Introducing the prebound effect: the gap between performance and actual energy consumption

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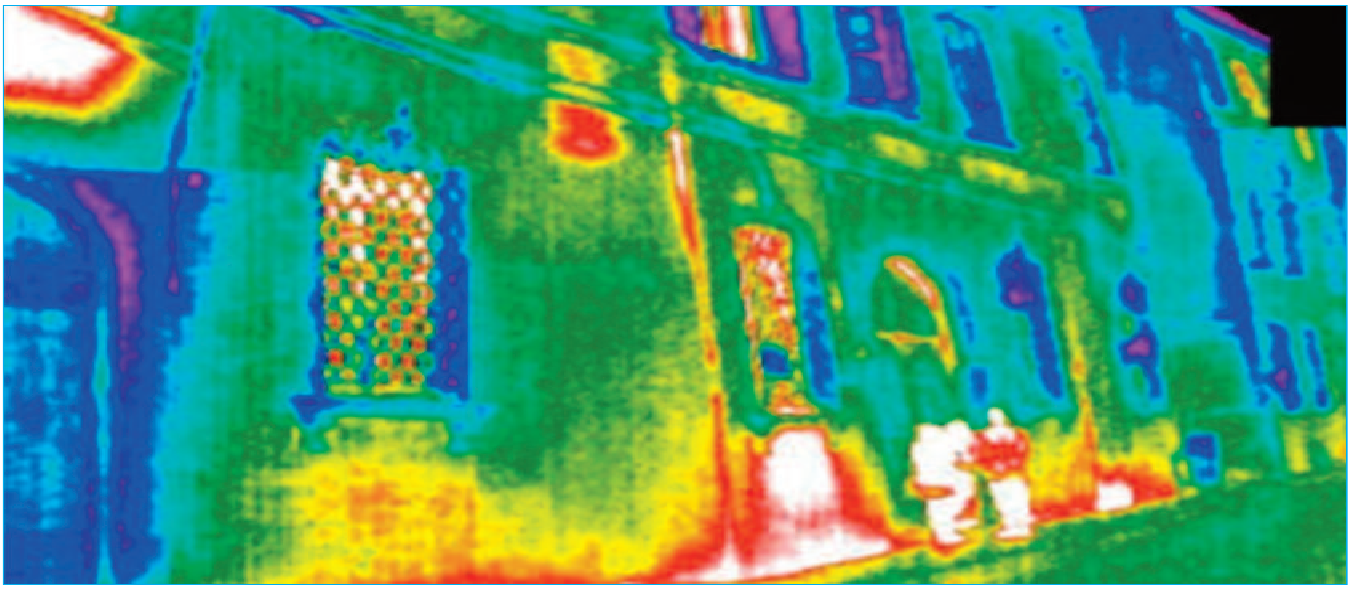

Summary

German regulations for the thermal renovation of existing homes demand high thermal standards, which the government claims are technically and economically feasible. This paper examines existing data on 3400 German homes; their calculated energy performance ratings (EPR) are then plotted against the actual measured consumption. The results indicate that occupants consume, on average, 30% less heating energy than the calculated rating. This phenomenon is identified as the 'prebound' effect and increases with the calculated rating.

The opposite phenomenon, the rebound effect, tends to occur for low-energy dwellings, where occupants consume more than the rating. A similar phenomenon has been recognized in recent Dutch, Belgian, French and UK studies, suggesting policy implications in two directions. Firstly, using a dwelling's energy rating to predict fuel and CO_2 savings through retrofits tends to overestimate savings, underestimate the payback time and possibly discourage cost-effective, incremental improvements. Secondly, the potential fuel and CO_2 savings through non-technical measures such as occupant behaviour may well be far larger than is generally assumed in policies so policy-makers need a better understanding of what drives or inhibits occupants' decisions.

Introduction

If governments and businesses are to address successfully ambitious CO2 reduction targets, then energy policies must explicitly address the existing housing stock (Boardman et al., 2005; Sunikka, 2006). **Germany has been one of the forerunners in thermal retrofit policies, characterized by mandatory standards and deep retrofit measures to reduce household energy consumption** (Sunikka, 2006; Meijer et al., 2009). **As domestic consumption of heating fuel in Germany fell by 15% in 2002 – 2010** (e.g. Bundesministerium für Wirtschaft und Technologie (BMWi), 2010), **Germany has been seen as a model for other countries** (de T'Serclaes, 2007; International Energy Agency (IEA), 2008).

The Energieeinsparverordnung (EnEV) (Bundesministerium für Verkehr, Bau und Stadtentwicklung (BMVBS), 2009b), last updated in October 2009, is a central pillar of the Federal government's long- running campaign to promote thermal renovation (BMVBS, 2009a; Deutsche Energieagentur, 2011).

These regulations demand that high thermal standards be reached for thermal retrofits of existing homes. The law that sets the parameters of the EnEV is the Energieeinspargesetz (Energy Saving law). It stipulates that the EnEV may only demand thermal standards that are wirtschaftlich (economically viable). This is interpreted to mean that the energy savings they cause must be sufficient to pay back the cost of the thermal aspects of the retrofit or construction within the lifetime of the measures undertaken.

Despite severe technical problems in thermally renovating many homes (Galvin, 2010, 2011), household energy savings through technical improvements are still considered as 'easy gain' in energy polices.

But how feasible are mandatory standards for existing homes?

It is generally well accepted in the academic literature that occupant behaviour is a major determinant of the energy consumed for space heating (Stern, 2000; Guerra-Santin et al., 2009; Guerra-Santin and Itard, 2010; Gram-Hansen, 2010, 2011). Much of this literature explores the cultural aspects of indoor lifestyle (e.g. Chappells and Shove, 2004, 2005; Cupples et al., 2007), social practices in the home (e.g. Gram-Hansen, 2008a, 2008b), or generic issues to do with training people to use their heating systems effectively (e.g. Martiskainen, 2008).

Due to the behaviour factor, heating energy saving achieved through retrofit measures can be remarkably lower than calculated (Haas and Biermayr, 2000). This paper builds on the observation of Walberg et al. (2011, p. 115), that, in the German context:

„For a realistic assessment of the thermal condition of the built environment only the analysis of actual, measured energy consumption can be used. . . . Theoretically calculated energy ratings give us an unrealistic picture of the energy savings potential that can be achieved through thermal renovation.“

However, this concept is developed further in this paper by exploring the implications of differences in actual energy consumption among various householders in thermally similar dwellings.

Taking Germany and the improvement level required by the EnEV as an example, this paper includes discussion on the technical constraints of the actual buildings (Galvin, 2010; GdW Bundesband deutscher Wohnungs- und Immobilienunternehmen e.V., 2011; Greller et al., 2010), the accounting system used by Federal policy-makers to determine the costs to be used in the calculations (Pöschk, 2009; Galvin, 2011), and the costs of deep thermal renovation (Tschimpke et al., 2011), major issues for the success or failure of a thermal retrofit policy, that tend to focus on investment behaviour and ignore what happens before or after the energy measures are adopted (IEA, 2008; Tambach et al., 2010; Schröder et al., 2010, 2011; Walberg et al., 2011).

The paper aims to clarify the technical and economic feasibility of the energy-saving potential of thermally retrofitting old dwellings, and the potential of non-technical measures, e.g. behaviour change, to contribute to energy policy targets.

Based on existing German datasets that include the energy performance ratings (EPR) and measured energy use data from around 3400 dwellings, this paper models the distribution of the proportional differences between the calculated energy rating and the actual measured consumption. It aims to answer the following questions:

- What are the distributional characteristics of the actual space and water heating energy consumption in German dwellings compared with the calculated values given in buildings' EPR?

- What can be learnt about the heating energy-saving potential in German dwellings from an examination of the distribution of these two parameters in relation to each other?

- What are the policy implications for achieving large savings in heating energy and CO_2 emissions from thermal retrofits?

This paper is structured as follows. The second section analyses German studies that compare the theoretical, calculated space heating energy consumption of dwellings with their actual, measured energy consumption (see Table 1 for the type of measured energy data).

The third section discusses reasons behind the gap between performance and actual energy consumption. The fourth section suggests a new concept of heating intensity which the authors call the 'prebound' effect.

The fifth section compares the authors' findings with those of recent research on the same issues in four other Western European countries. The sixth section suggests policy implications. The last section summarizes and offers concluding remarks.

The paper builds on previous work on policies for improving the thermal performance of the European housing stock (Sunikka, 2006; Sunikka-Blank et al., 2012) and German thermal retrofit policy (Galvin, 2010, 2011; Galvin and Sunikka-Blank, 2012). It should be considered that the policy developments described in this paper are subject to change and based on the situation in 2011–2012.

The actual measured energy consumption in German dwellings

Over the last decade in Germany a number of studies have compared the calculated heating energy consumption of dwellings with the actual, measured consumption (Kaßner et al., 2010; Knissel et al., 2006; Knissel and Loga, 2006; Greller et al., 2010; Loga et al., 2011; Erhorn, 2007; Jagnow and Wolf, 2008; Schloman et al., 2004; Schröder et al., 2010, 2011; Walberg et al., 2011). By gathering these studies together, this paper aims to identify consistent patterns.

While the datasets reveal the discrepancies between what is expected of buildings' technical performance, and what actually happens when people live in them, their authors have produced these mostly in pursuit of technical questions: whether measured data can be used as an inexpensive way to extrapolate back to an EPR (e.g. Knissel et al., 2006; Knissel and Loga, 2006); how various building typologies perform in practice (Greller et al., 2010; Loga et al., 2011); or how energy advisors can better inform consumers of the energy-saving potential of their properties (Erhorn, 2007).

Several recent empirical studies have quantified average actual energy consumption for various classes of residential building (Schloman et al., 2004; Schröder et al., 2010; Walberg et al., 2011) and for the residential building stock as a whole (Schröder et al., 2011).

However, there does not appear to be a German study exploring what the discrepancies between calculated and measured consumption might mean for policy development in terms of optimizing thermal retrofit requirements to the behaviour of the users in order to get the best outcome. By gathering the datasets together and exploring commonalities and differences among them, the present analysis aimed to propose guidelines for policies on thermal renovation of existing homes, and on engagement with household behaviour, that are better targeted and more cost-effective than current approaches.

These studies cover direct observations of actual energy consumption in over 1 million dwellings. This covers 3400 dwellings with precise information on the EPR and the measured data so direct comparisons can be made. This study is based on those 3400 dwellings as a primary source. Moreover, archived data on the physical characteristics and measured energy consumption of over 1 million dwellings (excluding information on their EPR) are used as a background material. Table 1 summarizes the type of measured energy data of all studies used in this research. The studies are summarized in relation to key technical data, such as sample size and sampling method. Measured data are generally collected from meters during a one- to four-year period. Space cooling is not included.

Table 1 gives the average EPR and the average measured consumption (kWh/m²a) in each study, with a heating factor and the 'prebound' effect that is discussed in the fourth section of this paper.

Source	Type of data source	Type of dwellings	Number of dwellings in the sample	How the energy performance rating (EPR) is obtained	Average EPR (kWh/m²a)	Average measured consumption (kWh/m²a)	Heating factor: measured/calculated consumption	Prebound effect (%, by which measured consumption is calculated)	Space heating, water heating or both
Knissel and Loga (2006)	National random survey of 4670 dwellings	All types with fewer than eight apartments	1178	Calculated[a]	261	150	0.57	43	Both
		Blocks of eight or more apartments	113	Calculated[a]	184	135	0.73	27	Both
Loga *et al.* (2011)	National random sample	All types	1702	Calculated[a]	220	152	0.69	31	Both
Kaßner *et al.* (2010)	Mixed sample, scope unclear	All types	44	Calculated[a]	209	153	0.73	27	Both
Jagnow and Wolf (2008)	sample from the OPTIMUS national survey	Not stated	Approximately 100	Calculated[a]	220	135	0.61	39	Both
		Not stated	Approximately 100	Calculated[a]	200	148	0.74	26	
Schröder *et al.* (2010)	metered from Brunata-METRONA	Oil heated	250 000	not considered		141			Both
		Gas heated				156			Both
		District heating				109			Both
		All				148			Both
Schröder *et al.* (2010)	From heating energy metering	Rented accommodation built prior to the 1995 regulations	230 000	Not considered		145			Both
Schröder *et al.* (2010)	From heating energy metering	Rented accommodation built prior to the 1995 regulations	143 000	Not considered		118			Space heating only
Schröder *et al.* (2011)	Metering from Brunata-METRONA in 2005–2010	All types, all cohorts, data weighted for proportions nationally	250 000	Not considered		148			Both
Walberg *et al.* (2011)	National statistics from a range of surveys	Detached and semi-detached	Approximately 1 million	Not considered		172			Both
		Three to seven apartment blocks	Approximately 1 million in various surveys	Not considered		145			Both
Erhorn (2007)	Nationwide DENA study	Detached houses	50	Calculated	240	170	0.71	29	Both
		Multi-apartment blocks	70	Calculated	175	140	0.80	20	Both

Note: [a]EPR was calculated from building characteristics according to the German Institute of Standards DIN V 4108-6:2003.

Table 1 Data sources used in the analysis

While it is recognized that the analysis is based on secondary data, several measures were taken to ensure the verification of the quality of the sources and the correct interpretation of the results. Only official statistical sources, work by established research institutes and peer-reviewed reports, were used as data sources. Only those studies where the data collection method and calculations used in processing the data were made transparent were taken into consideration for this study. In the few cases where raw data were not available, the present analysis is based on the studies' statistical summaries and graphical data presentation. The authors' previous research on German policies (Galvin, 2010, 2011; Galvin and Sunikka-Blank, 2012), knowledge of the language and expert interviews helped to ensure the critical use of the sources and the interpretation of the findings.

Based on the datasets examined (Kaßner et al., 2010; Knissel et al., 2006; Knissel and Loga, 2006; Greller et al., 2010; Loga et al., 2011; Erhorn, 2007; Jagnow and Wolf, 2008; Schloman et al., 2004; Schröder et al., 2010, 2011; Walberg et al., 2011), four features seem to stand out.

Firstly, as suggested in several recent studies, for any given energy rating there appear to be a very large spread of quantities of energy consumed for heating. Typical are ranges of over 600%, i.e. one home consumes six times as much energy for heating as another of the same thermal rating (Erhorn, 2007; Knissel and Loga, 2006; Loga et al., 2011). This phenomenon is not specific to Germany. It is also evident, for example, in Switzerland (Jakob, 2007), France (Cayre et al., 2011; Cayla, 2010), Austria (Roth and Engelman, 2010), the Netherlands (Tighelaar and Menkveld, 2011), and Denmark (Erhorn, 2007).

Secondly, the analysis indicates a gap between the calculated heating energy consumption of German homes – what generally equates to the energy rating (EPR), and the measured heating energy consumption.

The EPR (in German usually called the Energiekennwert) is a figure for a dwelling's expected heating energy consumption based on physical factors such as the thermal quality of the building envelope, the heating system and the location. The average EPR for German dwellings is around 225 kWh/m^{2}a, ranging from 15 to over 400 kWh/m^{2}a. The EPR is used to predict potential energy savings through thermal retrofits. By contrast, the average measured energy consumption for German domestic heating is estimated around 150 kWh/m^{2}a, e.g. 149 kWh/m^{2}a by Schröder et al. (2011) and 152 kWh/m^{2}a by Walberg et al. (2011). In general, this is 30% below the average EPR.

Thirdly, the datasets suggest a trend in energy con- sumption in relation to the magnitude of the EPR. In general, the higher the EPR, the lower the measured energy consumption seems to be in proportion to the EPR. For example, the average measured consumption of a home with an EPR of 300 kWh/m^{2}a is around 40% below its calculated value, while dwellings with an average EPR of 150 kWh/m^{2}a can have an actual energy consumption around 17% below their calcu- lated value.

These points are illustrated in **Figure 1**, which shows scatterplots of measured energy use (vertical axis) against EPR (horizontal axis) for detached houses (left) and multi-dwelling buildings (right), from data collected by the German Energy Agency and analysed by Erhorn (2007). In each graph the continuous line is the regression line, while the dotted line (added by the authors) is y 1⁄4 x, representing all the points where

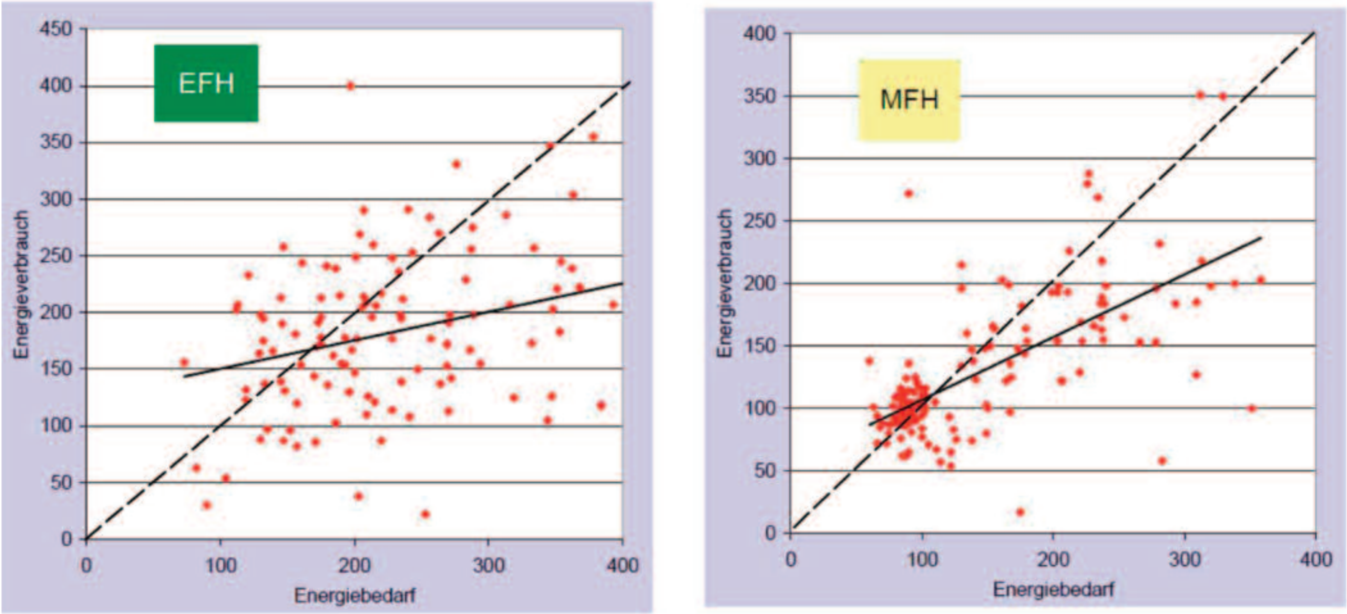

Figure 1 Scatterplots of measured energy consumption (vertical axes) against calculated energy consumption (horizontal axes) for detached houses (left) and multi-dwelling buildings (right). Source: Erhorn (2007)

actual consumption would be identical to the calculated EPR value, i.e. there would not be any net behavioural effects. The wide vertical scattering of the points at any particular x-value reflects the large variation in energy use regardless of the physical features of the building, while the general shape of the regression line indicates how average energy use varies with the EPR.

Plots such as these suggest that many households may be consuming less than their EPR. The left-hand graph in Figure 1 shows some consuming only around 100 – 130 kWh/m^{2}a in detached houses with EPR ratings up to 400 kWh/m^{2}a.

Other German studies suggest similar trends (Kaßner et al., 2010; Knissel and Loga, 2006; Knissel et al., 2006; Jagnow and Wolf, 2008; Loga et al., 2011). For dwellings with EPR above 100 kWh/m2a the effect is similar in all these studies. Further, the x-coefficient of the regression line ranges from 0.2 to 0.5. This suggests that for each 1% increase in the thermal leakiness of a German home there could be a 0.2 – 0.5% increase in heating energy consumption.

Fourthly, at the other end of the scale, low-energy dwellings generally seem to indicate the opposite ten- dency, the rebound effect. The right-hand graph of Figure 1 shows the majority of points at the low energy end falling above the line y 1⁄4 x, indicating that in many low-energy dwellings the actual consumption exceeds the calculated EPR.

Other datasets support this tendency. Loga et al. (2011) show average measured consumption rising above the EPR for dwellings with an EPR lower than 50 kWh/m^{2}a. This is more pronounced (around 65%) for dwellings with an EPR under 75 kWh/m^{2}a in Kaßner et al. (2010). Other analyses show a similar although lesser tendency (Knissel et al., 2006).

In a study of neighbourhoods of what Thomsen et al. (2005) called advanced solar low energy buildings, heating energy consumption in German homes was measured to be twice as high as the EPR.

Greller et al. (2010) investigated the actual heating energy consumption in German buildings according to year of build, and found that as thermal standards have tightened more and more in recent years, an increasingly larger proportion of new builds has failed to achieve the required thermal standard. An exception is a study of a small, homogeneous sample by Enseling and Hinz (2006), where the average post-retrofit consumption in low-energy retrofits falls within the new EPR.

With passive houses, however, the tendency seems less consistent. Berndgen-Kaiser et al. (2007) surveyed the performance of 700 passive and 370 low-energy houses in North Rhine-Westphalia. The measured heating energy consumption for 57% of the low-energy houses and 41% of the passive houses was above the EPR. In studies of small passive house estates conducted by Maaß et al. (2008) and Peper and Feist (2008), consumption was on average within the calculated energy rating. This suggests that dwellings rated below 100 kWh/m^{2}a that have traditional heating systems tend to consume above their EPR but the average consumption in passive houses, which do not have such systems, is more likely to be within their EPR.

Further, the range of consumption in both passive and low-energy houses appears to be large, and the reasons for this would be worth investigating.

Discussion: reasons behind the gap

There could be several reasons behind such a wide gap between the EPR and measured energy use. The EPR is based on standard calculation methods, given in German Institute of Standards DIN V 4108-6:2003. The assumptions built into the method of calculating the energy rating could be simply wrong or inaccurate, e.g. the factor used for ventilation loss calculations (0.7 air change/h) or standard indoor temperature (19^{0}C).

Deviation observed in old buildings could result from incorrect assumptions in energy rating algorithms, e.g. the possibility to compensate for ventilation loss with an exhaust air fan or heat recovery, or there could be a relatively low occupancy per large floor area such as in single-family homes.

The inability of standard calculation methods to include heating patterns may to a certain extent be unavoidable, but in practice the discrepancy between the theoretical figures and the actual consumption may be confusing for a household that needs to use the EPR when applying for subsidies, for example.

Even if the construction sector in Germany might have fewer problems with compliance with building regulations than the UK, for example, there could also be a difference in how buildings are designed to perform and how they are actually built in practice. This could apply to insulation and thermal leaks as well as to building services that could be calibrated differently than intended, or energy control devices such as thermostats that can be wrongly set.

However, even if there can be several pragmatic, technical causes for the gap between performance and the measured consumption, **it seems likely that at least a part of this discrepancy is due the fact that people have very diverse heating patterns.**

Firstly, there seems to be a large deviation in actual energy consumption in dwellings with similar EPR. It seems that several German households tend keep their homes cooler, or heat fewer rooms in their home, or have their heating on for less time – or various combinations of these – than is assumed in the EPR calculations (cf. Gram-Hansen, 2010).

Secondly, a consistent pattern in declining heating energy consumption in energy-inefficient dwellings can be identified. This effect is discussed in the next section.

The ‘prebound’ effect in household energy consumption

The German datasets discussed above indicate that the real measured household heating energy consumption could be on average 30% lower than calculated. The analysis of the German databases that include the EPR and measures energy data suggest that, in general, the worse a home is thermally, the more economically the occupants tend to behave with respect to their space heating.

For the purposes of this paper this phenomenon will be described as the ‘**prebound**’ effect, contrary to the fam- iliar rebound effect. The rebound effect is known to occur when a proportion of the energy savings after a retrofit is consumed by additional energy use, e.g. due to ‘increased internal temperature and comfort expectations, or any financial savings being spent on new appliances or energy consumption effect’ (Barker et al., 2007; Haas and Biermayr, 2000; Holm and Englund, 2009; Sorrell and Dimitropoulos, 2008).

By contrast, the ‘prebound’ effect refers to the situation before a retrofit, and indicates how much less energy is consumed than expected. **As retrofits cannot save energy that is not actually being consumed, this has implications for the economic viability of thermal retrofits.**

Loga et al. (2011) offered a general curve to display the relationship between EPR and measured heating energy consumption, for dwellings with an EPR above 100kWh/m^{2}a. One can expect, for example, that the average actual space heating consumption of dwellings with an EPR of 500 kWh/m^{2}a will be around 215 kWh/m^{2}a, while that for dwellings with an EPR of 200 kWh/m^{2}a will be around 145 kWh/m^{2}a.

This could offer a useful rule of thumb for calculating the average actual gains that can be gained through energy-efficiency measures - though there are obvious variations across types, sizes and ages of dwelling. Using Loga’s et al. modelling equation, a model is developed here to describe the ‘prebound’ effect, namely:

P (%) 1⁄4 100 [1.2 – 1.3/(1 + EPR/500)]

This is displayed in Figure 2. In this model the ‘pre- bound’ effect becomes zero where EPR is 50 kWh/m^{2}a, and for EPR below this it is negative, i.e. the rebound dominates. It should be considered that this might not hold for passive houses, as per the above discussion (see the second section). It is important to note, however, that the ‘prebound’ effect is likely to be higher for dwellings of high EPR.

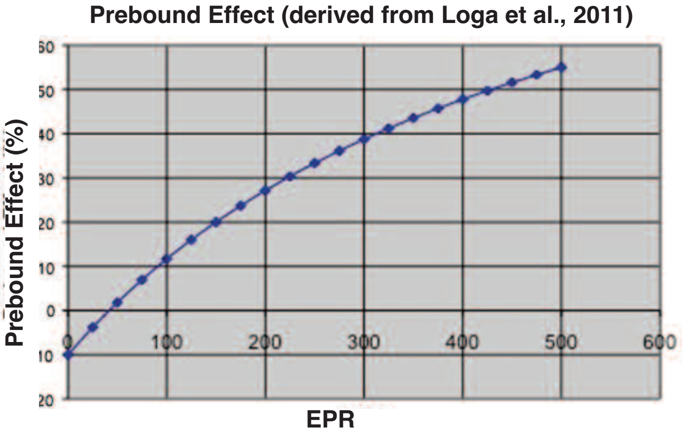

Figure 2 ‘Prebound’ effect, modelled on data from Loga et al. (2011), using P (%) 1⁄4 100 [1.2 - 1.3/(1 + EPR/500)]

There is a need for social science-based research to verify this phenomenon and to understand how some occupants manage to live in these poorly performing homes. Furthermore, it would be interesting to know why some households that could afford better thermal comfort standards choose to use so little heating energy in non-retrofitted homes.

This is not the same thing as finding out the mechanics of their fuel-saving strategies, such as when and in which rooms to keep what temperatures, where to put the smart meter and how much to ventilate. What is not so well known is the motivation behind it: what reasons do household members put forward for being or becoming fuel-thrifty.

Comparison with other European countries

In order to test their viability, the findings are compared with research in other Western European countries. A literature review suggests that a similar ‘prebound’ phenomenon (see the previous section) has been recognized among Dutch, British, Belgian and French households. Research findings were compared with Tighelaar and Menkveld (2011) and Cayre et al. (2011) in a workshop in Amsterdam in January 2012.

Dutch households

In their analysis of data from 4700 households in the Netherlands, Tighelaar and Menkveld (2011) found an identical phenomenon to the prebound effect, though they called this the ‘heating factor’ and quantified it inversely (heating factor 1⁄4 1 – prebound effect/ 100). They determined an average heating factor of around 0.7 (a prebound effect of 30%), reducing for less energy-efficient dwellings and increasing to 1.0 or higher for those with higher energy efficiency. These results correspond to the modelling of the ‘prebound’ effect presented above (Figure 2). Tighelaar and

Menkveld (2011, p. 356) noted that:

> occupants in an energetically efficient dwelling demonstrate more energy intensive behaviour compared to occupants in energetically poor quality dwellings.

They suggested this severely limits the potential savings through thermal retrofits.

UK households

In a study of the UK housing stock, Kelly (2011) found a correlation between dwellings' energy efficiency and their energy demand. Dwellings' energy efficiency is expressed in the UK as Standard Assessment Procedure (SAP) on a scale of 1 – 100, where 100 is the most energy efficient and 1 is the least (the opposite of the EPR scale).

Using data from the English House Condition Survey (EHCS) of 2531 dwellings, Kelly employed a structural equation model that enables cross-correlations to be examined for a range of factors likely to be associated with each other in relation to heating demand. Kelly uses the notion of 'propensity to consume more (or less) energy' for factors that are not dependent on the dwellings' physical thermal characteristics (indoor temperature, floor area, number of occupants and income level), all of which, Kelly found, to be positively correlated with energy consumption.

Homes with a high SAP have a 'propensity to consume more energy', while the opposite is the case for homes with a low SAP; in other words, the higher the energy rating, the lower the energy consumption in relation to the rating – as with German households (see the fourth section). Kelly suggested that, on the one hand, the costs of further thermal improvements in homes with a high SAP rating will be high due to the law of diminishing returns (cf. Jakob, 2006), while, on the other hand, ret- rofitting homes with a low SAP rating may lead to a rebound effect: increases in average internal temperature rather than decreases in energy consumption.

Belgian households

Hens et al. (2010) analysed a dataset of building characteristics and measured heating fuel consumption of 964 Belgian dwellings with known heat transmission loss figures. Rather than expressing the energy rating in terms of kWh/m^{2}a, their independent variable was 'specific transmission losses per m^3 of protected volume' (STV), expressed as W/m^{3}K. This is the average U-value of the building envelope, divided by its volume and multiplied by the building envelope's area. This is comparable with the German EPR, but has the advantage that no assumptions are made as to standard heating habits. For their dependent variable Hens et al. used 'heating energy consumption per unit volume' of dwelling, rather than per m^2 of living area. This corrects for variations in energy consumption due to different ceiling heights. They plotted this against the STV for the 964 exemplars.

Note the similarity between this and the plots of heating energy consumed against EPR for German dwellings (Figure 1). Hens et al. used curve matching with this plot to derive an equation for what they called the rebound effect, though more correctly it is what is called here the 'prebound' effect (see the above section), as it maps the percentage by which the actual energy consumption falls below the calculated value:

$$P\ (\mathrm{MJ/a})\ 1⁄4\ 100\ [1.355\ (U/C)0.16 - 1]$$

where U is the transmission loss (W/m^{2}K); and C is the compactness of building, i.e. volume/area of building envelope.

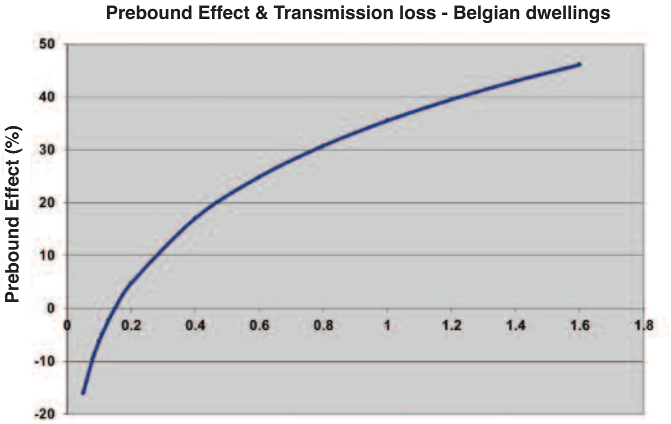

Figure 3 Curve fitting of a plot of a prebound efect for 964 Belgian dwellings, derived from Hens et al. (2010), P (MJ/a) 1⁄4 100 [1.355 (U/C)$^{0.16}$ -1]

This curve (Figure 3) has a similar form to that derived by Loga et al. (2011) (Figure 2). The higher is the specific transmission losses per m^3 (compared with the EPR), the larger seems to be the proportionate gap between measured energy and this variable. The equation employed also enables modelling to extend into the low transmission loss (1⁄4 high energy efficiency) area where the 'prebound' effect becomes negative, i.e. the rebound effect becomes dominant.

French households

Cayre et al. (2011) related measured space heating energy consumption to the Energy Performance Certificate (EPC) value for space heating in French households. Instead of using figures for kWh/m^{2}a, the EPC is given in MWh per dwelling/year (MWh/dw.y). This yields more information about users, as heating costs depend on both the size of the dwelling and the consumption per m^2. It thereby gives a direct comparison of expenditure against the dwelling's total energy rating. Furthermore, Cayre et al. related the EPC not directly to the absolute amount spent on heating, but to the proportion of household income spent on heating.

They graphed this against ‘energy intensity’, equivalent to ‘heating factor’ in Tighelaar and Menkveld (2011).

The results imply that on average most French households spend 2 – 5% of their income on space heating and achieve an energy intensity of around 0.6 (a prebound effect of 40%). In cases where income is low or the EPC is high, some households fail to achieve energy intensity as high as 0.5, even by spending up to 7.5% of their income on space heating.

Households in better buildings, or who have higher incomes, achieve an energy intensity of 0.8 – 1.1 (varying from a prebound effect of 20% to a rebound effect of 10%) by spending less than 2% of their income on space heating. The median energy intensity is about 0.6 (a prebound effect of 40%) and the median of spending is around 3% of income. Thermal retrofits are likely to move homes leftward on the graph as households might spend a smaller portion of their income on heating but keep higher indoor temperatures.

For low-income households or those in thermally poor dwellings, a modest depth of thermal renovation could bring them up to an energy intensity of 0.6 on, say, 3% of their income, thereby reducing fuel poverty. For everybody else, any amount of thermal renovation looks likely to result in some combination of higher energy intensity and a lower portion of income spent on heating fuel. This scenario contrasts with assumptions in German policy that all dwellings are already operating at an energy intensity of around 1 (i.e. there is no ‘prebound’ effect), and after a thermal retrofit to a certain standard, a household will reduce its spending on space heating proportionally to the gain in energy efficiency. It could be argued, however, that these curves reflect households’ current behaviour at a certain moment, rather than how their behaviour could change if their homes were thermally retrofitted.

Policy implications

In Germany the regulations that set mandatory thermal standards, given in the EnEV, are constrained by their economic viability (‘Wirtschaftlichkeit’) so that the payback time of measures should not exceed 25 years. A number of German researchers have started to criticize the way German policy-makers calculate economic viability: they base it on the EPR, having always assumed that actual fuel consumption approximates to this (GdW, 2011; Gerth et al., 2011; Schröder et al., 2010, 2011; Walberg, 2011; Walberg et al., 2011).

The present analysis suggests that actual fuel consumption is, on average, 30% below the EPR (see the second section), and that the gap seems to widen as the EPR increases (see the fourth section). This suggests that variations in the actual consumption compared with the EPR (with contributions from ‘prebound’ and rebound effects) are likely to swallow up a significant portion of the calculated gains in energy saving. This is shown schematically in Figure 4.

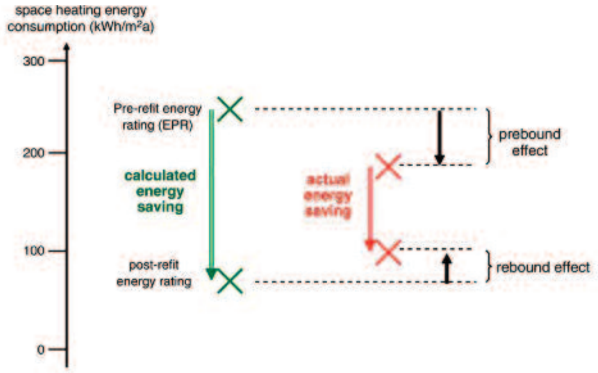

Figure 4 Schematic showing how the prebound and rebound effects may limit energy saving to be reduced from its theoretical amount

Federal policy aims to reduce German space heating energy consumption by 80% by 2050 (Umweltbundesamt (UBA), 2007; Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU), 2007; Tiefensee, 2006). This implies that the housing stock’s actual heating fuel consumption has to be reduced to an average of 30 kWh/m^{2}a.

The marginal costs of retrofitting to such standards can be extremely high (Galvin, 2010; Jakob, 2006; Tschimpke et al., 2011). Schröder et al. (2010, 2011) showed that economically feasible fuel savings through comprehensive thermal retrofits would typically amount to an average of 25 - 35% (also Sunikka-Blank and Galvin, 2012), rather than the 70 - 80% claimed by German policy-makers (BMVBS, 2009a; DENA, 2011).

This raises a policy question about the cost of avoided carbon emissions. At the level of thermal improvement demanded by the EnEV standard, the cost per kWh of energy saved over the lifetime of a retrofit that pays back within the technical lifetime of the retrofit measures is equal to the fuel price, currently € 0.069/ kWh. At a CO_2 emission rate of 0.26 kg for each kWh consumed, this would amount to a gross cost of € 265 for each tonne of CO_2 saved.

If the fuel saving is likely to be only half what was anticipated (as the analysis suggests could frequently be the case), the cost per kWh of energy saved would € 0.138/kWh, and the gross cost of avoided carbon would increase to €530 per tonne. Since around half of this cost could be offset by fuel savings, this implies a net cost of €265 per tonne of avoided CO_2 emissions. This can be ten times as much as it costs to save CO_2 by, for example, modernizing a gas-fired electricity generating plant in Western Europe, and 20 times as much as doing the same in Eastern Europe (Sinn, 2008).

However, empirical studies do suggest that it is possible to renovate many German homes modestly, i.e. below EnEV standards, such that positive savings can be achieved (Michelsen and Müller-Michelsen, 2010). For example, in recent policy attempts to make loft insulation compulsory to a certain standard, German policy-makers did relent from the hard line of the EnEV, adding clauses to allow for modest depths of insulation where the existing building structure makes the standard 22 cm depth technically unworkable (GdW, 2010). This is an example of how regulations for the existing stock would need to be attuned in a more nuanced way considering the characteristics of the buildings and householders. The next challenge is to formulate mandatory thermal retrofit policies, such as the EnEV, in such a way that instead of draconian standards, they would allow economically efficient, incremental improvements that suit the actual state of dwellings and optimize heating patterns.

In addition to regulatory instruments, fiscal incentives and economic constraints are likely to be key motivating factors behind heating patterns; in a study by Hacke (2007), low-income German householders reported that the cost of heating fuel was their main motivating factor in setting heating levels. Rehdanz (2007) reviewed studies on fuel price elasticity for the Netherlands, Denmark and the UK, and found an average elasticity of – 0.35 to – 0.65: for every 1% increase in the price of fuel, the quantity consumed went down by 0.35% to 0.65%. Rehdanz's study of German space and water heating expenditure gave comparable results.

In the UK context, a study by Summerfield et al. (2010) indicated that energy consumption in the UK is relatively inelastic, with an estimated average fuel price elasticity of –0.20: hence a 50% increase in energy price (as happened in real gas prices in less than a year in 2008) would lead to an approximate 10% decline in energy demand. This is supported by Hunt et al. (2003). The current authors' previous research on heating trends in German households in 2002–2010 suggests a year-on-year fuel price elasticity of –0.50 overall, and of –0.49 for households that did not take up thermal ret- rofit measures during this period (Sunikka-Blank and Galvin, 2012).

There could be a correlation between the 'prebound' effect and household income level, energy bills and consequently energy prices. On average, German households tend to spend around €880/year on space and water heating (Galvin and Sunikka-Blank, 2012).

The analysis of the German datasets shows that the distribution of heating fuel consumption per m^2 of living area has a smaller standard deviation (40%) than the distribution of EPR (60%). This suggests people's conscious management of their household budgets could be a causative factor in pulling the mean spent on heating energy consumption to a fairly consistent middle value across the EPR ratings. It seems worth investigating the extent to which both the 'prebound' and rebound effects are, at least partly, determined by a household's preconceived notions of what their heating budget should be, and how this knowledge could be used in energy policies to address behaviour and fuel poverty.

These research findings were discussed with a number of German policy-makers and key policy actors in Berlin in January 2012: CDU and SPD Federal MPs; Green Party parliamentary research personnel research staff of the GdW (National Association of Housing Providers); a DENA (Deutsche Energie-Agentur, German Energy Agency) housing-energy expert; and energy research personnel of NABU (Naturschutzbund Deutschland, Nature and Biodiversity Conservation Union).

These discussions indicate that there is a growing realization that Germany's carbon reduction goals in respect of home heating cannot be met by demanding ever-deeper thermal retrofit standards. Retrofit standards were due to be tightened by a further 30% in 2012, but discussions with Federal policy-makers indicate that there is growing reluctance to do this.

In fact a recent study by Tschimpke et al. (2011) showed that even if it were technically possible to retrofit the entire housing stock to twice the depth being currently achieved, the cost would be an order of magnitude higher than the state and homeowners could afford, and would divert funds from more economically efficient carbon reduction projects. Some policy-makers see this as an opportunity to think laterally as to how other approaches, such as a mix of modest retrofit measures and targeted behaviour campaigns, could increase the savings. However, the dominant view still seems to be that if the technical fix is not working adequately, one must simply try harder to make it work. The latter view is supported by government subsidies.

Conclusions

This study sought out existing datasets that give values for the calculated space and water heating energy consumption (EPR) of German dwellings alongside the actual, measured values. Based on the existing data of the EPR and the measured consumption in 3400 German homes (Table 1), the analysis suggests four features of these data that can be recognized in similar ways in the Netherlands, Belgium, France and the UK:

- Firstly, there seems to be a large range of magnitudes of space heating energy consumption (kWh/m^{2}a) for dwellings with identical EPR figures.

- Secondly, the measured consumption tends to be, on average, 30% below the EPR. This gap between performance and measured energy consumption can be due to technical reasons, such as inaccurate assumptions in energy rating algorithms set by the German Institute of Standards (DIN V 4108-6:2003), but it is probable that at least part of it is due to diversity in heating patterns.

- Thirdly, the average gap between the actual and predicted performance seems to increase in magnitude as the EPR increases, ranging from around 17% for dwellings with an EPR of 150 kWh/m^{2}a to around 60% for those with an EPR of 500 kWh/m^{2}a ('prebound' effect).

- Fourthly, for dwellings with an EPR below 100 kWh/m^{2}a, it looks like these factors go into reverse so that dwellers tend to consume more energy than calculated in the EPR (rebound effect).

The presented analysis of the German databases suggests that, in general, the worse a home is, thermally, the more economically the occupants tend to behave with respect to their space heating. As retrofits cannot save energy that is not actually being con- sumed, this phenomenon is labelled the 'prebound' effect, where less energy is consumed than expected and has implications for the economic viability of thermal retrofits.

This analysis appears to challenge the prevailing German policy view that large, deep cuts in energy consumption can be achieved by focusing on the technical aspects of thermal retrofits and by demanding extremely high thermal standards. The gap identified between performance and the measured consumption suggests that there could be less potential for economically feasible savings in Germany's domestic heating energy than assumed in the discourse that drives Federal policy.

The common practice of using the calculated energy rating to estimate the fuel savings that can be achieved through retrofitting tends to exaggerate the potential savings because of the assumptions built into the method of calculating the energy rating. Even if the German government were to achieve its aim of retrofitting all substandard homes to EnEV standards, the gap identified in this paper would mean that in reality this might only bring half the expected savings, or less, and because of the technical difficulties with many buildings, the cost for households could be unacceptably high.

The current authors' reading of German Federal policy, together with discussions with German policy-makers in January 2012, indicates that non-technical factors like behaviour might not have been taken properly into account by policy-makers in developing effective thermal retrofit policies. The EnEV makes rigid demands for thermal standards in retrofits, and in some cases may prevent homeowners from adjusting their retrofit projects to suit what would be economically viable for their particular heating patterns and circumstances: excessively draconian thermal standards may in fact limit the amount of energy to be saved in the household heating sector.

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The Prebound Effect - Summary and Conclusions

The University of Cambridge study (June 2012) compares, based on the data of 3,400 buildings in Germany, measured actual energy consumptions with calculated energy performance ratings and reveals that the buildings' occupants consume, on average, 30% less heating energy than the calculated ratings postulate. This discrepancy is termed the "prebound effect".

The term "prebound" refers to the well-known "rebound effect" which states that occupants of passive and low-energy houses consume about 10% more energy than predicted by these buildings' energy performance ratings. As disclosed by the Cambridge study, this rebound effect applies to any dwelling with an EPR below 100 kWh/m²a.

The German DENA study of October 2012, being based on the analysis of 35,000 energy performance and consumption certificates, does confirm a prebound effect of around 30% (dena, 2012, page 43). This effect applies to dwellings built before 1995, which make up about 80% of today's building stock.

A similar 'prebound' phenomenon has been recognized among Dutch, British, Belgian and French households.

Data sources of the Cambridge study

The study is based on data of 3,400 German existing dwellings for which energy performance ratings as well as actual energy consumptions are available. Space and warm water heating are both taken into account. Since there are approximately 18 million residential buildings (2011) and 62 million eligible voters (2012), this data base is seven times better than with an election poll (1,000 interviewees).

Authors of the study

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Technical terms: Final Energy Performance Rating and Final Energy Consumption Rating

The final energy performance rating (in short: EPR) is a figure derived from technical data on the building envelope and its heating system, which is calculated by a software ("norm consumption" with standard parameters). The final energy consumption rating (in short: actual consumption) is based on the measured actual heating energy consumption of the dwellings' inhabitants.

Error source prebound effect

The computation of thermal retrofit requirements pursuant to the German Energy Savings Ordinance (EnEV) and the subsidies for thermal retrofit measures is not based on the actual energy consumption, but instead on the calculated energy performance ratings. Since the latter is demonstrably overstated by 30%, the energy savings and the corresponding CO_2 reductions to be achieved are wrongly assessed. The payback time is underestimated. The costs per tonne of CO_2 reduced are calculated wrongly.

Reasons for the prebound effect

The Cambridge study as well as the DENA buildings eport both concordantly state two reasons for the occurrence of the prebound effect.

Firstly, inaccuracies of the EPR calculation methods, e.g. due to excessive and wrong U-values or due to inaccurate assumptions in energy rating algorithms set by the German Institute for Standardization (DIN V 4108-6:2003).

Secondly, it must be assumed that a large part of the prebound effect is to be explained by the heating patterns of the occupants. Apparently inhabitants adjust their heating behavior to the costs of heating. They heat selectively according to the time of day and their sojourn in different rooms, and they leave individual unused rooms (e.g. former children's rooms) unheated.

Result 1: promote occupants' behavior

Germany's thermal retrofit policy currently primarily concentrates on technical solutions. The existence of the prebound effect, however, does prove that the occupants' behavior plays a decisive role for energy saving. Climate protection policy must therefore also aim, through economic incentives, to make occupants' behavior part of energy conservation. For instance, inexpensive electrically adjustable thermostat valves could be subsidised or be made tax-deductible.

Result 2: the potential for energy savings is overestimated

Since energy which isn't consumed cannot be conserved, the savings potential of thermal retrofit measures is clearly being overestimated.

An example illustrates this:

A residential building has an energy performance rating of 240 kWh/m²a, meaning that it theoretically consumes 240 kilowatt-hours per square metre per year. The measured actual consumption, however, is only 160 kWh/m²a.

Now, subsidies for thermal retrofit measures (e.g. roof insulation, facade insulation) are applied for and granted on the basis of the building's theoretical energy performance rating, which calculatory are to provide for example energy savings of 160 kWh/m^{2}a and thus achieve an EPR of 80 kWh/m^{2}a.

Because of the prebound effect, however, the building's actual consumption prior to thermal renovation was only 160 kWh/m^{2}a. So even if we assume that the new calculatory EPR of 80 kWh/m^{2}a is realistic, we achieve actual energy savings of only 80 kWh/m^{2}a, instead of the precalculated savings of 160 kWh/m^{2}a.

Since the inhabitants now live in an energy-efficient building, they modify their heating behavior. Due to the rebound effect the actual energy consumption increases by 10%, to 88 kWh/m^{2}a. This ultimately reduces the actual savings of the retrofit to 72 kWh/m2a.

Result 3: the payback time is underestimated, the retrofit measure becomes uneconomical

Since much less energy is saved than calculated, the actual payback time is prolonged. Not taking into account the rebound effect, the actual energy savings in the example above are 80 kWh/m^{2}a, being only half of the calculated savings. This means that the calculated payback time of the retrofit investment doubles. Subsequently, this retrofit measure becomes uneconomical pursuant to the EnEV, since the EnEV requires that the investment must amortise within the lifetime of the retrofit measure.

Result 4: the costs per tonne of CO_2 reduced are too high

Because only half of the calculated energy savings are actually achieved, the net costs per tonne of CO_2 reduced by thermal retrofit measures in the building stock increase, based on current energy prices, to 265 €. These are CO_2 reduction costs ten times higher than those which would e.g. arise when modernising a gas-fuelled power station. Since thermal retrofit measures are subsidised from tax funds, the question has to be asked, whether these subsidies are still justifiable, or if these funds could not be put to more effective use elsewhere.

Result 5: focus subsidies on smaller insulation measures

Empirical studies prove that smaller insulation measures such as the replacement of windows and doors or the insulation of cellars or attics are economically viable. The large-scale insulation of exterior walls however proves to be uneconomical.

The authors of the Cambridge study therefore demand to formulate the regulations for thermal retrofit measures in such a way that instead of draconic standards, they would allow economically efficient, incremental improvements that suit the actual state of the buildings.

The results suggest the following political conclusions:

Conclusion 1: abandon the current subsidy calculation

It does not make sense to base the subsidies for thermal retrofit measures on energy performance ratings which have an error margin of 30%. The basis must instead be the metered actual consumption. 50% of the subsidies can be paid at the beginning of the measure, the remaining 50% can, after proof of success, be paid in the 3rd and 4th year of the measure in 25% installments. This ensures that not theoretical savings, but only actually proven energy consumption savings are rewarded.

Conclusion 2: abandon the passive house strategy for existing buildings

Up to now, retrofit ideology aimed at successively modifying the building stock towards the passive house standard, by predominantly reducing the heating energy consumption drastically through the complete insulation of existing buildings in the same way as a passive house. This strategy fails because of its economic inefficiency and annot be made successful even by ever more ambitious regulations.

Conclusion 3: don't dictate the solution

The EnEV prescribes the solution in specific centimeters of insulation thickness, because the thickness corresponds to the U-value. This impeeds alternatives and better solutions. An energy savings ordinance should rather define CO_2 ranges per building type. This leads to a market-driven competition of technical solutions.

Conclusion 4: use the whole CO_2 toolbox, promote alternatives

The goal of climate policy is to reduce CO_2 emissions in the buildings sector by 80% by 2050. This target can also be achieved if the measures of a reasonable and economically viable thermal retrofit policy provide a CO_2 reduction of "only" 35% – this figure is considered to be realistic in the academic community.

The remaining 45% CO_2 reduction must and can be achieved by more efficient heating systems and the substitution of fossil fuels by renewable energy sources.

Alternatives which can be promoted more inexpensively and more CO_2-effective could e.g. be:

- Conversion of existing district heating networks to more CO_2-free fuels
- Installation of smaller district heating networks using renewable energy sources
- Conversion to low-temperature heating systems (radiation heating)
- Promotion of solar thermics and heat pumps (in combination with low-temperature heating systems)
- Incentives which promote energy-saving behavior (e.g. electronic thermostat valves)

Conclusion 5: summary

The thermal retrofit regulations for the building stock are in need of a fundamental revision. They must be oriented along actual energy consumptions, economic incentives and the competition of technical solutions. As a positive side-effect, this would stop the architectural disfigurement of our cities.

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