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

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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 CO₂ savings through retrofits tends to overestimate savings, underestimate the payback time and possibly discourage cost-effective, incremental improvements. Secondly, the potential fuel and CO₂ 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.

Keywords: building performance, thermal retrofits, climate policy, energy rating, energy policy, energy use behaviour

La réglementation allemande relative à la rénovation thermique des logements existants exige des normes thermiques élevées, que le gouvernement prétend être techniquement et économiquement applicables. Cet article examine les données existantes sur 3400 logements allemands; leurs classes d’efficacité énergétique (CEE) calculées sont ensuite comparées à la consommation réelle mesurée. Les résultats indiquent que les occupants consomment, en moyenne, 30 % d’énergie de chauffage en moins que la classe calculée. Ce phénomène est identifié en raison de l’accroissement de l’effet de « pré-bond » avec la classe calculée. Le phénomène opposé, l’effet de rebond, tend à se produire dans les logements à basse consommation d’énergie, dans lesquels les occupants ont une consommation supérieure à la classe. Un phénomène similaire a été reconnu dans des études récentes néerlandaises, belges, françaises et britanniques, suggérant des implications en termes de politiques dans deux directions. En premier lieu, l’utilisation de la classe énergétique d’un logement pour prévoir les économies de combustible et de CO₂ pouvant être obtenues grâce à des rénovations a tendance à surestimer les économies, à sous-estimer le délai d’amortissement et éventuellement à dissuader d’effectuer des améliorations incrémentielles rentables. En second lieu, les économies potentielles de combustible et de CO₂ pouvant être obtenues par des mesures non techniques telles que le comportement des occupants peuvent se révéler être bien plus importantes que cela n’est supposé en règle générale dans les politiques, de sorte que les décideurs ont besoin de mieux comprendre ce qui motive ou empêche les décisions des occupants.

Mots clés: performance des bâtiments, rénovations thermiques, politique climatique, classe énergétique, politique énergétique, comportement de consommation énergétique

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 policies. 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 CO₂ 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

Table 1 Data sources used in the analysis

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/m ² a)	Average measured consumption (kWh/m ² a)	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 <i>et al.</i> (2011)	National random sample	All types	1702	Calculated ^a	220	152	0.69	31	Both
Kaßner <i>et al.</i> (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 <i>et al.</i> (2010)	metered from Brunata-METRONA	Oil heated	250 000	not considered		141			Both
		Gas heated				156			
		District heating				109			
		All				148			
Schröder <i>et al.</i> (2010)	From heating energy metering	Rented accommodation built prior to the 1995 regulations	230 000	Not considered		145		Both	
Schröder <i>et al.</i> (2010)	From heating energy metering	Rented accommodation built prior to the 1995 regulations	143 000	Not considered		118		Space heating only	
Schröder <i>et al.</i> (2011)	Metering from Brunata-METRONA in 2005–2010	All types, all cohorts, data weighted for proportions nationally	250 000	Not considered		148		Both	
Walberg <i>et al.</i> (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: ^aEPR was calculated from building characteristics according to the German Institute of Standards DIN V 4108-6:2003.

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.

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/m²a, ranging from 15 to over 400 kWh/m²a. 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/m²a, e.g. 149 kWh/m²a by Schröder *et al.* (2011) and 152 kWh/m²a by Walberg *et al.* (2011). In general, this is 30% below the average EPR.

Thirdly, the datasets suggest a trend in energy consumption 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/m²a is around 40% below its calculated value, while dwellings with an average EPR of 150 kWh/m²a can have an actual energy consumption around 17% below their calculated 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 $y = x$, representing all the points where 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/m²a in detached houses with EPR ratings up to 400 kWh/m²a.

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 tendency, the rebound effect. The right-hand graph of Figure 1 shows the majority of points at the low energy end falling above the line $y = x$, 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/m²a. This is more pronounced (around 65%) for dwellings with an EPR under 75 kWh/m²a in Kaßner *et al.*

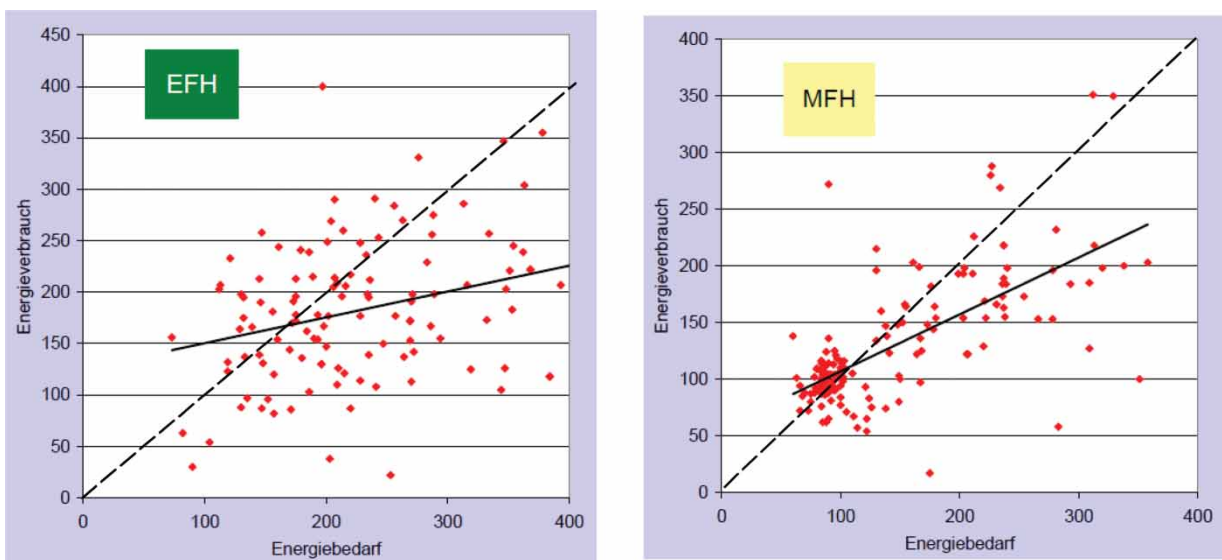


Figure 1 Scatterplots of measured energy consumption (vertical axes) against calculated energy consumption (horizontal axes) for detached houses (left) and multi-dwelling buildings (right). Source: Erhorn (2007)

(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/m²a 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°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 to 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 familiar 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 100

kWh/m²a. One can expect, for example, that the average actual space heating consumption of dwellings with an EPR of 500 kWh/m²a will be around 215 kWh/m²a, while that for dwellings with an EPR of 200 kWh/m²a will be around 145 kWh/m²a. 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:

$$P (\%) = 100 [1.2 - 1.3/(1 + \text{EPR}/500)]$$

This is displayed in Figure 2. In this model the 'prebound' effect becomes zero where EPR is 50 kWh/m²a, 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.

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 – 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

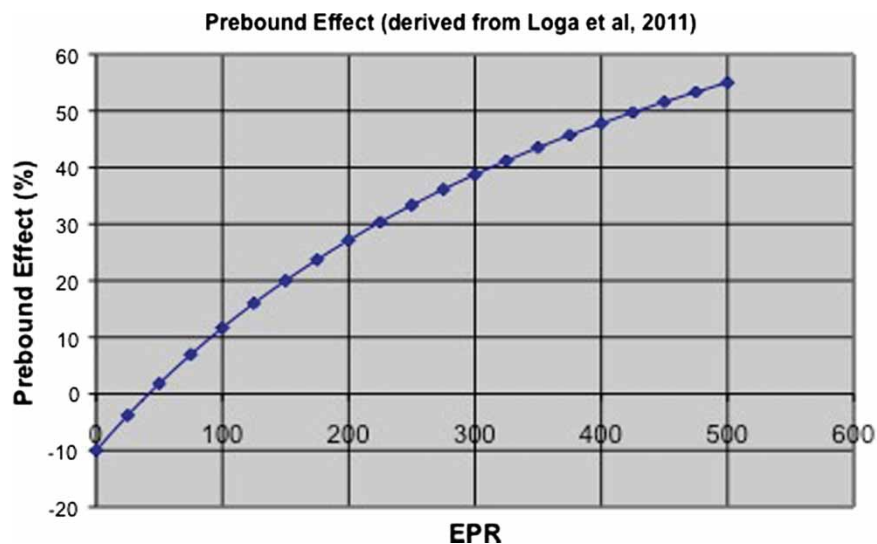


Figure 2 'Prebound' effect, modelled on data from Loga *et al.* (2011), using $P(\%) = 100 [1.2 - 1.3/(1 + \text{EPR}/500)]$

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, retrofitting 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/m²a, their independent variable was ‘specific transmission losses per m³ of protected volume’ (STV), expressed as W/m³K. 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 m² 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:

$$P \text{ (MJ/a)} = 100 [1.355 (U/C)^{0.16} - 1]$$

where U is the transmission loss (W/m²K); and C is the compactness of building, *i.e.* volume/area of building envelope.

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 m³ (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 (= 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/m²a, 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 m². 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 Menkeld (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

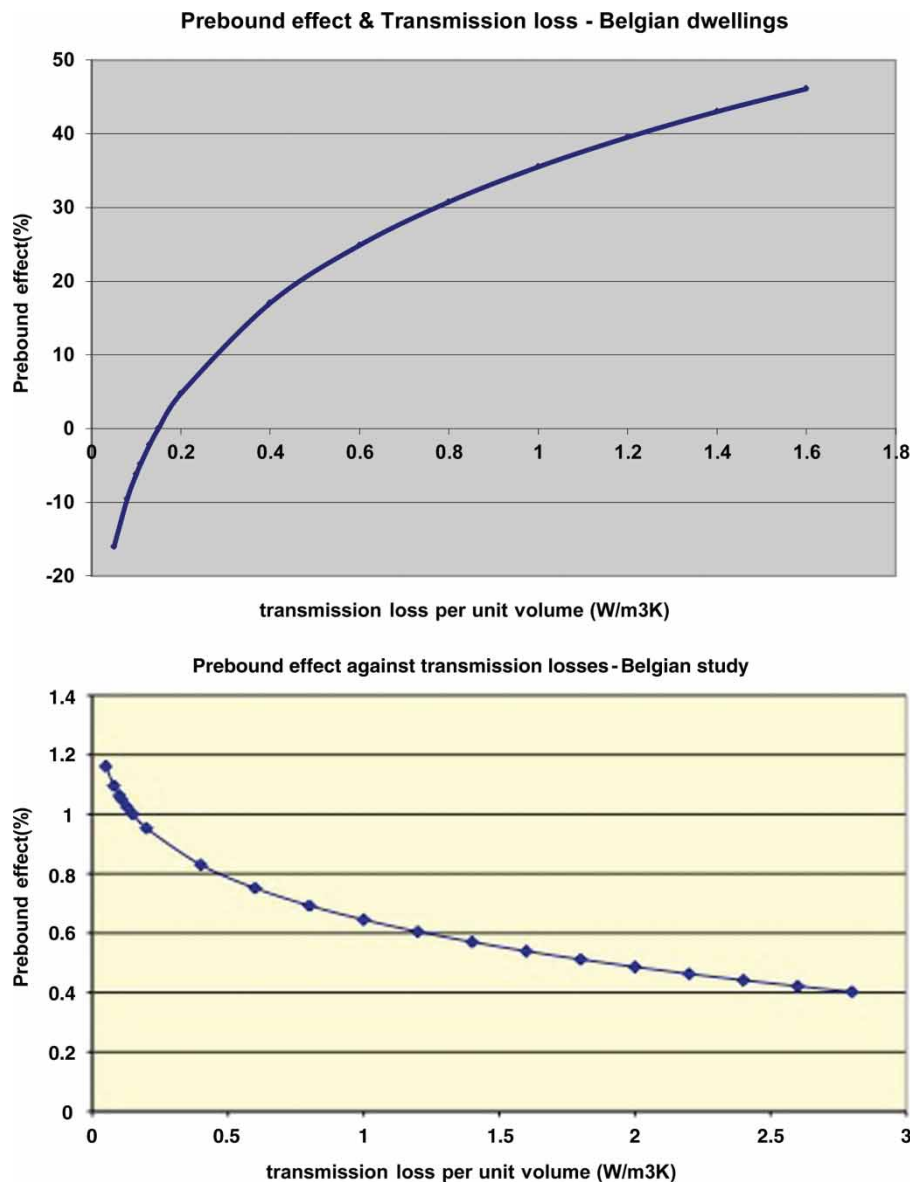


Figure 3 Curve fitting of a plot of a prebound effect for 964 Belgian dwellings, derived from Hens *et al.* (2010), P (MJ/a) = 100 [$1.355(U/C)^{0.16} - 1$]

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.

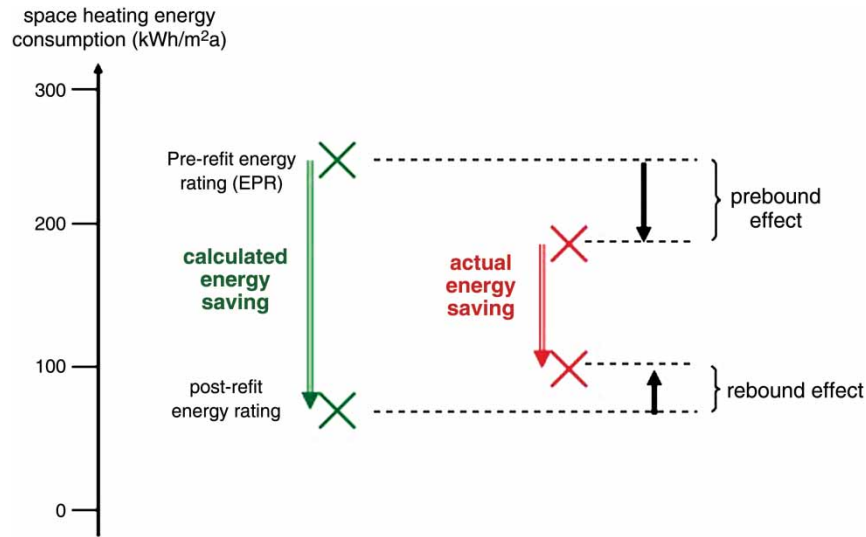


Figure 4 Schematic showing how the prebound and rebound effects may limit energy saving to be reduced from its theoretical amount

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/m²a. 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 CO₂ emission rate of 0.26 kg for each kWh consumed, this would amount to a gross cost of €265 for each tonne of CO₂ 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 double to €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 CO₂ emissions. This can be ten times as much as it costs to save CO₂ 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 retrofit 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^2a) 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 $150 kWh/m^2a$ to around 60% for those with an EPR of $500 kWh/m^2a$ ('prebound' effect).
- Fourthly, for dwellings with an EPR below $100 kWh/m^2a$, 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 consumed, 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.

References

- Barker, T., Ekins, P. and Foxton, T. (2007) The macro-economic rebound effect and the UK economy. *Energy Policy*, 35(10), 4935–4946.
- Berndgen-Kaiser, A., Fox-Kämper, R., Holtmann, S. and Frey, T. (2007) *Leben im Passivhaus: Baukonstruktion, Baukosten, Energieverbrauch, Bewohnererfahrungen*, Institut für Landes- und Stadtentwicklungsforschung und Bauwesen des Landes Nordrhein-Westfalen. 68 S.-ILS-NRW-Schriften Bd. 202, ILS NRW, Aachen (available at: http://www.ils-forschung.de/index.php?option=com_content&view=article&cid=348&Itemid=205&lang=de) (accessed on 18 November 2011).
- Boardman, B., Killip, G., Darby, S., Sinden, G., Jardine, C.N., Hinnells, M. and Palmer, J. (2005) *40% House Report*, Environmental Change Institute (ECI), Oxford.
- Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU) (2007) *Taking Action against Global Warming: An Overview of German Climate Policy*, Bundesministerium für Verkehr, Bau und Stadtentwicklung (BMVBS), Berlin.
- Bundesministerium für Verkehr, Bau und Stadtentwicklung (BMVBS) (2009a) *EnEV 2009 KfW-Programm Energieeffizient Sanieren* [online] (available at: <http://bis.bmvbs.de/static/flyer/index.html>) (accessed on 18 November 2011).
- Bundesministerium für Verkehr, Bau und Stadtentwicklung (BMVBS) (2009b) *Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden (Energieeinsparverordnung – EnEV 2009)*, BMVBS, Berlin (available at: http://www.enev-online.org/enev_2009_volltext/index.htm) (accessed on 17 November 2011).
- Bundesministerium für Wirtschaft und Technologie (BMWi) (2010) *Zahlen und Fakten: Energiedaten: Nationale und Internationale Entwicklung* Referat III C 3, BMWi, Berlin (available at: <http://www.bmwi.de/BMWi/Navigation/Energie/Statistik-und-Prognosen/energiedaten.html>) (accessed on 5 December 2010).
- Cayla, J.-M. (2010) From practices to behaviors: estimating the impact of household behavior on space heating energy consumption, in Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, US, 15–20 August 2010.
- Cayre, E., Allibe, B., Laurent, M.-H. and Osso, D. (2011) There are people in the house! How the results of purely technical analysis of residential energy consumption are misleading for energy policies, in Proceedings of the ECEEE 2011 Summer Study on Energy Efficiency First: The Foundation of a Low-Carbon Society, pp. 1675–1683.
- Chappells, H. and Shove, E. (2004) *Comfort: A Review of Philosophies and Paradigms*, Lancaster University Centre for Science Studies, Lancaster.
- Chappells, H. and Shove, E. (2005) Debating the future of comfort: environmental sustainability, energy consumption and the indoor environment. *Building Research & Information*, 33(1), 32–40.
- Cupples, J., Guyatt, V. and Pearce, J. (2007) 'Put on a jacket, you wuss': cultural identities, home heating, and air pollution in Christchurch, New Zealand. *Environment and Planning A*, 39, 2883–2898.
- de T'Serclaes, P. (2007) *Financing Energy Efficient Homes: Existing Policy Responses to Financial Barriers*, International Energy Agency (IEA), Paris.
- DENA (2011) *DENA-Sanierungsstudie. Teil 1: Wirtschaftlichkeit energetischer Modernisierung im Mietwohnungsbestand. Begleitforschung zum dena-Projekt 'Niedrigenergiehaus im Bestand'*, Deutsche Energieagentur, Berlin (available at: http://www.zukunft-haus.info/uploads/media/dena-Sanierungsstudie_Teil_1_MFH_01.pdf) (accessed on 17 November 2011).
- Enseling, A. and Hinz, E. (2006) *Energetische Gebäudesanierung und Wirtschaftlichkeit – Eine Untersuchung am Beispiel des 'Brunckviertels' in Ludwigshafen*, Institut Wohnen und Umwelt, Darmstadt.
- Erhorn, H. (2007) *Bedarf – Verbrauch: Ein Reizthema ohne Ende oder die Chance für sachliche Energieberatung?*, Fraunhofer-Institut für Bauphysik, Stuttgart (available at: <http://www.buildup.eu/publications/1810>) (accessed on 20 November 2011).
- Galvin, R. (2010) Thermal upgrades of existing homes in Germany: the building code, subsidies, and economic efficiency. *Energy and Buildings*, 42(6), 834–844.
- Galvin, R. (2011), Discourse and materiality in environmental policy: the case of German Federal policy on thermal renovation of existing homes. PhD thesis, School of Environmental Sciences, University of East Anglia, Norwich (available at: <http://justsolutions.eu/Resources/PhDGalvinFinal.pdf>) (accessed on 17 November 2011).
- Galvin, R. and Sunikka-Blank, M. (2012) How price elasticity affects the economic viability of domestic energy efficiency technology: case study of thermal refits of German dwellings. *Energy and Buildings*, DOI 10.1016/j.enbuild.2012.03.043.
- GdW Bundesverband deutscher Wohnungs- und Immobilienunternehmen e.V (2010) *Energieeffizientes Bauen und Modernisieren: Gesetzliche Grundlagen; EnEV 2009; Wirtschaftlichkeit*, GdW Berlin.
- GdW Bundesverband deutscher Wohnungs- und Immobilienunternehmen e.V (2011) *DENA-Sanierungsstudie zur Wirtschaftlichkeit von Modernisierungsmaßnahmen ist unrealistisch*, Medien-Information Nr. 05/11 vom 10.02.2011, GdW, Berlin (available at: <http://web.gdw.de/pressecenter/pressemeldung-gen/177-energieeffizienz/134-dena-sanierungsstudie-zur-wirtschaftlichkeit-von-modernisierungsmaßnahmen-ist-unrealistisch?tmpl=component&format=pdf>) (accessed on 29 December 2011).

- Gerth, M., Kämpke, T., Radermacher, F.J. and Solte, D. (2011) *Die soziale Dimension des Klimaschutzes und der Energieeffizienz im Kontext von Bau- und Wohnungswirtschaft*, Forschungsinstitut für anwendungsorientierte Wissensverarbeitung, Ulm (available at: <http://www.faw-neu-ulm.de/artikel>) (accessed on 18 November 2011).
- Gram-Hansen, K. (2008a) Consuming technologies – developing routines. *Journal of Cleaner Production*, 16(11), 1181–1189.
- Gram-Hansen, K. (2008b) Heat comfort and practice theory, in T.G. Ken, A. Tukker and C. Vezzoli (eds): *Sustainable Consumption and Production: Framework for Action*. Proceedings of the 2nd Conference of the Sustainable Consumption Research Exchange (SCORE!) Network Flemish Institute for Technological Research, Mol, pp. 53–72.
- Gram-Hansen, K. (2010) Residential heat comfort practices: understanding users. *Building Research & Information*, 38(2), 175–186.
- Gram-Hansen, K. (2011) Households' energy use – which is the more important: efficient technologies or user practices, in Proceedings of the World Renewable Energy Congress 2011, Linköping, Sweden.
- Greller, M., Schröder, F., Hundt, V., Mundry, B. and Papert, O. (2010) Universelle Energiekennzahlen für Deutschland – Teil 2: Verbrauchskennzahlentwicklung nach Baualtersklassen. *Bauphysik*, 32(1), 1–6.
- Guerra-Santin, O. and Itard, L. (2010) Occupants' behaviour: determinants and effects on residential heating consumption. *Building Research & Information*, 38(3), 318–338.
- Guerra-Santin, O., Itard, L. and Visscher, H. (2009) The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock. *Energy and Buildings*, 41, 1223–1232.
- Haas, R. and Biermayr, P. (2000) The rebound effect for space heating: empirical evidence from Austria. *Energy Policy*, 28, 403–410.
- Hacke, U. (2007) *Supporting European Housing Tenants in Optimising Resource Consumption. Deliverable 2.1: Tenant and Organisational Requirements, Version 1a*, Save@Work4Homes, Berlin and Frankfurt (available at: http://www.iwu.de/fileadmin/user_upload/dateien/energie/klima_altbau/SAVE_Work4Homes_Deliverable_2.1_V1a.pdf) (accessed on 27 October 2011).
- Hens, H., Parijs, W. and Deurinck, M. (2010) Energy consumption for heating and rebound effects. *Energy and Buildings*, 42, 105–110.
- Holm, S.-O. and Englund, G. (2009) Increased ecoefficiency and gross rebound effect: evidence from USA and six European countries. *Ecological Economics* 1960–2002, 68, 879–887.
- Hunt, L.C., Judge, G. and Ninomiya, Y. (2003) Underlying trends and seasonality in UK energy demand: a sectoral analysis. *Energy Economics*, 25, 93–118.
- International Energy Agency (IEA) (2008) *Promoting Energy Efficiency Investments: Case Studies in the Residential Sector*, IEA Paris.
- Jagnow, K. and Wolf, D. (2008) *Technische Optimierung und Energieeinsparung*. OPTIMUS-Hamburg City-State.
- Jakob, M. (2006) Marginal costs and co-benefits of energy efficiency investments: the case of the Swiss residential Sector. *Energy Policy*, 34, 172–187.
- Jakob, M. (2007) *The Drivers of and Barriers to Energy Efficiency in Renovation Decisions of Single-Family Homeowners*. Working Paper No. 56, Centre for Energy Policy and Economics (CEPE), Zurich.
- Kaßner, R., Wilkens, M., Wenzel, W. and Ortjohan, J. (2010) Online-Monitoring zur Sicherstellung energetischer Zielwerte in der Baupraxis, in *Paper presented at 3. Effizienz Tagung Bauen+Modernisieren*, Hannover, Germany, November, 19–20, 2010 (available at: http://www.energy-check.de/wp-content/uploads/2010/11/EFT_2010_ortjohann_2010-10-18.pdf) (accessed on 18 November 2011).
- Kelly, S. (2011) *Do Homes that are More Energy Efficient Consume Less Energy?: A Structural Equation Model for England's Residential Sector*. EPRG Working Paper No. 1117, Cambridge Working Paper in Economics 1139, University of Cambridge, Cambridge.
- Knissel, J., Alles, R., Born, R., Loga, T., Müller, K. and Stercz, V. (2006) *Vereinfachte Ermittlung von Primärenergiekennwerten zur Bewertung der wärmetechnischen Beschaffenheit in ökologischen Mietspiegeln*, Deutsche Bundesstiftung Umwelt, Osnabrück.
- Knissel, J. and Loga, T. (2006) Vereinfachte Ermittlung von Primärenergiekennwerten. *Bauphysik*, 28(4), 270–277.
- Loga, T., Diefenbach, N. and Born, R. (2011) *Deutsche Gebäudetypologie. Beispielhafte Maßnahmen zur Verbesserung der Energieeffizienz von typischen Wohngebäuden*, Institute Wohnen und Umwelt, Darmstadt, (available at: http://www.building-typology.eu/downloads/public/docs/brochure/DE_TABULA_TypologyBrochure_IWU.pdf) (accessed 29 January, 2012).
- Maaß, J.B., Walther, C. and Peters, I. (2008) *Erfahrungen mit Passivhaussiedlungen in Deutschland (Schwerpunkt Norddeutschland)*, Bezirksamt Harburg, Freie und Hansestadt Hamburg.
- Martiskainen, M. (2008) Household energy consumption and behavioural change – the UK perspective, in T.G. Ken, A. Tukker and C. Vezzoli (eds): *Sustainable Consumption and Production: Framework for Action*. Proceedings of the 2nd Conference of the Sustainable Consumption Research Exchange (SCORE!) Network, Flemish Institute for Technological Research, Mol, pp. 73–90.
- Meijer, F., Itard, L. and Sunikka-Blank, M. (2009) Comparing European residential building stocks: performance, renovation and policy opportunities. *Building Research & Information*, 37(5), 533–551.
- Michelsen, C. and Müller-Michelsen, S. (2010) Energieeffizienz im Altbau: Werden die Sanierungspotenziale überschätzt? Ergebnisse auf Grundlage des ista-IWH-Energieeffizienzindex. *Wirtschaft im Wandel*, 9, 447–455 (available at: <http://www.iwh-halle.de/d/publik/wiwa/9-10-5.pdf>) (accessed on 28 November 2011).
- Peper, S. and Feist, W. (2008) *Gebäudesanierung 'Passivhaus im Bestand' in Ludwigshafen/Mundenheim Messung und Beurteilung der energetischen Sanierungserfolge*, Passivhaus Institut Darmstadt.
- Pöschk, J. (ed.) (2009) *Energieeffizienz in Gebäuden: Jahrbuch 2009*, Medienservice Energie, Berlin.
- Rehdanz, K. (2007) Determinants of residential space heating expenditures in Germany. *Energy Economics*, 29, 167–182.
- Roth, K. and Engelman, P. (2010) Impact of user behavior on energy consumption in high-performance buildings – results from two case studies, in *Paper presented at the Fraunhofer Center for Sustainable Energy Studies*, Denver, CO, US.
- Schloman, B., Ziesling, H.-J., Herzog, T., Broeske, U., Kaltschnitt, M. and Geiger, B. (2004) *Energieverbrauch der privaten Haushalte und des Sektors Gewerbe, Handel, Dienstleistungen (GHD)*, Project No. 17/10, Abschlussbericht an das Ministerium für Wirtschaft und Arbeit, Fraunhofer Institut für Systemtechnik und Innovationsforschung, Karlsruhe (available at: <http://isi.fraunhofer.de/isi-de/e/projekte/122s.php>) (accessed on 26 November 2011).
- Schröder, F., Altendorf, L., Greller, M. and Boegelein, T. (2011) Universelle Energiekennzahlen für Deutschland: Teil 4: Spezifischer Heizenergieverbrauch kleiner Wohnhäuser und Verbrauchshochrechnung für den Gesamtwohnungsbestand. *Bauphysik*, 33(4), 243–253.
- Schröder, F., Engler, H.J., Boegelein, T. and Ohlwärter, C. (2010) Spezifischer Heizenergieverbrauch und Temperaturverteilungen in Mehrfamilienhäusern – Rückwirkung des Sanierungsstandes auf den Heizenergieverbrauch. *HLH: Lüftung/Klima Heizung/Sanitär*, 61(11), 22–25 (available at: http://www.brunata-metrona.de/fileadmin/Downloads/Muenchen/HLH_11-2010.pdf) (accessed on 8 December 2011).

- Sinn, H.-W. (2008) *Das grüne Paradoxon: Plädoyer für eine illusionsfreie Klimapolitik*, Econ, Berlin.
- Sorrell, S. and Dimitropoulos, S. (2008) The rebound effect: microeconomic definitions, limitations and extensions. *Eco-logical Economics*, 65(3), 636–649.
- Stern, P.C. (2000) Towards a coherent theory of environmentally significant behaviour. *Journal of Social Issues*, 56, 407–424.
- Summerfield, A.J., Lowe, R.J. and Oreszczyn, T. (2010) Two models for benchmarking UK domestic delivered energy. *Building Research & Information*, 38(1), 12–24.
- Sunikka, M. (2006) *Policies for Improving Energy Efficiency of the European Housing Stock*, IOS Press, Amsterdam.
- Sunikka-Blank, M., Chen, J., Britnell, J. and Dantsiou, D. (2012) Improving energy efficiency of social housing areas: a case study of a retrofit achieving an ‘A’ energy performance rating in the UK. *European Planning Studies*, 20(1), 133–147.
- Sunikka-Blank, M. and Galvin, R. (Forthcoming 2012) The economic viability of thermal retrofit policies: implications for the UK Green Deal based on the experience from German mandatory thermal renovation standards. *Energy Policy* (forthcoming).
- Tambach, M., Hasselaar, E. and Itard, L. (2010) Assessment of current Dutch energy transition policy instruments for the existing housing stock. *Energy Policy*, 38(2), 981–996.
- Thomsen, K.E., Schultz, J.M. and Poel, B. (2005) Measured performance of 12 demonstration projects – IEA Task 13 ‘advanced solar low energy buildings’. *Energy and Buildings*, 37, 111–119.
- Tiefensee, W. (2006) *The Programme for Refurbishment of Buildings to Reduce CO₂ Emissions is a Success Story of the Federal Government*. Press release, December, Bundesministerium für Verkehr, Bau und Stadtentwicklung (BMVBS), Berlin.
- Tighelaar, C. and Menkveld, M. (2011), Obligations in the existing housing stock: who pays the bill?, in Proceedings of the ECEEE 2011 Summer Study on Energy Efficiency First: The Foundation of a Low-Carbon Society, pp. 353–363.
- Tschimpke, O., Seefeldt, F., Thamling, N., Kemmler, A., Claasen, T., Gassner, H., Neusüss, P. and Lind, E. (2011) *Anforderungen an einen Sanierungsfahrplan: Auf dem Weg zu einem klimaneutralen Gebäudebestand bis 2050*, NABU/prognos, Berlin (available at: http://www.nabu.de/sanierungsfahrplan/NABU-Sanierungsfahrplan_endg.pdf) (accessed on 21 January 2012).
- Umweltbundesamt (UBA) (2007) *Wirkung der Meseberger Beschlüsse vom 23.08.2007 auf die Treibhausgasemission in Deutschland im Jahr 2020*, UBA Dessau.
- Walberg, D. (2011) *Energieeffiziente Highend-Gebäude: Wirklichkeit und Grenznutzen*, Proceeding of the 33rd International Uponor Kongress 2011, pp. 73–78. (available at: http://www.uponor.de/~media/Files/Uponor/Germany/Arlberg/Beitrag_6_Walberg.ashx) (accessed 16 May 2012).
- Walberg, D., Holz, A., Gniechwitz, T. and Schulze, T. (2011) *Wohnungsbau in Deutschland – 2011 Modernisierung oder Bestandsersatz: Studie zum Zustand und der Zukunftsfähigkeit des deutschen ‘Kleinen Wohnungsbaus’*, Arbeitsgemeinschaft für zeitgemäßes Bauen, eV, Kiel.