0, and they drop out of the equation. The term P_1

refers to the price of fuel in the first year, which does not directly affect the savings of CO₂, so this term also drops out. The result, S_{TDN} , is now directly proportional to the savings in CO₂. Hence, letting C_{TBN} = total CO₂ savings in N years with price elasticity, and C_1 = CO₂ saving in first year, we get:

$$C_{TBN} = \frac{C_1 (B^N - 1)}{B - 1}$$

But the accumulated savings without price elasticity, namely C_{TN} , are

$$C_{TN} = C_1 \times N$$

Hence the percentage change in CO₂ savings through including price elasticity are:

$$\% \Delta CO_2 = \frac{100 \times [C_1 \times N - C_1 (B^N - 1) / (B - 1)]}{C_1 \times N}$$

Table 2 Results of calculations of net present value (NPV), payback time (PBT), and CO₂ savings of thermal refits in Ludwigshafen, with selected annual fuel price rises, a discount rate of 5%, and fuel price of €0.05/kWh in first year after retrofit, showing changes with price elasticities of zero and -0.476.

Case	Case description (for all cases a pre-retrofit consumption of 210 kWh/m ² a is assumed); post-retrofit heating fuel consumption, and assumed future annual fuel price rise	Cost of thermal upgrade measures (€/m ²)	NPV without price elasticity (€/m ²)	NPV with price elasticity -0.476 (€/m ²)	De-increase in NPV (%)	PBT without price elasticity (years)	PBT with price elasticity -0.476 (years)	% in-increase in PBT	Effect of elasticity on economic viability (assuming 25 year technical lifetime)	Change in CO ₂ emission savings over 25 years due to price elasticity (%)
A	70 kW h/m ² a post-refit, 3% annual fuel price rise	122	140	120	14.3	21	25.5	21.4	Lost	-15.4
B	42 kW h/m ² a post-refit, 4% annual fuel price rise	187	188	152	19.1	24.9	34.7	39.4	Lost	-19.8
C	190 kW h/m ² a post-refit, 4% annual fuel price rise	36	20	16	20.0	50	Infinite	Infinite	No change	-19.8
D	28 kW h/m ² a post-refit, 4% annual fuel price rise	314	203	165	18.7	41.6	134.8	224.0	No change	-19.8
E	42 kW h/m ² a post-refit, 5% annual fuel price rise	187	210	160	23.8	22.3	31.3	40.4	Lost	-24.0
F	70 kW h/m ² a post-refit, 5% annual fuel price rise	122	175	133	24.0	17.4	22.2	27.6	Retained	-24.0

Data source: Enseling and Hinz [2]; own analysis.

i.e.

$$\% \Delta \text{CO}_2 = \frac{100 \times [N - (B^N - 1)/(B - 1)]}{N} \quad (11)$$

For a fuel price elasticity of -0.476 over 25 years, this reduction is 15.4% for an annual fuel price rise of 3%, rising to 24.0% for an annual fuel price rise of 5%. The baseline of these percentages is the carbon that would have been saved, through a retrofit, if there were no price elasticity of demand. Up to 24% less CO₂ is saved than would have been expected. The results are listed in Table 1 and displayed in Fig. 3.

This can also be expressed in terms of the percentage saving of CO₂ that would have been gained, through the effect of fuel price elasticity, if a dwelling had *not* been refitted. If the annual fuel price rise is 5%, and fuel price elasticity stays constant at -0.476 over the next 25 years, then German dwellings that are not refitted over this period can be expected to reduce their heating fuel consumption such that this sector of the building stock will save an accumulated 24% of its business-as-usual CO₂ emissions from home heating over the period. This also means that, if these factors continue to pertain, in the 25th year the CO₂ emissions would be 44% lower than those today (since $B = 0.9762$, and $0.9762^{24} = 0.56$). By the year 2050 they would reduce to 59% lower than today—though in reality there must be limits as to how far a household can reduce its heating energy consumption. Nevertheless, it appears that a large proportion of German households in non-refitted dwellings are already consuming well below the average consumption level and that there are great differences in heating energy consumption in similar dwellings [18,19,41–44]. Some of the possible causes and implications of this type of phenomenon are explored by Chappells and Shove [45].

7. Discussion and conclusions

This paper offers a method for incorporating fuel price elasticity of demand into models assessing net present value and payback time of thermal refits. Based on modelling and a case study, it demonstrates how including year-on-year fuel price elasticity of demand in calculations of economic viability of thermal refits lengthens perceived payback time, reduces NPV of fuel saved, and reduces the CO₂ saved as a consequence of the retrofit measures, over the lifetime of the energy efficiency measures. The degree and the significance of this effect depend on the mathematical relationships between variables and the choices of values for variables such as the discount rate, the assumed pre-refit consumption level, and the expected fuel price increase. The paper suggest five main findings as to why considering fuel price elasticity in assessing the viability of thermal refits is important:

Firstly, elasticity and future annual fuel price increase have a mutually offsetting effect on NPV and payback time. This is a purely mathematical interplay, but can be explained as follows with reference to the real world. A thermal retrofit investment increases in profitability if future fuel price increases are high, because this saves fuel costs that would have been incurred if the retrofit had not taken place. But if future fuel price rises are high, the impact of fuel price elasticity of demand tends to reduce this saving by a greater proportion. This is because, if the retrofit had not taken place, the elasticity would have reduced consumption as a response to these fuel price increases. Hence, for retrofits, price elasticity dulls the savings effect of high future fuel price rises. While energy price increases may increase the attractiveness of thermal retrofit investments, the behavioural response of fuel elasticity may limit their effectiveness as a market-based policy instrument.

Secondly, the discount rate has a mathematically synergistic interaction with price elasticity. The higher the discount rate, the lower the NPV. If the fuel price increase is tending to be cancelled

out by the price elasticity, as discussed above, the discount rate can become the dominant factor in the reduction of the benefits to be gained in future years. Hence a conventional – some would say realistic – discount rate, of around 8–9%, makes it harder to achieve NPV results that indicate economic viability of thermal refits, when price elasticity is included in the calculations. A low discount rate such as that used in this study would require, *inter alia*, lower interest rates, which could possibly only be achieved by government subsidy. An interesting topic for future studies would be to examine case studies of refits using higher discount rates than those employed here, together with a range of price elasticities.

Thirdly, the assumed fuel consumption prior to the refit has a large effect on NPV. In recent years empirical studies in Germany have shown that heating fuel consumption is, on average, 33% below the EPR [18,19]. Basing the NPV calculations on the actual fuel consumption may reduce the energy saving potential through retrofitting by up to 50%, and thereby lower the NPV of assumed future fuel savings accordingly. Since the inclusion of fuel price elasticity in our calculations lowered NPV by between 14% and 24%, its proportional effect on NPV and payback time will be considerable if it becomes more common to use the actual pre-refit fuel consumption in calculations of economic viability.

Fourthly, the figure for price elasticity of demand for domestic heating fuel in non-refitted dwellings used here, -0.476 , is by no means a certain value. Calculations such as those offered in this paper may be re-run with other elasticity values to see what the effects might be. There are further uncertainties as to whether householders would continue the patterns of fuel saving through which a particular elasticity value has been derived, and whether it can, indeed, be confidently known, given all the other influences on changing fuel demand [46]. But as there are uncertainties in almost all the parameter values in estimates of NPV and payback time, sensitivity analyses are required, to see what the range of possible investment consequences might be.

Fifthly, fuel price elasticity indicates real differences in projections of avoided CO₂ emissions through thermal refits. Our modelling suggests that carbon savings through refits may be less, in the real world, than they would be in models that do not consider the behavioural effect of fuel price elasticity. On the other hand, price elasticity may generate cost-free, accumulated carbon emission savings through behavioural change where there are no investments in technical energy-efficiency measures. These may be 10–20% for non-refitted dwellings over a 25-year time span. This has implications for climate policies and for investing climate mitigation funds where they will be most cost-effective. It may also have implications for considering the possible incorporation of heating fuel into the European Emissions Trading Scheme in coming years.

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