Back to reality: How domestic energy efficiency policies in four European countries can be improved by using empirical data instead of normative calculation

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Abstract

It is now well established that there is a serious gap between normative Energy Performance Certificate (EPC) calculations and measured energy consumption in the domestic sector. The fact that there are similarities in this gap between different European countries with varied housing stocks, different normative (EPC) dwelling consumption calculation methods and different cultural norms is surprising. This gap affects the analysis of current energy consumption and the estimation of future energy saving and its cost-effectiveness.

This paper presents the results of comparing the differences between measured consumption and normative estimations of residential energy consumptions using national standard (EPC) calculations in four European countries (United Kingdom, France, The Netherlands and Germany). The potential causes of this gap are discussed in terms of behavioural change, technological performance and the application of normative models.

Normative calculations are currently used to help develop both European and national energy efficiency policies. In the recast of the EPBD directive for example, cost-optimality calculations for major renovations and Nearly-Zero-Energy Buildings are based on normative standards. The paper provides examples of the potential impact that using normative as opposed to calculations grounded in empirical data may have on policy decisions.

Introduction

It is commonly assumed that there is a large and cost effective energy saving potential in the existing housing stock (IEA, 2008; de T'Serclaes, 2007). Consequently, many energy efficiency policies are focused on the residential sector.

Most European countries have set energy efficiency targets for the percentage decrease in building energy consumption, particularly in dwellings. For example, in France, the "Grenelle Action plan" has set a target of a 38 % reduction in building energy consumption by 2020 compared to 2008 (Grenelle, 2012). The residential sector is the primary focus of the Grenelle Action Plan, constituting 80 % of the total energy efficiency target by 2020 (authors' calculation).

Such targets aim to reduce the actual energy consumption and associated carbon emissions of the residential stock in these countries; however the policies designed to deliver these savings and their evaluation are often based on theoretical calculations using simple thermal models with standardised occupant behavioural assumptions (either average or idealised, e.g. assuming comfort temperatures). These models are often a mixture of simplified calculations, plus assumptions based on empirical evidence or expert guesses. The models used for policy making are often the same as those used for building energy labelling e.g. Energy Performance Certificates (EPC's). However, EPC models aim to normalise occupant behaviour enabling the comparison of two buildings independent of potential variations in occupant behaviour.

Policy makers need to understand how buildings perform on average, incorporating the large diversity of potential behaviours. But it is important for researchers and policy makers to understand this fundamental difference between these two different requirements and the potentially large impact that using a normative calculation can make on policy aimed at improving

Table 1. Percentage of national final energy consumption estimated for space heating and national normal climate (heating degree days).

	% of space heating	Normal climate (heating degree day, source: EDF-R&D*)
United Kingdom	66%	2713
The Netherlands	68%	2842
France	68%	2319
Germany	73%	3219

(*) hdd calculation: heating temperature: 18 °C, whole year considered, average value for 1996–2010 period.

the efficiency of an actual home. For example, normative models generally overestimate the energy consumption of a dwelling.

EPC models are also used to calculate the cost effectiveness of energy efficient improvements. The EPC calculated saving will however only be delivered for dwellings with normative behaviour. For the vast majority of occupants who use less than the normative energy consumption, fuel savings will be less and payback periods longer (Tigchelaar, 2011).

Several studies have highlighted the discrepancy between EPC normative calculations and current consumptions, especially for space heating. They are focused on national contexts and describe a country case (Der dena-Gebäudereport, 2012; Cayre, 2011; Tigchelaar, 2011; Sunnika-Blank, 2012; Allibe, 2012; Majcen, 2013; Guerra-Santin, 2012; Audenaert, 2011; Hens, 2010; Hong; 2006). However, EPC is a European initiative, even if applied in countries with national protocols. It is interesting to compare these "national" studies in order to observe if observed gaps have same order of magnitude.

This paper provides a review of the likely cause and impact of the gap between empirical energy data and normative EPC calculations in four European countries, i.e. United Kingdom, The Netherlands, France and Germany. Since space heating accounts for the majority of northern European domestic energy use (see Table 1) this paper focuses on this end-use consumption.

EPC: the current situation in UK, NL, FR, GER

The European Energy Performance of Buildings Directive (EPBD) specifies the requirements for issuing and rating the energy performance of buildings in the EU. For housing, a certificate is required when a dwelling is constructed, rented or sold and must provide a rating of its energy performance and CO_2 emissions and must provide a set of recommendations for energy performance improvement. The Directive requires that the methodologies used to calculate the ratings are based on a general framework set out in the EPBD, which take into account: thermal characteristics, heat and hot water systems, location and orientation, ventilation, air conditioning and indoor climate. The method (as defined under EN 15217) must 1) calculate the overall energy performance index in total and per area unit of energy and CO_2, 2) provide an overall minimum efficiency level, 3) provide a breakdown of energy use by dwelling component, and 4) display the results on an A to G banding.

UNITED KINGDOM

In the UK the implementation of the EPBD is devolved to local governments. In England, Wales and Northern Ireland, the government (HM Government, 2011), has mandated EPCs since 1st October 2008, with an EPC being required when a home is rented or sold (including new homes) and the rating is valid for 10 years. The EPC methodology is based on the government's Standard Assessment Procedure (SAP) for new dwellings with a reduced level of data input when calculating EPC's for existing dwellings (RdSAP). The A to G scale coincides with SAP ratings, where a 'D' rating is the median value for all dwellings, based on national estimates (DECC, 2012). As specified above, the ratings are calculated using a standard set of assumptions regarding the energy performance using characteristics of the home, such as age, layout, construction, the heat system type, lighting and the levels of insulation. The certificates are standardised against a 'notional' building to provide a benchmark that allows for comparison between properties. The calculations for energy and cost of running the homes assume a 'standard occupant' that has defined heating pattern and temperature and an average fuel price and climate. All EPC's are based on calculated energy use not measured.

The average SAP rating for English houses is 51.4, which is an 'E' rating (DECC, 2012 a).

As of November 2012, approximately 8.6 million EPCs have been logged (Landmark, 2012) (note this figures includes cancelled reports and multiple reports per dwelling), so there are approximately 4.2 million valid EPCs.

THE NETHERLANDS

The Netherlands introduced a voluntary energy labels for houses in 1995, the Energy Performance Advice (EPA). In 2008 the EPA was replaced by a less comprehensive but cheaper to administer EPC mandated by the EPBD. Like in the UK, the Dutch EPC has an A to G scale with a D rating set as a median level for dwellings.

Trust levels in the EPC are relatively low in the Netherlands (http://www.ecn.nl/publicaties/ECN-O--11-083). This is partly due to doubt about the calculations and the outcomes. Tests showed that different auditors came to different ratings for the same building. Also people loose trust because the theoretical normalised energy consumption on the label does not represent the actual consumption.

The lack of trust contributed to the low number of private homeowners that actually have an EPC when selling the house. In total there are over 2.1 million EPCs logged, but only 10 % of these are for private dwellings. The vast majority of these are for rented social housing.

To increase the level of trust in the calculation the method has been improved as well as the content and lay-out of the EPC.

FRANCE

Since 1st November 2006, the calculation and display of an EPC is mandatory in France at the point of sale of a home or building. In addition, since 1 July 2007, an EPC is mandatory when a lease is signed on a domestic property. All new dwellings whose construction permits were filed after July 1st 2007 also require an EPC. An EPC is usually valid in France for a 10 year period from its date of issue (Ademe, 2010).

A French EPC requires a description of the house including its size, orientation, walls, windows, materials, etc. as well as a description of its heating, hot water, cooling and ventilation equipment. The EPC estimates energy consumption for a standardized use of the building (Ministry of housing, 2011).

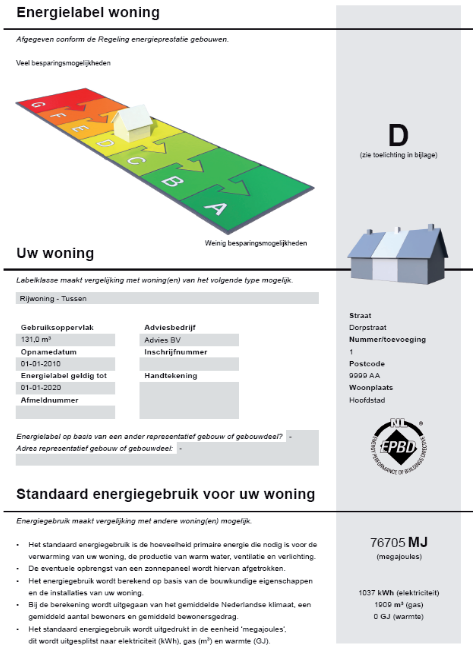
The main EPC outputs are summarised in two labels, energy and greenhouse gas emissions (Figure 2), with 7 classes from A to G (A being the best) to facilitate easy reading and interpretation.

In France the energy part of the label is displayed and used more frequently than the GHG emissions label.

The French EPC calculation method is a normative simplified annual calculation, based on the French 1988 thermal regulation (Ministry of Employment, 2006]), and coupled with a database describing thermal characteristics of French dwellings. The calculation assumes normative occupant behaviour and comfort standards. For old buildings (pre 1948) and apartments with a communal heating system, it is possible to calculate the EPC from the energy bills from the previous year instead of using modelled calculations. Comparisons of EPC certificates from different buildings is made more difficult by allowing two very different methods to calculate the EPC, one purely theoretical and one based on fuel bill information. Any labelling scheme has the challenge of communicating, in a simple easy to use way, complex information which could be used for a wide range of different applications across a very diverse range of climates and energy systems. The EPBD chose to display primary rather than final energy[1] as the key energy indicator. In many European countries fossil fuels are directly burnt in dwellings and this is a good indicator of the efficiency of use of fossil fuels. Also, in these countries there is little difference between considering primary or delivered energy for space heating. However in France where one third of dwellings are heated with electricity, there is a very large difference when considering primary as opposed to final energy. In this paper the authors have therefore focused on comparisons between EPC calculated and measured *final* energy.

The EPC also displays recommendations for the most cost effective energy efficiency interventions including improvements to the fabric, services, equipment, management and occupant behaviour. These recommendations provide guidance to encourage the uptake of energy efficient improvements but it is not mandatory to undertake them.

By 2010, almost 2 million dwellings have been EPC certified in France, (6.5 % of the domestic stock). A national register of French EPCs is currently being developed by the French National Agency for Energy Efficiency (Ademe). According to a study of 150,000 EPCs from French dwellings (Rex'Im 2011), the average EPC normative consumption is 270 kWh$_{pe}$/year.m^2 and 35 kgeqCO$_2$/year.m^2. The average energy label is class E.



Energielabel woning

Afgegeven conform de Regeling energieprestatie gebouwen.

Veel besparingsmogelijkheden

Weinig besparingsmogelijkheden

D

(zie toelichting in bijlage)

Uw woning

Labelklasse maakt vergelijking met woning(en) van het volgende type mogelijk.

Rijwoning - Tussen

Gebruiksoppervlak
131,0 m^3
Opnamedatum
01-01-2010
Energielabel geldig tot
01-01-2020
Afmeldnummer

Adviesbedrijf
Advies BV
Inschrijfnummer
Handtekening

Straat
Dorpstraat
Nummer/toevoeging
1
Postcode
9999 AA
Woonplaats
Hoofdstad

Energielabel op basis van een ander representatief gebouw of gebouwdeel? -
Adres representatief gebouw of gebouwdeel: -

Standaard energiegebruik voor uw woning

Energiegebruik maakt vergelijking met andere woning(en) mogelijk.

- Het standaard energiegebruik is de hoeveelheid primaire energie die nodig is voor de verwarming van uw woning, de productie van warm water, ventilatie en verlichting.
- De eventuele opbrengst van een zonnepaneel wordt hiervan afgetrokken.
- Het energiegebruik wordt berekend op basis van de bouwkundige eigenschappen en de installaties van uw woning.
- Bij de berekening wordt uitgegaan van het gemiddelde Nederlandse klimaat, een gemiddeld aantal bewoners en gemiddeld bewonersgedrag.
- Het standaard energiegebruik wordt uitgedrukt in de eenheid 'megajoules', dit wordt uitgesplitst naar elektriciteit (kWh), gas (m^3) en warmte (GJ).

76705 **MJ**
(megajoules)

1037 **kWh** (elektriciteit)
1909 **m^3** (gas)
0 GJ (warmte)

Figure 1. Example of the new style of EPC for the Netherlands.

GERMANY

In Germany the EPC is related to and derived from the whole-building thermal performance standard used in the thermal building regulations *(Energieeinsparverordnung* – EnEV). This specifies the quantity of primary energy a building is calculated to consume for space and water heating combined, in kilowatt-hours per square meter of floor area per year (kWh$_{pe}$/m^{2}a).

The whole-building primary energy consumption is calculated according to a formula known as DIN-4108 (DIN, 2003a), and published by the *Deutsches Institut der Normung* (German Institue of Standards – DIN). This takes account of the following factors and assumptions:

- the volume of the building and its floor area[2]
- the area of the building envelope
- a standard ventilation and air leakage factor of 0.7 times the volume of the dwelling(s) per hour
- a solar gain factor based on the building's orientation to the sun
- a standard factor for heat energy gain through indoor activities
- a factor based on the efficiency of the heating system
- the dwelling is subjected to the average number of German heating degree days regardless of its actual location.

The DIN-4108 standard was never intended to indicate actual energy consumption. Rather, it was designed to provide

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[1] Different countries have different naming conventions for energy, this paper defines final energy as the energy delivered and metered at the boundary to the dwelling which is also sometimes called delivered energy in some countries.

[2] The notion of 'floor' area (Nützfläche) is complicated in German building regulations. It includes the actual area inside the front door (the Wohnfläche), plus a theoretical proportion of the public areas of the residential building – stair wells, landings, shared drying rooms, etc.

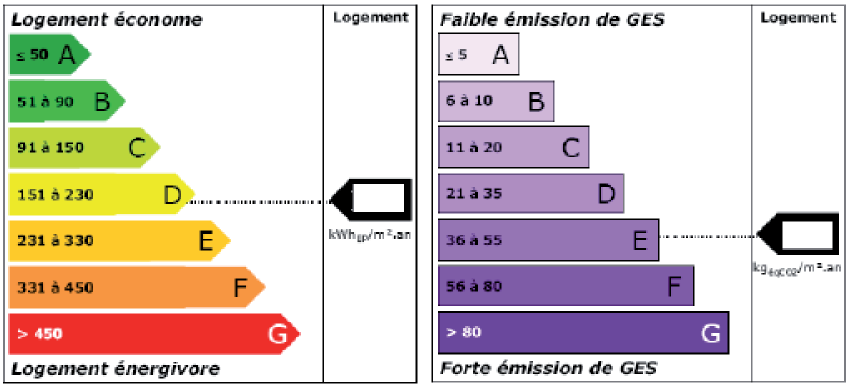


Figure 2. French EPC labels: left: primary energy (kWh$_{pe}$/m^2/yr), right: emissions (kgeqCO$_2$/m^2/yr).

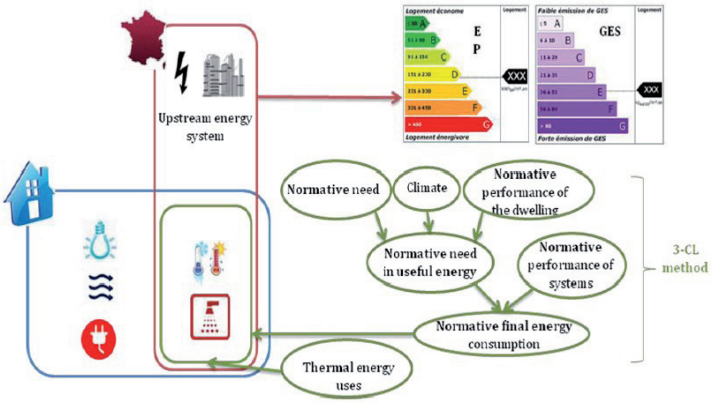


Figure 3. Process for the evaluation of a dwelling energy performance via the French EPC (Allibe, 2012).

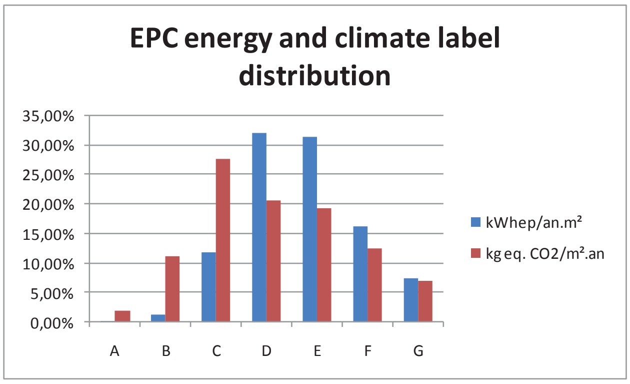


Figure 4. French dwellings: EPC energy and climate labels distribution (Rex'Im, 2011).

an objective whole-building performance standard that would measure conformity to thermal building regulations and enable a comparison between buildings. A subsequent DIN advice publication, DIN EN 832:1998 (DIN, 2003b), points out that the theoretical consumption arrived at using the methodology of DIN-4108 can differ by 50–150 % depending on the assumptions made about user behaviour (see discussion in Beecken and Schulze, 2011: 340).

New or retrofitted domestic buildings have to conform to thermal standards based on the DIN methodology, and in official publications and expert reports it is this figure that is used to estimate their heating energy consumption.

The same figure, with one modification, is that recorded on EPCs of new builds and all comprehensively retrofitted properties. The modification is that local weather conditions may be used to determine the number of heating degree days used in the calculation. Dwellings being sold or rented must also have an EPC. For those built prior to 1977 that have not been comprehensively retrofitted and are in buildings of more than 4 dwellings, the theoretically calculated value must be used. All other dwellings may use the primary energy for *actual, measured* heating energy consumption on their EPC, provided they have 3 consecutive years of fuel bills.

The DIN-4108 figure is also used in official processes in Germany to calculate energy savings through thermal retrofits. This applies, for example, where homeowners are seeking Federal subsidies, which they may receive if their retrofit is designed to do better than the legal standard. Each year the German Development Bank *(Kreditanstalt für Wiederaufbau* – KfW), which provides the subsidies, commissions a study on the amount of energy saved through these retrofits. These studies (Clausnitzer et al., 2007; 2008; 2009; 2010; 2011) base their findings solely on the changes in the physical features of the building, using the DIN-4108 methodology for estimating pre- and post-retrofit consumption. Hence their estimates of fuel saved are based on these theoretical figures, not on actual, measured savings.

Theoretical energy savings are also used in government promotional literature for thermal retrofitting, where it is typically claimed that savings of 80 % are possible (e.g. BMVBS, 2012; DENA, 2012). They are also used in expert reports on savings achieved in specific retrofit projects. An important example is Enseling and Hinz's (2006) study of a large housing estate retrofit project in Ludwigshafen-am-Rhein, which is frequently cited as showing the economic benefits of thermal retrofits. Although the actual, measured post-retrofit consumption was used here, the pre-retrofit consumption figure was the theoretical value (Galvin and Sunikka-Blank, 2012).

The difficulty with this approach is that empirical studies consistently show a large difference between the theoretical calculations and the measured energy consumption.

Table 2. Comparative table

	UK	NL	France	Germany
Year RPC implementation	2007, SAP rating in 1990's	1995 (before EPBD creation)	2006 (recast 2013)	2002 (recast 2009)
National register	England & Wales: HEE Database: Northern Ireland: www.epbnindregister.com	Maintained NL Agency: www.ep-online.nl or www.energiecijfers.nl	On final development by Ademe	No, data protection concern
% of labelled dwelling	~20%	25%	6,5% (2 millions)	?
Considered end uses	Space heating, domestic hot water, air conditioning, ventilation			
Unit	SAP (fuel cost per m^2 floor area and GHG emissions)	Primary energy (MJ) and delivered energy (kWh electricity, m^3 natural gas and GJ district heating)	Primary energy, GHG emissions	Primary energy
Type of modelling	Normative, monthly energy balance calculation SAP	Normative based on modelling (for Custom made label adjusted for real consumption)	Normative, simplified, annual consumption	Normative
Behavioural assumptions	Space heating: only 9 hours per week day (6–8; 5–12), demand temperature 21 °C			all rooms are kept at 19°C throughout the heating season
Penalties foreseen for EPC noncompliance	Theoretically yes	Under debate in parliament	Theoretically yes	Theoretically yes
EPC cost	£30–100/housing	€100–250/housing	€80–250€/housing	€150–600, considerably lower if the EPC is online-based

Source: BPIE 2012: Europe's buildings under the microscope, BPIE and authors.

Comparing the differences between measured consumption and normative estimations: UK, NL, FR, GR

UNITED KINGDOM

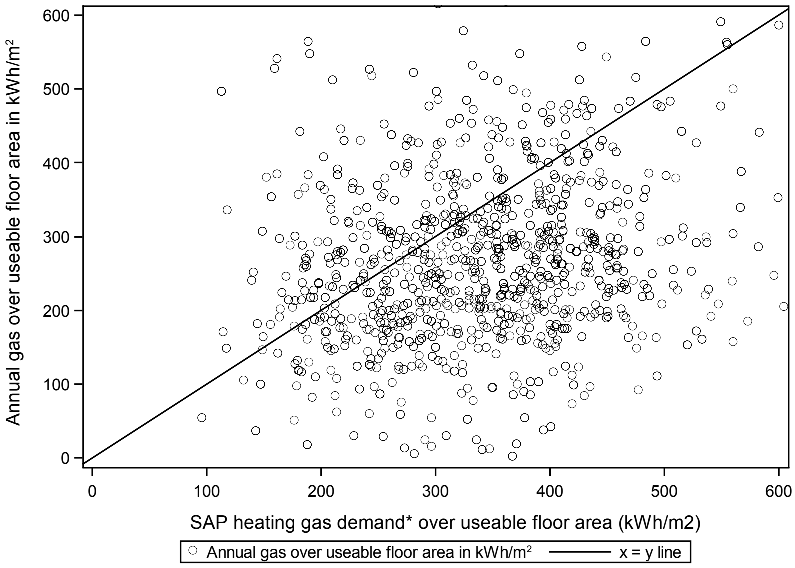
As part of a recent study, the performance gap between SAP assessed buildings and actual energy for England was investigated using a national housing survey from 1996.

The *1996 English House Conditions Survey* (EHCS) is a representative sample of the English housing stock and households collected between 1995 and 1996 (OPDM, 1998). The survey includes details on the physical characteristics of the house (e.g. age, size, location, etc. …) along with details on the household (i.e. occupants). As part of the survey, details on the dwelling's energy performance (e.g. wall construction and insulation, glazing type, loft insulation levels) were collected and a SAP rating was calculated. For this particular survey year, a Fuel and Energy Survey was carried out to determine the actual energy demand and fuels used for a subset of houses within the 1996 EHCS. The combination of the calculated and actual fuel use provided an opportunity to examine the performance gap. A crude comparison of the actual and predicted annual gas demand in dwellings for all English regions showed that the notional and measured energy demand diverged significantly, see Figure 5. The average ratio between measured and normative calculated final energy consumption is 0.79 (median of 0.72). Further analysis to look at the factors that explain the gap will be beneficial to understanding how energy demand prediction models could be improved.

Using the same dataset, a comparison of the energy performance gap by building age reveals that the gap widens as dwelling age increase, with older (i.e. pre-1850) dwellings using on average 41 % less and post-1850 dwellings using on average 23 % less than the predicted demand, see Figure 6. The performance gap is also greatest as the energy performance rating decreases (i.e. >D). The ratio of actual over predicted space heating energy demand at D and C is near unity.

THE NETHERLANDS

The WoON 2006 survey, conducted by the Dutch Ministry of Housing, Spatial Planning and the Environment, contains detailed information for more than 4,700 Dutch households. For every dwelling in the sample, an auditor performs an EPC calculation. Each respondent was coupled with a weighting factor to enable the data set to provide a representative image of the Dutch housing stock and division of households. This makes it a very detailed representative indication of the Dutch housing stock for the year 2006.



*SAP heating gas demand is an estimate and is adjusted by regions (east pennines is baseline)

Figure 5. Measured annual gas heating consumption vs SAP calculated heating for gas heated homes.

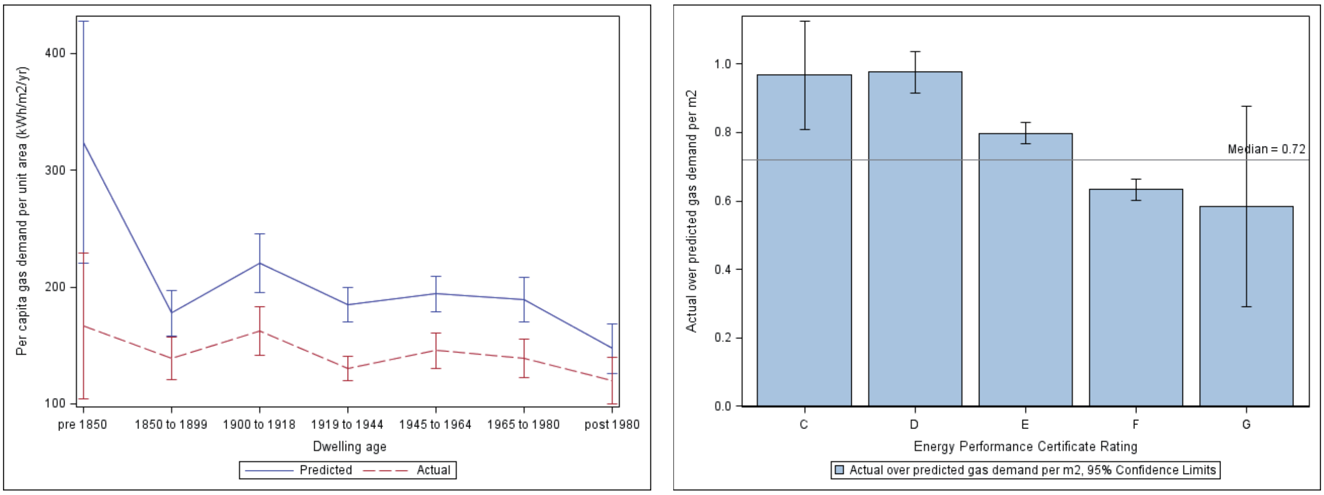


Figure 6. Measured annual gas heating consumptions vs SAP calculations of gas heated homes by age (left) and EPC rating (right).

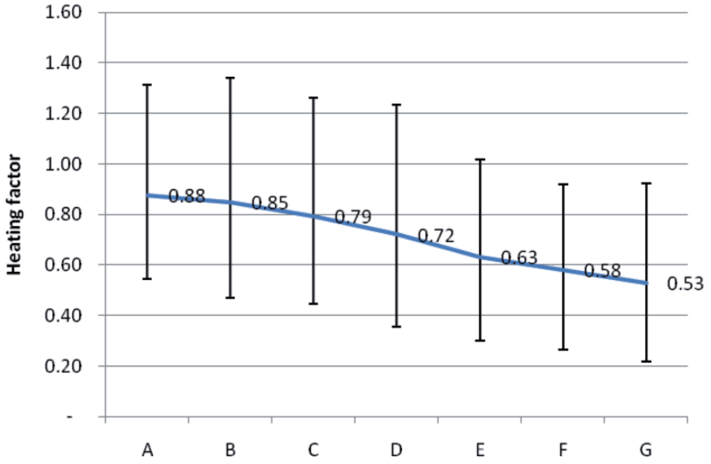


Figure 7. Relation between the energetic efficiency of a dwelling expressed in label score and the heating factor. The heating factor varies also among households with the same label. 95 % of the households have heating factors within the limits illustrated with the bars).

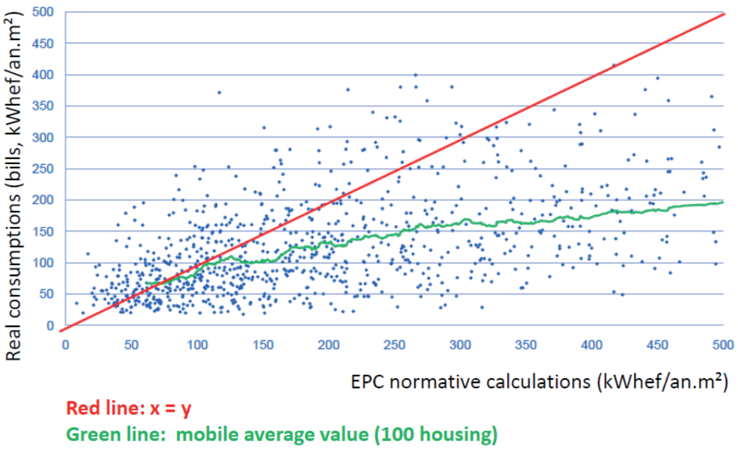


Figure 8. Measured annual space heating consumptions vs EPC calculations (centralized individual space heating equipment, final energy).

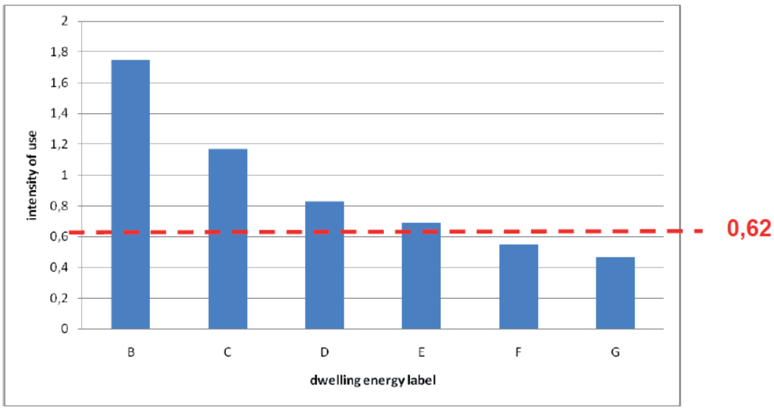


Figure 9. Ratio between real and calculated space heating consumption (Heating Factor) vs energy label class for French dwellings (centralized individual space heating equipment, final energy).

The theoretical energy consumption based on normative calculation used in the EPC has been compared to the actual energy use, based on energy bill data for each respondent in the data set. By dividing actual use by theoretical use, a score ("Heating Factor") was calculated. A *Heating Factor* of 1 means that the energy demand exactly matches the theoretically expected energy demand. A heating factor below 1 implies a lower demand than expected and a heating factor higher than 1 means that demand is higher than expected. In the data set the scores vary from little over 0.25 to 1.75, indicating a wide range.

A study in the Netherlands shows (Tigchelaar, 2011) there is a correlation between the technical characteristics of a dwelling and the non-technical variation among households. It looks as though energetically efficient dwelling demonstrate more intensive *Heating Factors* compared to energetically poor quality dwellings. This striking relation has been indicated in Figure 7. The energetic quality of the dwelling in this figure is expressed by the same letters as used on an EPC in the Netherlands. An 'A' represents an efficient dwelling and a 'G' refers to an inefficient dwelling. In an average dwelling with label A the *Heating Factor* is 27 % more intense than in the average Dutch dwelling. In an average G labelled dwelling the *Heating Factor* is 23 % less intensive than in the average Dutch dwelling.

FRANCE

A survey conducted on 900 dwellings equipped with centralized[3] individual space heating equipment (Cayla, 2009); have demonstrated that, on an average, the EPC theoretical calculation overestimates space heating consumption. For French housing stock, the average *Heating Factor* is 0.62.

The *Heating Factor* decreases as the energy efficiency of the housing (represented with EPC energy label) declines, from 1.7 for class B to 0.4 for the worst class G.

GERMANY

A number of recent studies have compared the calculated with the measured primary heating energy consumption of dwellings in Germany (Kaßner et al., 2010; Knissel et al., 2006; Knissel and Loga, 2006; Loga et al., 2011; Erhorn, 2007; Jagnow and Wolf, 2008).

In a sample of 1,709 residential buildings of all sizes (Knissel and Loga 2006) found the average measured consumption 42 % lower than the average calculated consumption (alternatively

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[3] "Centralized individual" means for example one boiler per housing and not one collective boiler for several housing. Organized electric heating is considered as centralized individual heating.

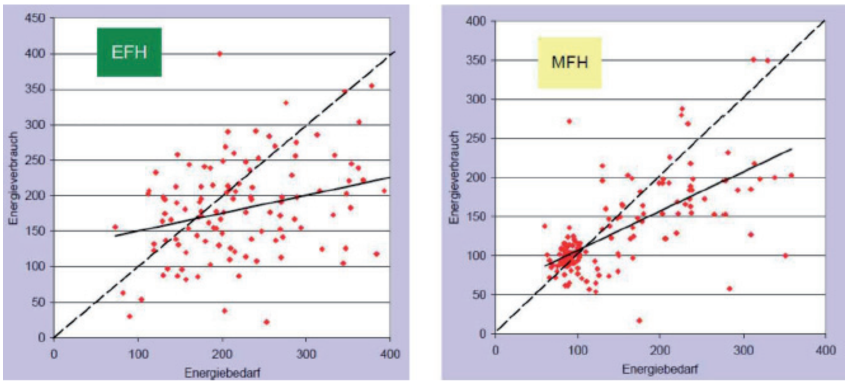

Figure 10. Scatter Plots of measured primary energy consumption (vertical axes) against primary calculated energy consumption (horizontal axes) for detached houses (left) and multi-dwelling buildings (right). Source: (Erhorn 2007). Solid line is line-of-best-fit; dotted line is y-x, where measured consumption = calculated consumption.

stated, the calculated consumption was 74 % higher than the measured consumption). However, in a sub-sample of buildings with 8 or more dwellings these figures fell to 26 % and 36 %. The ratio of calculated/measured consumption varied greatly, with a standard deviation of 41 % in the all-building sample and 30 % for buildings of 8 or more dwellings. For the all-building sample each 1 % increase in calculated consumption led to an average 0.576 % increase in measured consumption, while this figure was 0.704 % for buildings of 8 or more dwellings.

(Knissel et al 2006) made similar comparisons in 4,670 residential buildings divided into categories according to their type of heating fuel and the number of dwellings per building, and found the same general pattern as above for each category. For oil heated buildings the average measured consumption was 43.6 % below calculated consumption; for gas heating this was 42.4 %; and for district heating 29.8 %. For 1–2 dwelling buildings the figure was 43.8 %; for 3–7 dwelling buildings 38.3 %, and for 8+ dwelling buildings 26.5 %.

(Kaßner et al. 2010) report the measured performance of 300 retrofitted or partially retrofitted residential buildings in comparison to the calculated post-retrofit consumption. They find a similar pattern where calculated consumption is over 100 kWh_{pe}/m^2a: measured consumption is lower than calculated, here by around 30 %. However, the effect is reversed for low energy buildings, i.e. with calculated consumption below 100 kWh_{pe}/m^2a, where measured consumption is, on average, around 75 % higher than the calculated rating.

The German Energy Agency *(Deutsche Energie-Agentur* – DENA) also found a 30 % discrepancy between calculated and actual heating energy consumption, based on analysis of 35,000 dwellings covering all levels of thermal standard (Der dena-Gebäudereport 2012: 43).

(Erhorn 2007) compared the measured and calculated consumption of 50 detached houses and 70 apartment blocks and found the same pattern, displayed in Figure 10. In each graph the dotted line is *y=x,* representing the points where data values would lie if the measured and calculated consumption figures were equal. The solid line is the line of best fit, again indicating a gap between the two values, which expands as the calculated energy rating increases. This goes into reverse for calculated consumption below 150 kWh_{pe}/m^2a for detached houses, and 100 kWh_{pe}/m^2a for multi-dwelling buildings.

Almost identical graphs are produced in (Jagnow and Wolf 2008: 27), for a dataset of approximately 70 residential buildings[4]. A novel feature here is that a graph for final energy demand is compared to one for primary energy consumption. While there are individual differences between results for each building using the two methods, the overall pattern is the same: on average, measured energy consumption is around 35 % below calculated consumption; the percentage gap increases as the calculated rating increases; the two values draw equal at 70 kWh_{pe}/m^2a for primary energy and 100 kWh_{fe}/m^2a for final energy demand; and below that the phenomenon goes into reverse.

(Loga et al. 2011) developed a graphical model to display the ratio of average measured to calculated consumption for any given calculated consumption, in a dataset of 1,702 buildings of all sizes and heating fuels. Adapting their model gives:

$$Q_M = Q_P \times \left[-0.2 + \frac{1.3}{1 + \frac{Q_P}{500}} \right]$$

Where:
Q_M = measured energy consumption;
Q_P = calculated energy consumption.

The resulting curve is displayed in Figure 11.

This indicates that the average measured heating energy consumption of residential buildings with a calculated consumption of, for example, 400 kWh_{pe}/m^2a is 209 kWh_{pe}/m^2a, while for a calculated consumption of 225 kWh_{pe}/m^2a (the national average) it is 156 kWh_{fe}/m^2a. The percentage gap between measured and calculated consumption rises steadily as the calculated consumption increases, but is negative below a calculated consumption of 52 kWh_{fe}/m^2a. On average, measured consumption is 35 % below calculated consumption.

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[4] The precise number is not given, but the scatter-plots of measured again calculated energy consumption show approximately 70 data points each.

This pattern is consistent in all datasets that give both measured and calculated primary energy consumption for domestic heating.

A lot of similarities

Despite significant differences across Europe in how EPCs are calculated; it is interesting that there seems to be a consistent over prediction in space heating energy use with measured energy use being between 60 to 70 % of EPC calculated energy. Some of the gap between EPC calculation and measured performance is due to a deliberate decision that EPC should aim to predict the energy use in well heated properties which many are clearly not. However, it is unlikely that this is the only cause of this discrepancy as there are many un-validated assumptions in EPC calculations.

Another remarkable (but more intuitive) common result is that *Heating Factor* (ratio between real and theoretical space heating energy consumption) decreases as the energy efficiency of the dwelling (represented with EPC rating) decreases.

Discussion: explaining the gap

We hypothesize four potential causes for the differences between the engineering-based predictive models and measured space heating energy consumptions:

1. *Uncertainty in the core modelling:* the EPC models are a mixture of simplified thermal model and empirically defined relationships often involving considerable extrapolations (for example in France, ventilation rate is a simple assumption: 1 volume/h for all natural ventilations). The validity of these models has not necessarily been rigorously tested.

2. *Uncertainty in technical and climatic model data inputs:* For example, it is normally assumed when modelling energy efficient technologies that their installed performance will be similar to that of the laboratory, e.g. 100% of a cavity wall is insulated, condensing boilers are installed correctly and condense etc. … The reality is that there is significant underperformance due to the practical problems associated with the real world. This would also lead to a systematic bias of over predicting the potential for energy savings. Where input data is not known defaults are often used, and these defaults have not always been tested.

3. *Uncertainty in the measurement of domestic energy consumption:* Ideally all energy meters would be read on the same day across the whole country, until smart meters become common this is impossible. Instead there is a process of creating annualized data from a mixture of meter readings involving a correction for weather. There is a potential to introduce systematic bias in the measured data.

   There are often problems in relating meter data to a particular energy end use, heating is particularly problematic as incidental gains contribute to the heating and often dwellings have both primary and secondary heating systems some of which are not metered. For example, many dwellings use communal heating systems that are very difficult to meter at an individual dwelling level. This has the potential to introduce biased energy data.

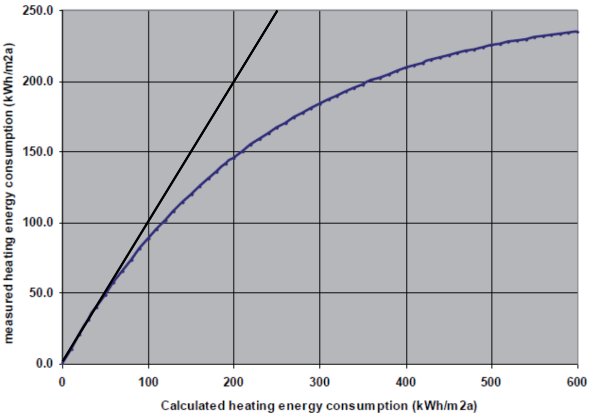

Figure 11. Modelled relationship between calculated and measured primary space heating and Domestic Hot Water energy consumption in dataset of 1,702 German residential buildings of all sizes and fuel types. Source: derived from modelling in (Loga et al. 2011).

4. *Behavioural issues:* EPCs assume a normative behaviour that may have been chosen to be an aspirational behaviour rather than normal/average behaviour.

The first bias (i.e. model validity) has been studied for the French case, using different models of varied accuracies (Allibe, 2010). This analysis shows that there is more difference within the same model using normative or declared behavioural scenarios (survey data) than between two different models (one very simple and one more complex) with the same behavioural scenario. Calculation with *real* behavioural scenarios gave the results closest to measured or observed space heating consumptions. Nevertheless, this comparison has not been made for all considered countries in this paper, and modelling bias could remain important for some countries.

The second bias is a real one. For some countries, its quantitative impact is quite small and cannot explain by itself such a gap. For others, quantitative impact is important and some countries – as UK – have begun taking into account correction factors[5].

Part of the third bias was eliminated in several studies: some consider only centralized individual space heating equipments and use some form of smart/instantaneous feedback metering; others consider only space heating with mono-fuelled equipments. These specific studies show important gaps between calculations and observations; with same order of magnitude that the results presented in the previous sections of this paper.

We conclude that behavioural factors are not the only component of the energy gap, but nevertheless are a major one. This is confirmed with calculations and measures concluding that behavioural impact can change space heating consumption by

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[5] For France, for instance: taking into accounts assumptions of non respect of energy efficiency regulations gives better results, but on a marginal way. For UK, the underperformance for new buildings may be significant in this respect in part because of poor enforcement in regulations.

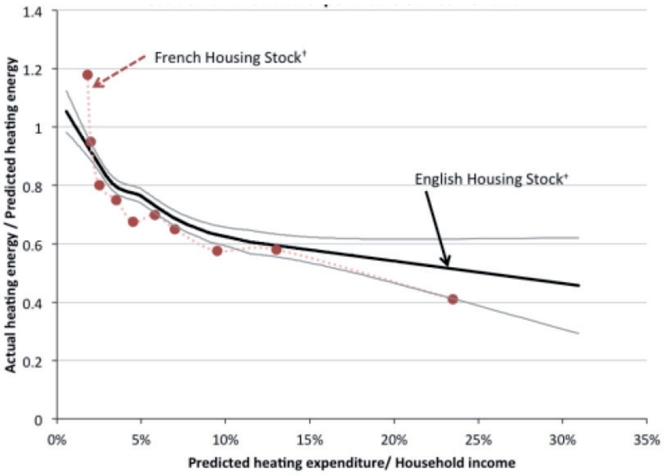

Figure 12. Intensity of heating to expenditure and income ratio for English and French dwellings (UK: English House Survey – approx 2,100 households, includes only households where gas is primary fuel for heating; France: EDF R&D 2009 survey, approx 900 households with individual space heating all fuels).

a factor of 3 (from lowest to highest modelled behaviours with the same technical efficiency of the housing (Allibe, 2009).

Recent work (Allibe, 2012) has proposed that this behavioural effect is, in part, a multi-component of elasticity of energy demand for space heating, energy price, income and efficiency elasticity (rebound effect). The *Heating Factor* can be expressed as a function of theoretical budget share for space heating (the % of the space heating bill in the household budget if the household has a normative behaviour). Figure 12 shows this relationship for UK and France dwellings.

At the present, in order to deal with the problem of the differences between actual and theoretical space heating energy consumptions, we propose to use a correction factor to "translate" space heating EPC theoretical consumptions in current ones with national "Intensity curves" along the lines shown in Figure 12. This work has been conducted for space heating in UK and France. For the French case, different types of regressions, functional forms and samples have been tested and discussed (Allibe, 2012). No functional form is free from defects; it appears that – for the French case – the "*power regression*" fits the best with averaged data. Figure 13 gives Intensity curves with relationship between Intensity of use for space heating and Theoretical Heating Cost (THC) for France. Further studies must be conducted for other end-uses and countries.

In the longer term, however, it will be essential to interrogate the underlying relationships that under-pin the model parameters of empirical data that drive the prediction models. This will only occur with more rigorous data collection, quantifying measurement error within the data, and detailing and correcting for biases that are taken into account in following analysis. The models built with these relationships should then better represent the factors that drive energy demand, thus leading to a convergence between modelled and actual demand.

What implications: impacts on energy saving potentials estimation and the evaluation of their financial efficiency

The first impact is the overestimation of current space heating consumptions that some authors have named "*prebound*[6] *effect*" (Sunnikka-Blank, 2012). The lower the energy efficiency of the housing is, the higher the overestimation of the consumption is.

The priority in many countries is the energy efficient renovation of older poorly insulated properties. Yet it is these same properties that are often under-heated, so their real energy consumption is lower than the calculated one. Therefore the cost effectiveness of energy efficient technologies may not be as great in these properties as is assumed.

The second effect is the overestimation of the energy savings after a refurbishment operation conducted in order to improve energy efficiency of the housing. This effect is commonly named the "*rebound effect*" and is the change of households' behaviour of increasing the level of their thermal comfort after retrofitting. In fact, this second effect is a mixture of the 3 biases: rebound effect (behaviour), discrepancy effect (data) and model bias. Meanwhile, the "*prebound effect*", implication of this second effect is an overestimation of financial efficiency of retrofitting programs.

It is not uncommon for those encouraging the uptake in energy efficiency measures to use the occupants' *real* energy costs and combine this data with *theoretical* potential savings, thereby very significantly overestimating the cost effectiveness of a particular technology (see German section of part 1 of this paper).

The combined effect of the above is that historically energy efficiency technologies and policies have been evaluated in a very optimistic light. As a result of some of the research presented and referred to in this paper this is changing, for example in the UK 'in use' factors are being introduced under proposed efficiency strategy policies to take account of some of these factors (DECC, 2012 b). In France, Figure 15 shows projections of the same scenario with EPC normative and more realistic calculations. The normative approach overestimates both current consumptions and energy savings (energy consumptions are declining faster than the realistic curve). The more realistic approach can change results of Energy Efficiency Action Plans, as for Grenelle Action Plan in France which was considered efficient enough with a normative calculation but not with a more realistic calculation (Giraudet, 2011).

Similar observations can be made when evaluating the financial viability of energy efficiency retrofit technologies. Figure 16 shows that financial efficiency of installing double-glazing in The Netherlands is very sensitive to the Heating Factor.

Of course, these results are first works and our analysis is indicative, but not conclusive. Further works should be conducted at least in two directions:

- These figures are average values. Due to important heterogeneity of the residential market, these results cannot be used

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[6] There is a discussion about the use of the word "effect" in that case because the idea is to point a static difference between a theoretical evaluation and a current consumption and not to name the consequence of an action as refurbishment increasing the energy efficiency of the dwelling as for "rebound effect".

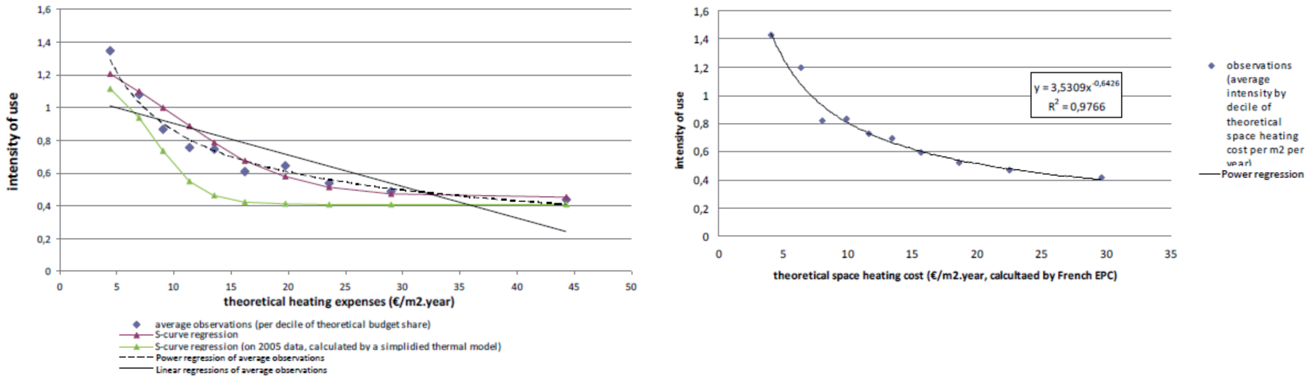

Figure 13. Intensity of heating to theoretical heating cost: different studied functional forms (left) and form adopted (right): power regression based on deciles of standardized service costs.

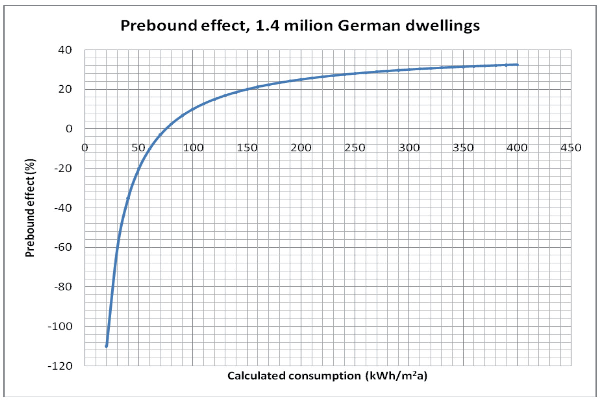

Figure 14. Prebound effect vs theoretical calculations of space heating consumption in Germany (authors' calculations from Der dena-Gebudereport 2012: 43).

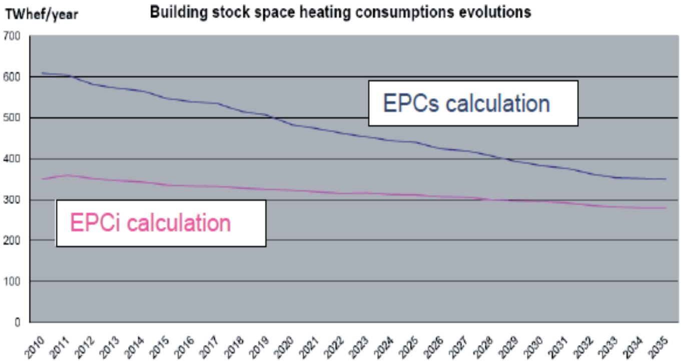

Figure 15. French dwelling stock space heating projection by 2035 with theoretical (EPCs) and realistic (EPCi) calculations (Cayre 2011).

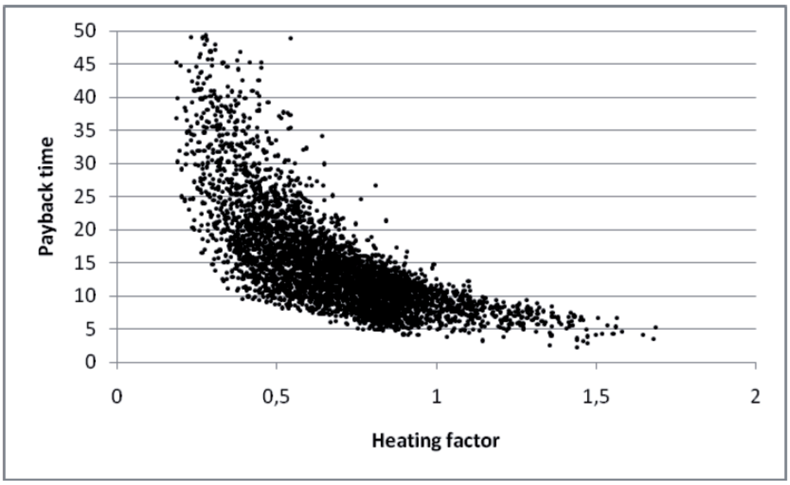

Figure 16. Relation between heating factor and payback time for installing low-E glazing (Tigchelaar 2011).

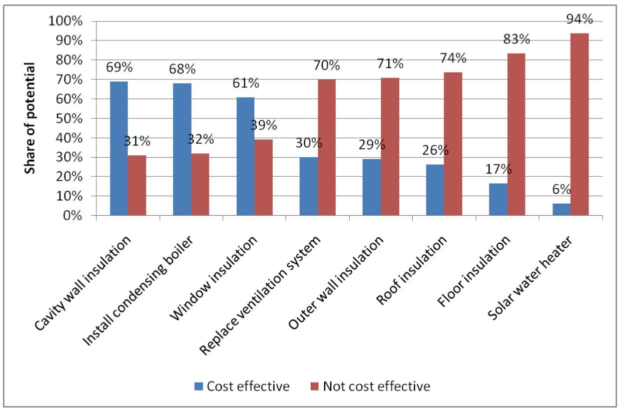

Figure 17. Average vs individual cost effectiveness of 8 retrofitting actions (Tigchelaar, 2011).

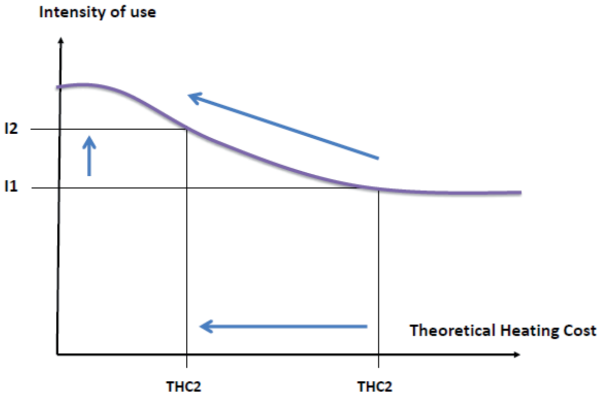

Figure 18. Change of Intensity of use after retrofitting operation: visualisation on Intensity curve (Allibe, 2011).

for individual cases. Specific methods have to be developed for that purpose.

- Due to the specific kind of energy use variation observed in residential market, other kinds of statistical analysis could be applied.

The impact on policy

Normative EPC calculations are a useful tool for comparing the energy efficiency of one property against another independent of occupant and climate variability. However, it is not appropriate to use theoretical normative calculations to estimate the absolute energy use of a particular dwelling. EPC calculations are not an evaluation of the energy consumption of the household but are an evaluation of energy efficiency of the housing. It is a useful reference but it must only be used to evaluate policies with tremendous care. Although predictive models can be used to estimate potential savings in a dwelling, they do so only for a reference case and not a given dwelling. Importantly for policy, this means that energy savings should not be evaluated using normative models for the simple reason that they have been shown to over-estimate the potential savings and underestimate their cost effectiveness.

Research conducted in The Netherlands shows that (for 8 evaluated retrofitting actions) there are always households whose retrofitting action applied to their case will not be financially efficient, even if the action is averagely cost effective.

However, the Energy Performance of Building Directive (EPBD) is planning to oblige the universal installation of EPC calculated cost-optimal energy efficiency measures as part of major renovations across Europe. This could mean that homeowners will undertake energy efficient interventions which are not cost effective.

In order to deal with the problem of the differences between actual and theoretical energy savings after a retrofitting operation, some countries have proposed to use correction factors. In the UK, for example, there is already a standard estimate of the energy efficiency gap for thermal retrofits of 15 % (DECC, 2010). This would not be a perfect solution because the post-retrofit energy performance gap varies from case to case, but it is small in relation to the expected fuel saving as calculated by this method, so there is far less risk of retrofits proving in practice to bring far smaller gains than anticipated.

Another possibility is the use of *Intensity Curves* as presented in Figure 13 in a dynamic way; to define new "Intensity of use" after refurbishment (Allibe, 2012). The new situation after retrofitting defines a new Theoretical Heating Cost (THC2, see Figure 18). The theoretical estimation of savings supposes that "Intensity of use" is unchanged after refurbishment. In real life, changes in THC imply changes in Intensity of use. Magnitude of this change can be seen on in Figure 18. With this kind of curve, it is easy to numerate the post-retrofitting intensity of use. Knowing theoretical post-retrofitting energy consumption evaluation, it is now easy to deduce realistic consumption after refurbishment. As the relationship between Intensity of use and Theoretical Heating Cost is representative of the 4 discrepancy causes we have described upper, this difference between theoretical and current post-retrofitting consumptions is not only due to famous rebound effect, but also to model's bias, and global lack of quality in retrofitting operation.

Conclusions

There is a huge energy saving potential in dwellings. Many European countries have developed energy savings targets (and are currently implementing policies to meet these national targets). Space heating represents the largest energy saving potential in this sector for northern European countries.

However, if the policies are based on the use of theoretical normative calculations, there is a risk that the evaluation of this potential and the speed of its achievement could be overestimated. In order to confirm (or not) that risk more research works are needed. National surveys must be conducted with appropriate samples and statistical analysis in order to define national and end-uses adapted correction factors.

Another common assumption is that a large part of the energy saving potential for dwellings is cost-effective, especially for space heating. But this does not mean that it is cost-effective for all households. Instead, the cost-effectiveness varies with specific household characteristics, in particular the proportion of income spent on fuel. Cost effectiveness is not solely linked to technical features of buildings, but also to occupants' behaviour. With an increase in the amount of available empirical data, it will be possible to take account of the underperformance of normative calculations and hence both improve policies and also help individual homeowners make cost effective refurbishment choices.

Last, but not least, due to the heterogeneity of energy efficiency of dwellings and households' behaviour, policy makers must keep in mind that any type of obligations (aimed at energy suppliers, end-user, or based on cost-optimality) will have its negative side-effects that must be addressed and properly treated in European and national energy efficiency programs. For that item again, further research must be conducted in order to catch characteristics of households that could be imposed unprofitable renovation operations.

This paper is a first comparison of gaps between EPC normative calculations and current energy consumptions in different European countries, further research must be conducted in order to propose solutions able to translate theoretical consumptions and savings to real ones.

In the coming decades, Europe will spend billions of Euros refurbishing its stock of dwellings. Before this investment is undertaken it is essential that a few million Euros is invested by public authorities to collect empirical data about dwelling energy consumption and its heterogeneity; and in improving methods of evaluation of energy consumptions. This investment will enable better targeted investment and the development of appropriate policies and regulation.

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Glossary

EPA	Energy Performance Advice (pre EPC in The Netherlands, 1995)
EPBD	Energy Performance Building Directive
EPC	Energy Performance Certificate
eq	equivalent
EU	European Union
final energy	delivered energy
GHG	Green Gas Houses
hdd	heating degree days
Heating Factor	Ratio between space heating current and calculated (theoretical) consumption
kWh_{fe}	final (or delivered) energy measured by the property meter kWh
kWh_{pe}	primary energy kWh
SAP	Standard Assessment Procedure
THC	Theoretical Heating Cost

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