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Energy consumption for heating and rebound effects

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Abstract

When comparing calculated heating consumption in residential buildings assuming standard usage with standardized measured data, then the two typically does not fit. In fact, measured consumption may be a fraction only of what was calculated. The reason is direct rebound behavior by the inhabitants. The paper shows the importance of direct rebound through measured results. First the temperatures, recorded in daytime and sleeping rooms in a sample of dwellings, are commented. Then follows a discussion of the indoor temperatures found when calculated energy consumptions for heating were forced to give the same numbers as measured. Next, two small scale analyses of energy data gained in low-income estates are commented, followed by test results on direct rebound in two dwellings, one non-insulated, the other well insulated. These data prove that the benefits of direct rebound are much larger in non-insulated than in well insulated homes. That fact is used to construct a rebound curve, starting from the normalized consumption data gained in 964 houses. The paper ends by showing the effect of energy price on direct rebound.

Keywords

Energy consumption for heating, field data, user's behavior, rebound

INTRODUCTION

Rational use of energy in buildings is a concern since the energy crisis of 1973 [1]. Over the past 36 years the motivation behind shifted from economics to environmental awareness [2], though the last two years economics surface again.

The instruments for realizing energy efficient residential buildings without degrading the indoor environment are well known. In heating climates one should strive for a high compactness, being the ratio between protected volume and envelope, an excellent thermal insulation, windows with highly insulating glass units, solar shading of windows oriented east over south to west, the best air-tightness achievable in combination with a designed dedicated ventilation system, a very efficient correctly dimensioned heating system and usage of renewables when payable in terms of life cycle costs [3].

During the seventies and eighties theoretical studies assuming preset usage patterns showed that annual heating consumption was nearly proportional to the specific transmission losses, both per cubic meter of protected volume:

$$\frac{E_{\text{heat,a}}}{V} = \alpha \left(\frac{U_m A_T}{V} \right) \quad (\text{MJ}/(\text{m}^3 \cdot \text{a})) \quad [1]$$

In the formula, $E_{\text{heat,a}}$ is the annual heating consumption in MJ/a, A_T is the envelope surface area in m^2 , V the protected volume in m^3 , U_m the whole envelope (average) thermal transmittance in $\text{W}/(\text{m}^2 \cdot \text{K})$ and α a proportionality factor. Energy modeling results in fact indicated that solar and internal gains more or less compensated for the infiltration and dedicated ventilation losses. As the formula looks easy, it became a kind of paradigm used in any large scale prediction of the impact of thermal insulation on energy consumption. Legislation in most countries also focused on thermal insulation as

most important measure with an impact proportional to the mean thermal transmittance demanded. Later, heating systems got their share in the models, resulting in more scatter though least square analyses still suggested the above linearity.

Questionable as an assumption in equation [1], however, is the implementation of standard usage patterns. These never reflect reality that merely depends on the inhabitant's attitudes and behavior and may lead to less heating than found using calculation tools containing standard patterns. Cornish [4] already mentioned it when commenting the impact of better thermal insulation on the annual heating consumption in UK dwellings. In a recent paper, Sanders et al [5] quantified the effect using as reduction factor the sum of a comfort factor due to the effective internal temperatures and another factor due to other benefits taken by the inhabitants.

In this paper, rebound is the term used. The aim is to underpin the concept. First user's behavior and rebound are discussed and refined. Then the fact that physics limit rebound impact in better insulated dwellings is highlighted using measured temperature and consumption data collected in Belgium, a country in North-Western Europe with its center situated 51° North and a weather pattern characterized by cool, dark winters and mild summers.

USER'S BEHAVIOR AND REBOUND

In the early eighties, Van Raaij et al [6] already noted the impact of user's behavior on annual heating consumption using measured data. They discerned five behavioral patterns: conservers, average users, spenders, cool dwellers and warm dwellers.

Conservers combined minimal ventilation with low mean inside temperatures. Spenders loved high ventilation and high mean inside temperatures. Average users were quite

moderate for both. Cool dwellers aired intensively while heating moderately and warm dwellers aired moderately while heating intensively. In the estate of 157 homes they investigated the increase in energy consumed between conservers and spenders touched 38% compared to the conserver's use. Conservers also had a somewhat higher degree of energy concern. They had fewer children and seemed to be more absent from home. For the warm dwellers, comfort was the main reason to heat more. A further analysis showed that higher levels of energy use were characteristic for some stages in family life. A remarkable result was that cool dweller consumption was independent of the insulation quality, while the other four groups profited from a good thermal insulation. Market economy links the behavior commented to what is called rebound, being the way improved efficiencies are compensated by increased spending. As is illustrated in figure 1, in the case of heating, lower annual consumption costs will most probably be compensated by a demand for more heating related benefits. Van Raaij et al [7] mention such rebound as one of the factors linking attitude to the five behavioral patterns discerned, with the term attitude used as umbrella for concerns and benefits -price, environment, energy, health and comfort- and behavior standing for the way attitudes are translated in every day's life. Heating related benefits are health and comfort. Since the energy costs for both are highest in energy inefficient homes, a conserving behavior should be most likely in such dwellings.

Figure 1

Greening et al [8] refined the rebound definition by considering a direct and indirect effect. Direct rebound relates to the cost-benefit relation mentioned, indirect rebound to the fact that direct rebound allows households to spend more for other activities which demand energy, such as traveling.

Several direct rebound models can be found in literature. Examples are the single-service model of Khazzoom [9] and the multi-services model of Cuypers [10]. The first assumes families have to decide on one energy service only; they have well defined preferences which are transitive and inexhaustible, are fully informed, while taking more services generates no extra costs. Khazzoom then proves that an increase in energy efficiency of X% results in a decrease of the energy consumed with $X(1 - |\varepsilon_{P_E}(E)|)$ %, where $\varepsilon_{P_E}(E)$ is the price elasticity of the energy:

$$\varepsilon_{P_E}(E) = \frac{\partial E}{\partial P_E} \bigg/ \frac{E}{P_E} \quad [2]$$

with E the energy needed for the service considered and P_E related energy costs. Despite its apparent exactness, the single-service model had weaknesses: families must decide on many services which all cost money, energy is not the only input needed for comfort and health, investments are as necessary and, investments are not reversible as presumed in the model. The multi-services model corrects for some of these weaknesses. It considers multiple choices and accounts for the income limiting possible investments. Anyhow, these corrections do not change the conclusion of the single-service model that families respond the same way to efficiency improvements as they do to decreasing energy prices.

The opportunities for direct rebound are anyhow limited physically. As less energy efficient dwellings have a lower average inside temperature when partially heated, possible direct rebound should augment with increasing losses. Or, badly insulated dwellings may offer rich possibilities for direct rebound, while excellent insulated dwellings must perform much poorer from that point of view.

Both the direct and indirect rebound have a macro-economic impact, such as less energy avoided than expected by efficiency measures in the built environment or, a decreasing consumption as a result of higher energy prices, which in turn will moderate price increase thanks to a growing unbalance between demand and offer.

NORMALISING MEASURED CONSUMPTION DATA

The factual proof builds on consumption data measured during a given period of time. Anyhow, using these correctly demands a conversion to the reference year, here for Belgium. This is done by calculating the number of (daily mean outside temperature/18°C inside)-degree days ($D_{\theta_e}^{18}$) during the data collection period and multiplying the consumption measured per degree day with the number of degree days in the reference year, 2748 for Belgium:

$$E_{\text{heat},a,\text{meas},\text{norm}} = 2748 \frac{E_{\text{heat},\text{meas}}}{D_{\theta_e}^{18}} \quad (\text{MJ/a}) \quad [3]$$

Direct rebound is valued by dividing the difference between calculated reference consumption ($E_{\text{heat},a,\text{ref}}$) and the normalized measured consumption by that reference:

$$a_{\text{rebound}} = 100 \frac{E_{\text{heat},a,\text{ref}} - E_{\text{heat},a,\text{meas},\text{norm}}}{E_{\text{heat},a,\text{ref}}} \quad (\%) \quad [4]$$

References were estimated using the methodology imposed by the energy performance regulation as it was introduced in Flanders, Belgium, based on EN ISO 13790 [11][12].

The tool calculates annual end energy for heating, using twelve monthly means.

For a given residential building, the monthly net energy demand ($Q_{\text{heat},\text{net},m}$) equals:

$$Q_{\text{heat},\text{net},m} = (Q_{T,m} + Q_{V,m}) - \eta_{\text{util},\text{heat},m} (Q_{S,m} + Q_{I,m}) \quad (\text{MJ}) \quad [5]$$

where $Q_{T,m}$ is the monthly transmission loss in MJ, $Q_{V,m}$ is the monthly exfiltration and dedicated ventilation loss in MJ, $\eta_{util,heat,m}$ is the monthly mean utilization factor of the gains (-), $Q_{S,m}$ is the monthly solar gain through the transparent parts in MJ and $Q_{I,m}$ is the monthly internal gain by lighting, appliances and people in MJ.

The heating season mean inside temperature to be used is fixed at 18°C, a number that accounts for some rebound behavior by the tenants. The reference year for Belgium figures as the outside climate. The infiltration rate is linked to the 50 Pa air-tightness of the building with as default value $12A_T/V$ (h^{-1}), A_T being the envelope surface area in m^2 around the protected volume V (m^3), while the dedicated ventilation rate depends on the protected volume:

$$\text{Infiltration} \quad n_{infilt} = 0.04n_{50} V \quad (h^{-1}) \quad [6]$$

$$\text{Ventilation} \quad n_{vent} = 0.2 + 0.5 \exp(-V/500) \quad (h^{-1}) \quad [7]$$

The internal gains look like:

$$Q_{I,m} = (220 + 0.67V)t_m \quad (MJ) \quad [8]$$

with t_m the number of mega-seconds per month.

Gross heat demand ($Q_{heat,gross,m}$) introduces system efficiency ($\eta_{sys,heat,m}$) in the balance:

$$Q_{heat,gross,m} = Q_{heat,net,m} / \eta_{sys,heat,m} \quad (MJ) \quad [9]$$

End energy consumption ($Q_{heat,m}$) in turn depends on production efficiency ($\eta_{gen,heat,m}$):

$$Q_{heat,m} = Q_{heat,gross,m} / \eta_{gen,heat,m} \quad (MJ) \quad [10]$$

The reference end energy consumption on an annual basis ($E_{heat,a,ref}$) so becomes:

$$Q_{heat,a,ref} = \sum_{m=1}^{12} (Q_{heat,gross,m} / \eta_{gen,heat,m}) \quad (MJ) \quad [11]$$

Anyhow, the calculated reference for existing dwellings using the methodology outlined has limited accuracy. In fact not all floor, wall and roof assemblies could always be controlled in full detail. The age of the house, partial information by the owners or inhabitants and experience had to help in defining a most probable assembly. Testing by introducing variance in the thermal transmittances showed error bars of 10% to be quite realistic.

FACTS PROVING DIRECT REBOUND

Temperatures in daytime and sleeping rooms

During a couple of decades, temperatures have been logged in hundreds of daytime and sleeping rooms. The results look straight forward: sleeping rooms are cooler than daytime rooms and show a more pronounced relation with the outside temperature, see table 1. Apparently, sleeping rooms are only accidentally heated. Analogous results were found in the UK, Germany and Italy [13].

Table 1

Mean inside temperature calculated from annual energy consumption data

In [14] the heating season mean inside temperature that gave a calculated annual heating consumption equal to the normalized measured data, was estimated for 47 dwellings built between 1921 and 1986 with whole envelope thermal transmittances ranging from 0.3 to 2.5 W/(m².K). Following relation was found:

$$\bar{\theta}_{i,\text{heating season}} = 15.7 - 0.00435(U_m A_T) \quad (^\circ\text{C}) \quad [12]$$

$r^2=0.34$, 47 data

That value is much lower than the 18°C of the energy performance regulation and drops with increasing specific transmission losses ($U_m A_T$). Both facts underline direct rebound is real and a better thermal insulation moderates its impact.

Energy consumed for heating in two low income estates

The first estate dates from the fifties and consists of one story dwellings, terraced in rows of two or four. The dwellings were retrofitted during the nineties with the single glazed window in the living room exchanged for a double glazed PVC window, the roof insulated with 10 cm mineral fiber and local heating skipped for central heating with radiators, thermostat in the living room and high efficiency boiler. The dwellings have a whole envelope thermal transmittance of 1.09 W/(m².K), a protected volume of 159 m³ and envelope surface area of 173 m² (figure 2) [15].

Figure 2

Reference energy consumption for heating totaled 74450 MJ/a. The normalized consumption as measured in eight of the dwellings is summarized in table 2.

Table 2

Although the differences between the eight dwellings are large, comparison with the reference consumption shows pronounced direct rebound. Assuming only the living room, kitchen and bathroom to be heated, consumption calculated with a multi-zone model, heated rooms 18°C warm, decreased to 49000 MJ/a, i.e. much closer to the measured average of 41700 MJ/a. Most dwellers clearly economize on energy by not heating the hall, the sleeping room and the storage room and by intermittently heating the other rooms.

The two story terraced houses of the second estate were built after the energy crisis of 1979 (figure 3). Although energy was expensive then and thermal insulation was already promoted as necessary, roofs, floors on grade and cavity walls got none. Double glass was the only efficiency measure taken. Many inhabitants however post-insulated the roof pitches. Some even insulated the garage door, what of course has no sense. Anyhow, the houses have a whole envelope thermal transmittance around 1.93 W/(m².K), a protected volume of 333 m³ and an envelope surface area of 263 m² [15].

Figure 3

Calculated reference energy consumption for heating totaled 150 100 MJ/a. Normalized consumption as measured in twelve dwellings is summarized in table 3. Also here, the consumption was recalculated using a multi-zone model and assuming only the ground floor was kept at 18°C. That brought the reference down to 82700 MJ/a, closer to the normalized measured average of 74050 MJ/a but still too high. Probably, also the hall and the bathroom were hardly or only intermittently heated. Yet, rebound behavior seemed quite clear!

Table 3

Direct rebound in two dwellings with different insulation quality

In the eighties, a long-lasting energy audit on two dwellings was performed. One was a pre-war, large, non-insulated villa, whole envelope thermal transmittance 1.94 W/(m².K), the other a well insulated detached house, constructed in 1984, whole envelope thermal transmittance 0.4 W/(m².K). During the audit the inhabitants were asked to heat the whole house for 6 weeks, after which they turned back to their normal heating behavior. Figure 4 shows the results as found after normalization. While in the

well insulated house hardly a difference was found between both heating regimes, in the non insulated villa normal behavior decreased the energy for heating with 39% compared to the whole volume on comfort temperature. Or, excellent thermal insulation clearly counteracts the energy economy direct rebound offers [16].

Figure 4

Trnsys calculated heating consumption by a cubic two story dwelling with volume to envelope ratio 1.1 m supported that observation. The cube contained four rooms on each floor. In a first round all were heated at 18°C. In a second round two rooms on the ground-floor were kept at 20°C during daytime with at night a set-back down to 15°C. On the first floor the bathroom was 24°C warm between 7 and 8 a.m. and 10 and 11 p.m. The rebound realized that way touched 61% for a whole envelope thermal transmittance of 1.92 W/(m².K) but turned zero once 0.26 W/(m².K) [17].

Direct rebound curve based on measured data for 964 dwellings

Figure 5 shows a compilation of normalized measured annual heating data for 964 dwellings in relation to the specific transmission losses, both per m³ of protected volume [18].

Figure 5

Contrary to the paradigm of the seventies and eighties that the dots should scatter around a straight line, the cloud reflects a power function with an exponent less than one. In fact, a best fit looked like:

$$\frac{E_h}{V} = 229.6 \left(\frac{H_T}{V} \right)^{0.84} \quad (\text{MJ}/(\text{m}^3 \cdot \text{a})) \quad [13]$$

with H_T the specific transmission losses in W/K and V the protected volume in m³.

At very low specific transmission losses per m³ of protected volume, direct rebound opportunities should turn zero. The Trnsys calculations commented above suggests this to happen at a specific transmission loss per m³ of protected volume of 0.3 W/(m³.K). If instead a value 0.15.W/(m³.K) is assumed for zero direct rebound, the physically most probable straight line through that one point becomes:

$$\frac{E_h}{V} = 311 \left(\frac{H_T}{V} \right) \quad (\text{MJ}/(\text{m}^3.\text{a})) \quad [14]$$

resulting in a statistically significant direct rebound factor:

$$a_{\text{rebound}} = 100 \left[1.355 \left(\frac{U_m}{C} \right)^{0.16} - 1 \right] (\%) \quad [15]$$

where C is the compactness of the building in m, equal to the ratio between the protected volume and the envelope surface area. Annual heating consumption per unit of protected volume so equals:

$$E_{h,\text{real}} = \left[1 - \frac{a_{\text{rebound}}}{100} \right] E_{h,\text{valc,EPB}} (\%) \quad [16]$$

Figure 6 shows equation [15] in graphic form, together with a collection of measured direct rebound factors, underlining that the curve is a mean to be used when large numbers of dwellings are considered. In fact, the curve does not allow predicting energy consumed for heating annually in individual cases.

Since, the graph and equation [16] have been used in a bottom-up model to predict energy for heating in the residential sector in Flanders (in total some 2 500 000 homes). The results fitted well with top-down data gathered by the administration, while not considering rebound overrated reality with a factor 2.

Figure 6

Energy price and direct rebound

Price effects on direct rebound could be analyzed thanks to a series of normalized annual consumption data gathered in several fossil fuel and direct electricity heated dwellings. In countries with thermal power plants, direct electricity is more expensive than fossil fuels. A least square analysis of the data gave as linear functions [19]:

$$E_{T,\text{fossilfuel}} = 35.0H_T + 19330 \quad [17]$$

$$r^2=0.39, T=11.07 (>2.58) \text{ and } F=122.5 (>7.88)$$

$$E_{T,\text{all electr}} = 22.0H_T + 12508 \quad [18]$$

$$r^2=0.22, T=4.16 (>2.66) \text{ and } F=17.3 (>7.88)$$

Or, for identical specific transmission losses direct electricity heated dwellings show a lower heating consumption than fossil fuel heated dwellings. Energy price clearly matters, underlining that drops may produce a same reaction as upgrading the thermal insulation: less rebound. Vice versa, people will moderate their comfort wishes when prices turn higher, which may gave more direct rebound.

CONCLUSIONS

Most standardized calculation tools typically predict energy consumption for heating in residential buildings assuming standard dwelling use: mean temperature fixed, infiltration plus dedicated ventilation rate imposed and internal gains standardized. Such models allow evaluating and characterizing the energy efficiency of a combined building/HVAC design. They in fact should be seen as quantification of a building quality, in the case being the energy efficiency of the whole design. They however are of no value when it comes to quantifying energy consumption. Main reason for that are

human attitudes and behavior, leading to direct rebound impacting energy usage. The effect anyhow is subjected to physical limitations as the average temperature in partially heated homes increases with higher insulation quality.

Temperature data show that direct rebound is a fact. The normalized annual energy consumption for heating, measured in two low income estates, reflects the impact: usage systematically lower than calculated with the reference calculation model, which is based on the EN-ISO 13790 method under the assumption that the whole protected volume is heated, that the heating season mean indoor temperature is 18°C, that preset numbers can be used for the infiltration and dedicated ventilation rate and that the internal gains are a function of the protected volume only. A monitored comparison between full and partial heating and multi-zone transient modeling further confirmed that direct rebound looses impact as economizing measure in very well insulated dwellings. Finally, starting from the normalized annual consumption data of 964 homes, a statistically relevant direct rebound curve could be constructed, which was used for better predicting heating consumption in the residential sector. Last but not the least, also energy prices motivate direct rebound, as was shown by comparing energy consumption for heating in fossil fuel and direct electricity heated homes.

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Captions

Figure 1 Schematic representation of the rebound effect

Figure 2 First estate, dwellings and floor plan

Figure 3 Second estate, dwelling

Figure 4 Two dwellings, one non-insulated and the other well insulated, impact of normalized full and partial heating on energy consumption in relation to the specific transmission losses, both per m^3 of protected volume

Figure 5 Normalized measured annual heating consumption for 964 dwellings as a function of the specific transmission losses, both per m^3 of protected volume

Figure 6 Rebound factor in % as a function of the specific transmission losses per m^3 of protected volume, estimated by assuming rebound zero for $U_m A_T/V = 0.15 \text{ W}/(\text{m}^3 \cdot \text{K})$ and a physically plausible straight line ($U_m A_T/V, E_{\text{heat},a}$) through that point. The dots give individual rebound factors measured over time in different dwellings

Table 1: Temperatures in daytime and sleeping rooms

	Daytime rooms	Sleeping rooms
Number of weekly means	124	177
Overall weekly mean	21.0	17.0
Impact of weekly mean outside temperature	$19.8 + 0.12\bar{\theta}_e$	$12.8 + 0.42\bar{\theta}_e$

Table 2: Normalized measured energy consumption in the first estate

Dwelling	$U_m A_T / V$ $W/(m^3.K)$	Number of dwellers	Measured MJ/a	Fraction calculated value $(1 - a_{\text{rebound}}/100)$
1	1.21	2	32830	0.44
2	1.21	1	34290	0.46
3	1.21	2	45390	0.61
4	1.21	1	33960	0.46
5	1.21	1	28790	0.39
6	1.21	1	45690	0.61
7	1.21	1	50320	0.68
8	1.21	1	64130	0.86
Average			41700	0.56

Table 3: Normalized measured energy consumption in the second estate

Dwelling	$U_m A_T / V$ $W / (m^3 \cdot K)$	Number of dwellers	Measured MJ/a	Fraction calculated value $(1 - a_{\text{rebound}} / 100)$
1	1.2	2	47450	0.31
2	1.2	2	73506	0.49
3	1.2	4	89193	0.59
4	1.2	2	86543	0.57
5	1.2	2	110052	0.73
6	1.2	2	111509	0.74
7	1.2	2	104163	0.69
8	1.2	5 students	81887	0.54
9	1.2	5	94338	0.62
10	1.2	2	88413	0.59
11	1.2	4	72153	0.48
12	1.2	2	69175	0.46
Average			74050	0.49