# A proposal to go beyond the rebound effect: how to evaluate the financial value of comfort after retrofitting?

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## Abstract
Evaluation of energy savings of retrofitting programmes are relativized due to the rebound effect. Moreover, their economic relevance (i.e. NPV calculation) is questioned because of the discouraging paybacks. The underlining question of both problems is missing consideration of comfort improvement, often hidden behind the concept of rebound effect.

Yet, it can be considered that some potential energy savings in an initially uncomfortable dwelling are assigned to achieving decent comfort. In this case, the household sets aside some of the potential savings to improving thermal comfort and thus part of the rebound effect is simply to catch up. It therefore imports to distinguish within the so-called rebound effect between the share of legitimate comfort improvement and the energy "wastage".

We propose an approach embodied in a formula to monetize the comfort catch-up relying on the comparison of ex-ante and ex-post energy savings. This approach has been applied to regional energy efficiency programmes consisting for each participant to the realisation of one to two energy efficiency measures concerning insulation and/or heating equipment of his housing. These cases study are located in 3 different regions with different climates (oceanic, continental and Mediterranean). After refurbishment, we evaluate the level of comfort catch up according to the set-temperature and the difference between the real consumption and its potential value at a conventional set-temperature.

The methodology turned out to be quite easily applicable providing that some essential data are available (energy consumptions and set-temperatures before and after retrofit). Quantitative results of comfort catch up are in the same order of magnitude of energy savings.

## Introduction
Although existing buildings are an important source of potential energy savings in Europe, widespread renovation of these buildings is particularly difficult to implement, particularly in the residential sector, for economic cost effectiveness reasons. It is not always economically cost effective for the investor to make energy saving improvements based only on reducing the energy bill. However, the method usually used for evaluating the benefits in such an investment can be considered to be restrictive, since the occupant of the home also evaluates retrofit through benefits other than the reduction in the invoice, such as improved comfort or increased home value (green value). One way of broadening the cost effective range of these investments is to take account of other benefits (multiple[1] benefits) associated with these measures and to broaden the scope of the analysis beyond the building (IEA, 2014, Amann 2006). Improved thermal comfort is one of these multiple benefits.

The concept of thermal comfort is a subjective evaluation (Lavoye F. 2008) that, however, is usually modelled by several physical parameters (Bourgogne Bâtiment Durable (Burgundy Sustainable Building), 2013): the occupant's metabolism, his or her clothes, the ambient air temperature, the average wall tem-

1. Also called *no energy benefits* (*NEBs*), *no energy impacts* (*NEIs*) or *co-benefits*.

perature, the relative humidity and the air speed. Thermal comfort in buildings is evaluated using simple methods and tools produced based on statistical approaches to take account of its subjective aspect. The most frequently used thermal comfort models in buildings are models derived from work done by Fanger (ISO, 2005) and Gagge (ASHRAE, 2013).

Note that standard EN 15251 (AFNOR, 2007) qualifies comfort in residential housing starting from a minimum heating temperature in the winter season depending on the occupant's activity, the type of room and as a function of a predictable percentage of dissatisfied persons (PPD -*Predicted Percentage Dissatisfied*[2]): 21 °C for PPD < 6 % and 19 °C for PPD < 10 % in dwellings.

Occupants of a dwelling may modify their comfort conditions when an energy efficiency action is performed in a home. Increased thermal comfort following energy renovation work is a well-known effect known as the rebound effect, and in the case of heating it can result a lack in potentially achievable energy savings of 30 % (Grenning et al, 2000; Sorrel et al, 2009; Haas and Biermayr, 2000). However, in some cases this rebound effect can be considered as a benefit in that it leads to an improvement in the well-being of the occupants, a reduction in the number of illnesses related to humidity and also an improvement in productivity (IEA, 2014). A study of the variations in the rebound effect in different household types shows that the most important rebound effects are obtained for low-income households that are not satisfied with their initial comfort and are therefore potentially in a situation of restricted thermal comfort (Hediger et al., 2016; Hong et al., 2006).

Thus, nowadays, the rebound effect is considered largely as no more than "wastage" and therefore with no value (or a negative value) while some studies (Steinach et al., 2016) show that if 100 % of the rebound effect is included, the cost effective potential of energy efficiency actions can be doubled. Although taking account of 100 % of the rebound effect would seem to be excessive, it demonstrates that a closer study of the question of the financial value of the rebound effect is very useful for evaluating the cost effectiveness of energy renovations.

## Principle of determining the value of comfort

Comfort valuation as a Non Energy Benefits (NEB) of an energy efficiency investment has already be handled in several papers. A first set of papers (Amann 2006 and Skumatz, 2002) used some stated preference approach to determine the willingness to pay (WTP) of concerned people for NEB, including improved comfort. Depending of the WTP estimation approach (contingent valuation, labelled magnitude scaling approach, comparative valuation), these surveys came out to a WTP scaling $65/y. up to $1000/y for the whole NEBs associated with the American north-eastern weatherization program (Amann, 2006). Based on revealed preference analysis conducted in the Canton of Zurich (Switzerland), Jakob (2006) came up to a WTP for improved indoor air quality of 5 % of the rental price. In France, a valuation of the WTP for efficient dwelling (i.e. green value based on EPC labelling) was assessed showing a gap of more than 25 % between the extreme bands (Dinamic, 2015).

How valuable these estimates may be, they did not really deal with the relationship between rebound effect and comfort improvement related with increased temperature (starting from the state of an insufficiently heated housing). Assumptions made for indoor air temperature change are either not clearly presented or implicitly considering that no change occurs (Jakob 2006). Moreover, little attention was paid on the relation between comfort improvement on the one hand and the gap between conventional assessed and actual energy savings. His paper focuses explicitly on the (potential) impact of an increased indoor temperature on comfort.

It can be considered that some potential energy savings in an initially uncomfortable house are assigned to achieving decent comfort. The household can thus set aside some of these potential savings to improving thermal comfort. In this case, it is thus considered that part of the rebound effect is genuinely catch up and must be evaluated financially. It will be noted that this proposal to determine a value of comfort was briefly presented in a previous paper (Osso et al., 2016) in the wider framework of multiple benefits and that this article describes a more detailed study of the initial proposal.

We will use the inside temperature, considered to be the same as the air temperature, as the only calculation variable associated with thermal comfort, to obtain a method of evaluating comfort that is fairly easy to apply in that it only requires a small amount of data. It will be noted that the air temperature is not strictly equivalent to the temperature perceived by the occupant that is closer to the operative temperature, which can simplistically be seen as the average of the air temperature and surface temperatures.

The modification of the share of heated area should be also look at to encompass totally the rebound effect but due to lack of data this point will not be studied here. However, from a theoretical viewpoint, this effect could be easily include in the valuation on the basis of a new consumption calculated from the specific consumption of the dwelling (expressed in kWh/m²) and the newly heated area (see eq. 12).

Financially, this assignment of potential energy savings to thermal comfort is the amount that the household is willing to pay for more comfort ($WTP_c$). The initial household utility level used in the neoclassical formalism is: $U_0$(income=$I_0$, temperature=$T_0$), the income $I_0$ being net of energy expenses. Energy saving refurbishment should modify it to $U_1(I_0+ES_p, T_0)$, $ES_p$ being the potential energy savings (in €) where $U_1>U_0$.

Thus, the consumer (Figure 1) prefers to be on the utility curve $U_1$ rather than on $U_0$ (preference for work undertaken) but is indifferent about his position on $U_1$ (the consumer can then decide on a compromise between his comfort and financial savings with constant utility). Formally, we obtain:

$$U_1(I_0 + ES_p - WTP_c, T_1) = U_1(I_0 + ES_p, T_0), \text{ where } T_1 > T_0 \quad (1)$$

$$\text{and } WTP_c = ES_p - ES_r \quad (2)$$

where:

$ES_r$ real energy savings.

$ES_p$ potential energy savings.

$WTP_c$ willingness to pay for improved comfort.

2. The PMV-PPD index takes account of 6 thermal parameters (clothes, activity, average radiant and air temperature, air speed and humidity) and can be used directly as a criterion. Category I: PPD <6 %, category II: PPD <10%, category III: PPD < 15 %.

Equations (1) and (2) clearly show that ($ES_p$-$ES_r$) is a willingness to pay in the financial sense of the term.

## The reference comfort

As mentioned above, the objective is to put a financial value on improvements in comfort to a decent level. Thus, the "desirable" or "acceptable" or even "legal" comfort level has to be defined. Standard EN 15251 (AFNOR, 2007) recommends a temperature of between 18 and 21 °C for homes. The French construction code[3] imposes a conventional indoor temperature of 19°C during occupancy periods (Energy Code, 2016a) and 20°C is now the temperature recorded in the living room in most French households (CGDD, 2013). It should also be noted that 72 % of French households declare that they reduce their heating temperature and 62 % that they reduce their heating duration (CREDOC, 2014).

It should be noted that the average temperature inside homes has varied over time: 12 °C in the 1900s, 16 °C in the 1950s and at least 19 °C nowadays (Moulinie, 2015). However, it should be mentioned that this important trend towards increasing the "socially acceptable" temperature is questioned by some, opposing lifestyle and environmental rationality (Quelle Energie, 2016).

We will choose to use 19 °C as the minimum decent comfort level. For the remaining part of this paper, this temperature is called the reference temperature ($T_{ref}$).

Therefore the proposed value of comfort is determined by considering a value of increased comfort up to a maximum of $T_{ref}$, when the initial temperature[4] ($T_0$) is less than $T_{ref}$ (reference temperature of 19 °C) and the inside temperature is increased ($T_1 - T_0 > 0$). We have decided not to evaluate increased comfort above $T_{ref}$, although this point can be debatable depending on the prospect considered (customer, social welfare).

## Calculating the value of comfort

Heating consumption in a home depends partly on heating degree-days (HDD) associated with the location of the home (Day, 1999) (Broc, 2006). Heating degree-days (HDD) are defined during a heating period in France from 1 October until 31 May the following year (San, 2015), the value being the sum of the positive differences[5] between average daily outdoor temperatures during this period and an indoor temperature threshold. Firstly, we will assume that at a given indoor threshold temperature (T), they can be written as follows:

$$\mathrm{HDD}(T) = \mathrm{ND} * (T - T_{ext}) \quad (3)$$

where:

- ND the number of heating days per year (namely 240 for the period considered).
- T the indoor temperature threshold.
- $T_{ext}$ the outdoor temperature.

3. Historically, in the construction and housing code, decree No. 79-907, 22 October 1979, clause R. 131-20.

4. If $T_0$ is more than $T_{ref}$, there is no value.

5. In other words, when the average outdoor temperature for one day is less than the threshold temperature.

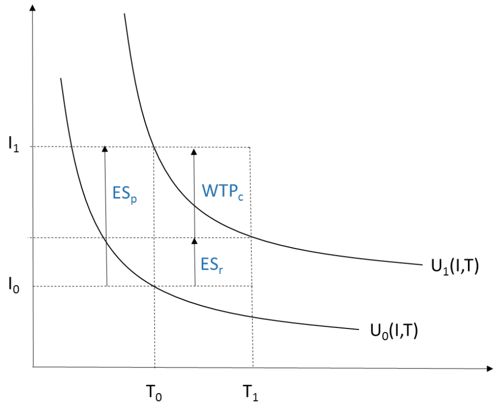


*Figure 1. Diagrammatic view of the utility ($U_i$) as a function of the income (I) and the comfort temperature (T) of households performing energy renovation work. $ES_p$: potential energy savings, $ES_r$: observed energy savings, $WTP_c$: willingness to pay for a comfort increase.*

Secondly, we can therefore express HDD(T) as a function of HDD($T_{ref}$) such that:

$$HDD(T) = ND^{*}\left[\frac{HDD\,(T_{ref})}{ND}\text{-}(T_{ref}\text{-}T)\right] \quad (4)$$

The term (HDD($T_{ref}$)/ND) corresponds to an "average temperature difference over the heating season" between an indoor space at $T_{ref}$, (namely 19 °C) and outdoors. In the above formula, a "difference" between $T_{ref}$ and the temperature T inside the home is algebraically subtracted from this term. Thus, when a home is heated to a temperature less than[6] $T_{ref}$, the number of HDDs at T is lower than HDD($T_{ref}$), which results in a "lower heating effort" to be supplied (lower indoor/outdoor temperature difference to be corrected).

Furthermore, since space heating consumption (*sh*) are considered to be directly proportional to HDDs (Day, 1999) (Broc, 2006), the heating consumption observed at the indoor temperature $T_1$ ($C^{T_1}_{1,sh}$) after the work can be adjusted to its potential value at the initial temperature ($C^{T_0}_{1,sh}$) using the following formula:

$$C^{T_0}_{1,sh} = C^{T_1}_{1,sh} * \frac{HDD(T_0)}{HDD(T_1)} \quad (5)$$

If $T_1 \leq T_{ref}$, the share of the additional consumption after the work assigned to catching up to a decent level of comfort is calculated as the difference between the heating consumption observed after the works ($C^{T_1}_{1,sh}$) and the potential consumption without any change in comfort after the works ($C^{T_0}_{1,sh}$):

$$C^{T_1}_{1,sh}\text{-}\,C^{T_0}_{1,sh} = C^{T_1}_{1,sh} * \left[1 - \frac{HDD(T_0)}{HDD(T_1)}\right] \quad (6)$$

6. If $T > T_{ref}$, the "subtracted" term is negative and thus the number of HDDs at T is more than HDD($T_{ref}$) (larger temperature difference to be corrected).

If $T_1 > T_{ref}$, the share of the additional consumption after the work assigned to catching up to a decent level of comfort is limited to $T_{ref}$:

$$C_{1,sh}^{T_{ref}} - C_{1,sh}^{T_0} = C_{1,sh}^{T_1} * \left[\frac{HDD(T_{ref}) - HDD(T_0)}{HDD(T_1)}\right] \quad (7)$$

Which can be written as follows in a general formula:

$$C_{1,sh}^{\min(T_1,T_{ref})} - C_{1,sh}^{T_0} = C_{1,sh}^{T_1} * \left[\frac{HDD(\min(T_1,T_{ref})) - HDD(T_0)}{HDD(T_1)}\right] \quad (8)$$

By replacing the HDD values by their simplified expression (eq. 4) and determining the monetary value of this additional consumption at the price of energy after the works ($P_1$), we obtain a willingness to pay $WTP_c$ amount:

$$WTP_c = \left[C_{1,sh}^{T_1} * \frac{\min(T_1;T_{ref}) - T_0}{\left[T_1 - T_{ref} + \left(\frac{HDD(T_{ref})}{ND(T_{ref})}\right)\right]}\right] * P_1 \quad (9)$$

This quantity evaluated over a full year could also be evaluated over the life of the energy efficiency action taking account of a discount rate, but this study does not consider this because it is outside the direct scope of this study and should be based on future assumptions about behaviours and prices of energy.

In practice, in the sense of a measurement or the response of a household to a questionnaire, the definition of a single indoors temperature for an entire home can also create a number of problems. We propose to make at least a distinction between the living area and the remainder of the home, and then to define the temperature inside a home as being the weighted average of the areas ($A_{room}$), of the temperatures inside each of these zones:

$$T = \sum_{\text{room}}^{\text{living,other}} \left[T_{room} * \frac{A_{room}}{A_T}\right] \quad (10)$$

where:

$A_{room}$ room concerned (in m²).

$A_T$ total inhabitable area of the home (in m²).

When no precise data are available, the area of the living room is assumed to be 27 % of the inhabitable area[7] of the home ($A_T$).

Finally, after correcting the space heating consumption observed after the works ($C_{1,sh}^{T_1}$) at a real climate (HDD) to a so-called normal climate (average outdoor weather over 20 years, $HDD^{norm}$; *cf.* eq. 5 and eq. 12), we therefore obtain a financial evaluation for the improved comfort due to an energy efficiency action by the following formula:

$$WTP_c = C_{1,sh}^{T_1,norm} * \frac{\min(T_1;T_{ref}) - T_0}{\left[T_1 - T_{ref} + \left(\frac{HDD^{norm}(T_{ref})}{ND}\right)\right]} * P_1 \quad (11)$$

where:

$T_0 < T_{ref}$ (if $T_0 \geq T_{ref}$; $WTP_c = 0$)

$T_j = \sum_{room}^{living,other} \left[T_{j,room} * \frac{A_{room}}{A_T}\right]$ and $j$=0 (before the work) or 1 (after the work).

7. Based on a 27 m² living room for an inhabitable area of 100 m². The latest surveys provide disaggregated data on set temperature by room types (living room vs. other rooms).

To be theoretically complete and stay simple, we should add to the WTPc calculated before (eq. 11), the value of the potential modification of the heated area ($WTP_{area}$):

$$WTP_{area} = \frac{C_{1,sh}^{T_1,norm}}{A_T} * A_{new} * P_1 \quad (12)$$

where:

$A_{new}$ the new heated area after retrofit (non-heated before) (in m²).

## Energy savings

The calculation of energy savings made for each participant in the programme is based on the difference in consumption between years before the work ($C_0$) and after the work ($C_1$). We study energy consumption including all energies and for all uses as reported by households. The share of consumption associated with heating (α=0.7) is estimated based on the national fraction for individual homes (CEREN, 2009). Finally, energy savings (ES) were corrected for the weather in proportion to the Heating Degree Days (HDD) for a normal climate ($HDD_{norm}$), so as to estimate energy savings (ES) related to actions rather than simple consumption changes (Suerkemper et al. 2012):

$$ES = \left(C_0 * \left(\alpha * \frac{HDD^{norm}}{HDD^o} + (1-\alpha)\right)\right) - \left(C_1 * (\alpha * \frac{HDD^{norm}}{HDD^1} + (1-\alpha)\right) \quad (13)$$

The methodology has already been described in another paper (Raynaud et al., 2015) and the interested reader should refer to this paper.

## Energy efficiency programmes and participant survey

This study is based on an analysis of the results of the investigation carried out on different regional energy efficiency programmes located in 3 different regions of France: West, East and South-East.

The questionnaire used for this study is similar to questionnaires used for previous studies (Raynaud et al. 2015) and therefore is not described in detail in this document. This questionnaire was used to collect general information about the home and persons living in it and on its energy characteristics, the nature of the renovation work and energy bills for the last 3 years, allowing for energy renovation works.

The contexts of the three studies programmes are different (refer to the publication by (Du Tertre et al., 2017) in this same conference for further details) but they share the implementation of energy efficiency measures concerning insulation or heating equipment.

Globally, most of the studied programmes apply to the following energy efficiency actions:

- West Region, ENBRIN programme: installation of a wood stove in an SFH heated by electricity (Osso et al., 2016).
- South-East Region, SBE programme: installation of a heat pump (mainly air-air) and roof insulation (Raynaud et al., 2016).

**Table 1. HDD for normal climates (source: COSTIC).**

| Region | East | West | South-East |
|---|---|---|---|
| Normal HDD | 2,663 | 2,364 | 1,450* |

** Average HDDs between 1,309 and 1,627.*

**Table 2. Temperature in the living room and in other rooms before and after the work in the different regions.**

| Region | (°C) | Living room | | Other room | |
|---|---|---|---|---|---|
| | | $T_0$ before the action | $T_1$ after the action | $T_0$ before the action | $T_1$ after the action |
| West | Minimum | 14 | 17 | 14 | 15 |
| | Maximum | 27 | 28 | 23 | 25 |
| | Mean | 18.8 | 21.4 | 17.7 | 19.2 |
| | Standard deviation | 2.1 | 1.8 | 1.7 | 1.7 |
| South-East | Minimum | 16 | 18 | 15 | 16 |
| | Maximum | 23 | 23 | 22 | 22 |
| | Mean | 19.7 | 20.3 | 18.3 | 18.8 |
| | Standard deviation | 1.6 | 1.1 | 1.6 | 1.4 |
| East | Minimum | 17 | 18 | 12 | 15 |
| | Maximum | 25 | 25 | 23 | 25 |
| | Mean | 20.2 | 20.2 | 18.3 | 18.7 |
| | Standard deviation | 1.8 | 1.3 | 2.3 | 2.2 |

**Table 3. Price of energies (€/kWh) depending on the year (source: MEDDE 2016).**

| *€/kWh* | Electricity | Gas | Fuel oil | LPG | Wood |
|---|---|---|---|---|---|
| 2009 | 0.1163 | 0.0589 | 0.0577 | 0.1068 | 0.0353 |
| 2010 | 0.1191 | 0.0628 | 0.0718 | 0.1139 | 0.0371 |
| 2011 | 0.1278 | 0.0709 | 0.0890 | 0.1307 | 0.0371 |
| 2012 | 0.1340 | 0.0745 | 0.0972 | 0.1401 | 0.0394 |
| 2013 | 0.1438 | 0.0754 | 0.0930 | 0.1327 | 0.0429 |

- East Region, MDE52-55 programme: various energy efficiency works (condensation boiler, air-water heat pump, insulation, double-glazed window, etc.) (Suerkemper et al., 2012; Suerkemper et al., 2011).

These three energy efficiency programmes are in very different climates, as is seen very clearly in the differences between the normal HDDs for each of these regions (Table 1).

For indoor thermal comfort, in all investigations, the average temperature after energy renovation is slightly higher (Table 2) even if the majority of households declare that they did not change the set temperature ($T_1$). Recentring of indoor temperatures around a “social” standard (19–21 °C) is observed after the work, demonstrated particularly by a reduction in the standard deviation.

We must keep in mind that only for the South-East program the question about the share of non-heated area of the dwelling was included in the questionnaire: around 30 % of households declared a non-heated area for around 30 % of the overall area (Raynaud, 2014). Unfortunately no distinction was made between before and after retrofit. Thus, this point will be not studied further in this paper.

It should also be noted that the consumption years considered are different for the different regional programmes studied, since the investigations were carried out for each region during different years (between 2009 and 2011 for the East Region, in 2012 for the South-East Region and in 2013 for the West Region). This, for each case analysed to determine the financial value of improved comfort (eq. 11), an adjustment of the price to the year of consumption considered is necessary (see Table 3) in addition to the adjustment of the price of energy to the heating energy used.

## Results

The results are presented firstly at the scale of regional programmes and are compared with each other. An awareness analysis of parameters used to calculate the $WTP_c$ will then be put forward. Finally, the last section will present a detailed household by household analysis for the programmes with the highest $WTP_c$ values.

**Table 4. $WTP_c$ for the different regional programmes and comparison with energy savings observed after the works and the heating bill after the works.**

| Region | West | East | South-East |
|---|---|---|---|
| Number of households | 33 | 50 | 33 |
| Average $WTP_c$ | €162 | €25 | €59 |
| Average $WTP_c$ on average energy savings | 42 % | 9 % | 10 % |
| Average heating bills after the works | €868 | €1,127 | €1,075 |
| Average $WTP_c$ / average heating bill | 19 % | 2 % | 5 % |
| Average $WTP_c$ if $WTP_c \neq 0$ | €244 | €180 | €177 |

**Table 5. Average $WTP_c$ (€) depending on the reference temperature ($T_{ref}$) and the energy efficiency programme.**

| Region | Average $WTP_c$ ($T_{ref}$=19 °C) | Average $WTP_c$ ($T_{ref}$=20 °C) | | Average $WTP_c$ ($T_{ref}$=21 °C) | |
|---|---|---|---|---|---|
| East | 25 | 35 | 40 % | 41 | 64 % |
| West | 162 | 256 | 49 % | 333 | 94 % |
| South-East | 59 | 84 | 42 % | 115 | 95 % |

#### AVERAGE WILLINGNESS TO PAY FOR THERMAL COMFORT

This section gives an average value of the $WTP_c$ for increased comfort on the analysed sample such that:

$$\overline{WTP_c(T_{ref})} = \sum_{j=1}^{n}\left[WTP_j(T_{ref})\right] * \frac{1}{n} \quad (14)$$

where:
$n$ number of households in the sample

This implies that households that do not modify their comfort or for which the initial temperature $T_0$ is greater than or equal to 19 °C have a $WTP_c$ equal to zero and are accounted in the average calculation. Calculated average $WTP_c$ values are very variable for the different programmes (Table 4) and logically depend on changes in the declared temperatures (Table 2). For the West region, where temperatures before the works are lowest (i.e. $T_0$–$T_{ref}$ maximum), the $WTP_c$ is the highest. This is also the region in which the highest maximum temperatures after the works are observed (i.e. $T_1$–$T_{ref}$ maximum).

Unlike the East region, since the average temperature in the living room before the works $T_0$ is 19 °C and energy management are not much changed after the works, the estimated $WTP_c$ remains low. The average $WTP_c$ for the programme[8] in the South-East region is between these two extremes.

The average financial value of improved comfort compared with heating energy savings observed *ex-post* after the works is large compared with heating energy savings observed for the West region and is lower although not negligible for the other two regions.

Finally, there would seem to be a correspondence between a high average $WTP_c$ and a low average heating bill after the works. If only positive $WTP_c$ values are considered, therefore excluding households that do not change their heating management method and/or having a decent comfort level before the works (i.e. $WTP_c$=0), obviously values are higher, especially for programmes in which a majority of households declared that they had not changed anything (particularly the East region).

8. It will be noted that the WTP of households is not considered herein for air conditioning when a reversible air-air heat pump is installed in the South-East region. This would require a completely independent study.

In this case, $WTP_c$ values are much less different in the different programmes studied. This would appear to indicate that when households are in the position of improving comfort, their economic evaluations of improved comfort are similar.

#### SENSITIVITY STUDY

The calculation of $WTP_c$ is based on two main parameters, namely the reference temperature ($T_{ref}$) and the number of heating days (ND). Remember that ND is considered to be independent of $T_{ref}$, within the variation range of this temperature. Thus, we can vary these two variables separately:

- The reference temperature (T*ref*) has an important influence on the average $WTP_c$. For a +1 °C increase in the reference temperature $T_{ref}$, we observe a 40 % increase in the average $WTP_c$ (Table 5).
- Moreover, the number of heating days (ND) also has a significant impact on the average $WTP_c$. The reduction in the $WTP_c$ is almost proportional to the reduction in ND (Table 6): reduction to the average WTPc for a change from ND=240 day to ND=200 days, namely -17 %.

A last important variable in the calculation of $WTP_c$ is the distribution of areas between the living room and the other rooms related to spatial energy management of temperatures in the home. The distribution of areas ($A_{living}/A_T$) between the living room and the other rooms has a very variable impact on the average $WTP_c$ depending on the programme. Thus, an increase in the area of the living room from 27 % of the inhabitable area to 50 % has a mediocre effect on the $WTP_c$ for the South-East and East regions with reductions of -2 % and -20 % respectively, compared with an increase of 11 % for the programme in the West region. These differences can be explained by the energy management for the living room and for other rooms (e.g. different temperature between areas) and temperature differences before and after the works.

#### INDIVIDUAL EVALUATION

This section only considers the West region for which absolute values of $WTP_c$ are highest and the number is greatest ($WTP_c \neq 0$), and studies individual variations of the $WTP_c$ for house-

**Table 6. Average $WTP_c$ (€) depending on the number of heating days (ND) and the energy efficiency programme.**

| Region | Average $WTP_c$ (ND=240) | Average $WTP_c$ (ND=200) | | Average $WTP_c$ (Tref=21 °C) | |
|---|---|---|---|---|---|
| East | 25 | 21 | -16 % | 18.9 | -24 % |
| West | 172 | 143 | -17 % | 129 | -25 % |
| South-East | 59 | 49 | -17 % | 43.74 | -26 % |

**Table 7. $WTP_c$ as a function of the reference temperature ($T_{ref}$) and the number of households concerned (West region).**

| $T_{ref}$ | 16 °C | 17 °C | 18 °C | 19 °C | 20 °C | 21 °C | 22 °C | 23 °C | 24 °C | 25 °C | 26 °C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Average (€/year) | 62 | 82 | 88 | 84 | 92 | 120 | 170 | 210 | 310 | 161 | 209 |
| Number of households | 5 | 9 | 18 | 33 | 51 | 47 | 33 | 16 | 8 | 2 | 2 |

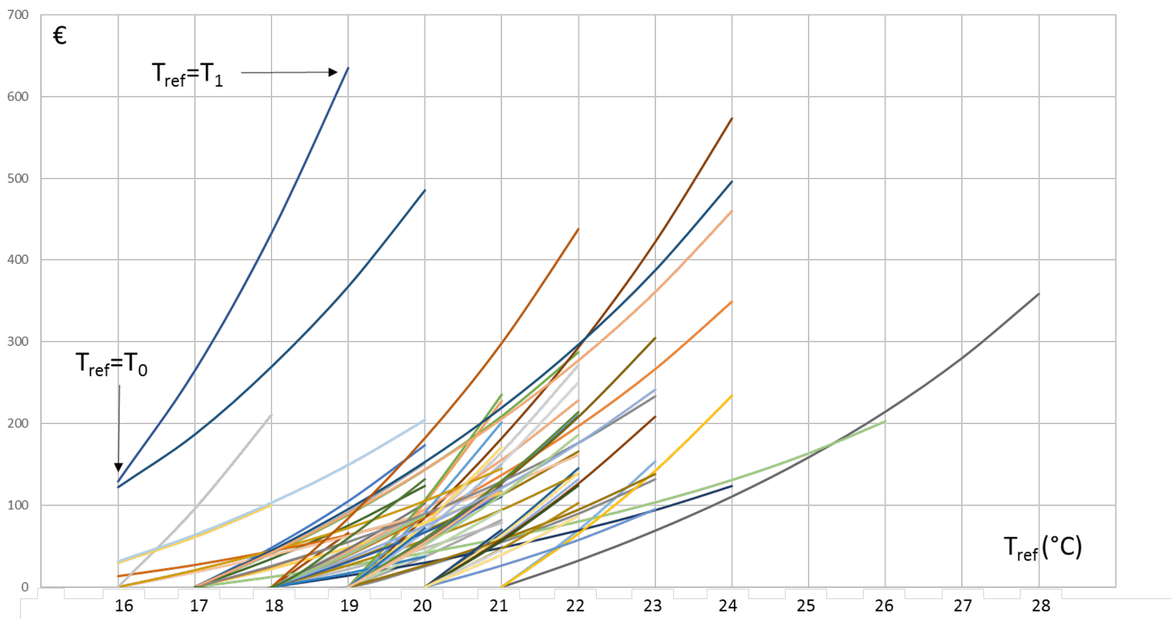


*Figure 2. Evaluation of comfort ($WTP_c$) by household depending on the reference temperature ($T_{ref}$ varying from 16 °C to 28 °C) such that: $T_{ref} \leq T_1$ and $WTP_c$ = €0/year for $T_0 = T_{ref}$ (West sample).*

holds depending on the selected comfort temperature ($T_{ref}$). The idea here is to relax the hypothesis of a reference temperature based on 19 °C in the context of an evolution of the societal norm. Obviously, the highests $T_{ref}$ are theoretical, on the other hand it is not necessarily illusory that $T_{ref}$ will eventually increase to 20 °C or 21 °C.

Apart from these set values before and after the works, the $WTP_c$ depends (eq. 7) on the heating energy consumption ($C^{T_1}_{1,sh}$) of the household that itself depends on the characteristics of the home (insulation level, inhabitable area, performance of the heating system, etc.). Therefore the $WTP_c$ is variable in the different studies (Figure 1) and in some cases it can be several hundred Euros. For most households, the maximum $WTP_c$ ($T_{ref} = T_1$) is between €200 and 300. Note that the two extreme cases with a very low temperature before the works ($T_0$ < 16 °C) quickly show an increase in the evaluation of comfort (Figure 1, blue curves at left). On the other hand, households with a high temperature after the works ($T_{ref} = T_1$ ≥ 23 °C) do not have a higher maximum $WTP_c$ than most households.

Therefore we can see that the evaluation of comfort is higher when increasing from 16 °C to $T_{ref}$ = 21 °C that it is when increasing from 21 °C to $T_{ref}$ = 26 °C (same temperature difference). This is quite compatible with the principle of the "marginal utility" of the inside temperature that is decreasing. The value of the same "temperature gain" is thus determined to be less when the temperature "before works" is higher (even if the "reference" temperature is higher).

$WTP_c$ values calculated as a function of the reference temperature between 19 °C and 21 °C, therefore within the comfort range considered to be normal[9], remain of the order of a hundred Euros per year.

9. It will be noted that when $T_1$ is higher than 26 °C, the heating (i.e. HDD) should be changed to air conditioning (i.e. CDD – Cooling Degree Day) (Energy Code, 2016b).

## Conclusion

We have proposed an economic value of comfort, through the rebound effect subsequent to energy efficiency retrofit. This proposal goes beyond a Manechean view of either totally including the economic evaluation (Steinach et al., 2016) of the rebound effect or completely ignoring it in the evaluation of energy efficiency actions.

We believe that the possibility of separating the increase in comfort following works between "conventional" comfort and excess comfort is a significant improvement. The question that then arises is the threshold temperature between "conventional" comfort (i.e. to bring up to standard or socially acceptable) and excess comfort because it depends on the culture of the climate and societal change. At the present time the standard would appear to be between 19 and 21°C. One advantage of the proposed calculation method is that it can be adapted to societal changes. Obviously, this calculation method is particularly applicable if the rebound effect is large (particularly the case of energy insecurity (Hong et al., 2006)).

An improvement of the economic valuation could be made by taking into account the modification of heated area but due to a lack of data this point was out of this study.

Finally, another application of this approach might concern the use of air conditioning during the installation of an air-air heat pump, as in the programme in the South-East region, based on CDD (cooling Degree Day). An impact of this programme on energy savings has been estimated (Raynaud et al., 2015), when air conditioning is used significantly.

The average value of comfort depends on the programmes studied (here, consisting of one to two energy efficiency measures concerning insulation and/or heating equipment) and it is difficult to draw any general conclusions. Nevertheless, taking all the necessary precautions, we can see that when there is a rebound effect after the refurbishment, households appear to put a value of about €200/year on their increase in comfort, despite their claims to the contrary in most cases. Furthermore, the value placed on comfort seems to be higher when the heating bill is lower. This latter point confirms the advantage of placing an economic value on comfort because the price signal (in the sense of the space heating bill) appears to play its role. Thus, when households use a relatively inexpensive fuel like wood as secondary energy in the case of the West region programme, the willingness to pay for thermal comfort appears higher.

This paper focuses on the revealed WTP of the dwelling for an improved comfort seen as an increase in indoor temperature. It does not take into account related extra benefit such as health improvement. Osso et al. (2016) underline that improved comfort in the case of initial thermal discomfort ($T_0$<16 °C) reduces medical expenses reimbursed by the Health Service (and therefore not supported by the dwelling), which can be an approach to monetize health improvement.

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