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Original
Influence of Comfort Expectations on Building Energy Need / Madonna, Francesco; Quaglia, Pietro; Corrado, Vincenzo; Croci, Lorenzo. - In: ENERGY PROCEDIA. - ISSN 1876-6102. - ELETTRONICO. - 140:AiCARR 50th International Congress; Beyond NZEB Buildings, 10-11 May 2017, Matera, Italy(2017), pp. 265-276.

Availability:
This version is available at: 11583/2702010 since: 2018-02-27T23:38:10Z

Publisher:
Elsevier

Published
DOI:10.1016/j.egypro.2017.11.141

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 140 (2017) 265–276

Energy Procedia

www.elsevier.com/locate/procedia

AiCARR 50th International Congress; Beyond NZEB Buildings, 10-11 May 2017, Matera, Italy

Influence of Comfort Expectations on Building Energy Need

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Abstract

Increase thermal comfort is considered as one of the main benefits of a deep renovation right after energy saving. However, an increase in thermal comfort could be seen as a behavioural change caused by the energy efficiency improvement that reduces expected energy saving: the so-called rebound effect.

This paper shows how building energy need is correlated to comfort category, defined in EN 15251. The study is conducted via dynamic simulations performed by TRNSYS 17 software using 3D multi-zone models. Models are tailored on occupant behaviour and driven by thermal comfort constraints. Calculations of energy need for space heating and space cooling is done both before and after a deep renovation. The effect of building and user characteristics is evaluated too. Users are differentiated by number of persons and occupancy schedule.

The relation between thermal comfort, set-point temperature and energy need is investigated, focusing attention on changes that occur after the building has been thermally insulated. Computational results are critically discussed and compared with an empirical study on building renovation that includes a survey on thermal comfort perception and user behaviour. Finally, rebound effect is discussed and its magnitude is evaluated.

Peer-review under responsibility of the scientific committee of the AiCARR 50th International Congress; Beyond NZEB Buildings.

Keywords: End User Behavior; Energy Refurbishment; Rebound Effect

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1. Introduction

To reach 2020 goal on energy savings in Europe, representing a significant part of total final consumption, it is decisive to define factors that affect energy needs for space heating and cooling in residential buildings. Climate and

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1876-6102
Peer-review under responsibility of the scientific committee of the AiCARR 50th International Congress; Beyond NZEB Buildings
10.1016/j.egypro.2017.11.141

building characteristics (U-values, shape factors, system performances, etc..) remain central aspects; however comparing calculated and measured energy consumption of similar dwellings, frequently brought to sensible differences [1]. Occupant behavior is the key factor to understand divergences between expected and resulted energy needs for residential space heating and cooling [2,3].

Concerning building renovation, this issue has been intensely discussed in scientific literature. The gap between the estimated and the actual energy savings, caused by a behavioural response to the gain in energy efficiency, has been defined "rebound effect" [4-7].

Overtaking the assumption of default user with fixed behavioural issues, this paper illustrates how building energy need is correlated to comfort categories. Investigations has been conducted with TRNSYS, transient system simulation tool, correlating thermal comfort (has defined in EN 15251), air set-point temperature and energy need, in two different building typology. In both cases results have been discussed before and after a relevant energy refurbishment. Simulations results have been discussed and analyzed considering previous study and applied experiences [8].

2. Simulations framework

The energy need for space heating and space cooling is calculated as a function of the comfort expectation tailoring the assessment on user. The objective is to show how comfort category and user characteristics affect building energy need. Buildings are simulated in TRNSYS 17 software. Particularly, 3D multi-zone models are built using SketchUp embedded in Trnsys 3D plug-in tool (allowing the investigation of diffuse radiation distribution and longwave radiation exchange using view factors calculation).

2.1. Buildings and building renovation

Venice Typical Meteo Year data (TMY 2) were used (2345 heating degree days), to represent climatic conditions of Italian climate zone E. Two building typologies, namely a single-family house and a flat in a multi-family building have been considered (Figure 1).

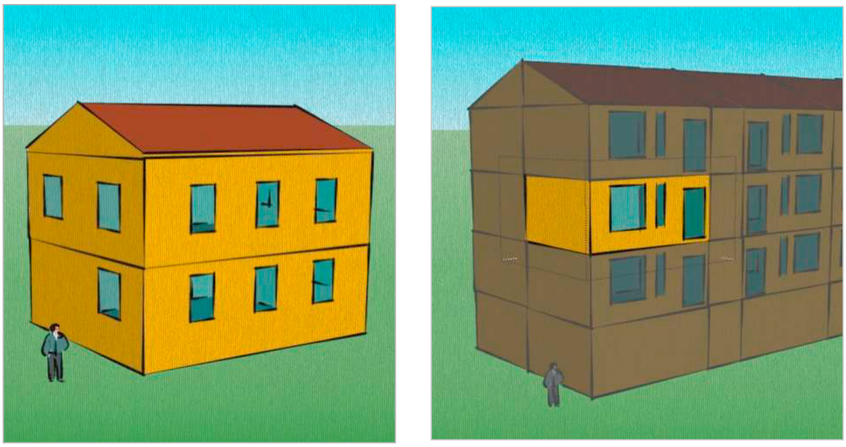

Figure 1. Considered building typologies: single family (left) and flat in a multi-family building (right).

Both buildings are selected from a database of buildings representative of the Italian climatic zone E building stock [9], with typical construction characteristics of the 60s when there were no energy conservation requirements in the building code: therefore the envelope is poor insulated and the building technical systems are quite inefficient.

Main geometrical data of envelope components are reported in Table 1.

Table 1. Main geometrical data of the buildings.

Building typology	A_f [m^2]	V_g [m^3]	A_{env}/V_g [m^{-1}]	A_w/A_{env} [-]	No. of apartments	No. of floors
Single-family house	162	584	0.73	0.048	1	2
Multi-family house	27	3076	0.51	0.095	12	3

A specific kind of deep renovation has been considered, determined by several ministerial decrees:

- intervention includes opaque casing heat insulation and replacement of windows and doors to achieve the levels of thermal transmittance set for the reference building, in function of the climatic zone and the type of the building component, from Appendix A of D.M. 26/06/2015 [10];
- the thermal transmittance values referred to D.M. 26/06/2015 are respected by the average value of the thermal transmittance of the same component type (eg. opaque vertical structures), including the effect of thermal bridges;
- intervention of thermal insulation is also extended to opaque components, delimiting the heated space, to not-conditioned environments (eg. walls toward the stairwell without conditioning);
- the thermal transmittance values referred to D.M. Minimum Requirements in case of structures delimiting heated space to not-conditioned rooms are taken as the value of the relevant building component divided by the correction factor of heat exchange between conditioned and not-conditioned environment, as indicated in standard UNI/TS 11300-1 in tabular form;
- it is not provided a thermal insulation action on floors adjacent with ground;
- it is has been installed an external mobile shading device, usable during the day, to decrease thermal solar gains;
- it is assumed that the solar factor of the glass system is equal to or less than 0.35, as provided by D.M. 26/06/2015 for all climatic zones;
- management of solar shading devices is defined according to UNI/TS 11300-1;
- heating and cooling thermal emission terminals and heat generators are not replaced;
- ambient temperature control subsystem is replaced with a type of "comfort controller (based on predicted PMV)", descripted in par. 2.3.

In Table 2 thermal transmittance of envelope components for both buildings, ante and post renovation, is reported.

Table 2. Thermal transmittance of envelope component, climate zone E

Building typology	Building Situation	U-Value External Wall [W/m^2K]	U-Value Adjacent Wall to not conditioned zone [W/m^2K]	U-Value Roof [W/m^2K]	U-Value Floor [W/m^2K]	U-Value Windows [W/m^2K]	Shading Devices [-]
Single-family house	Ex ANTE	1,26	-	1,65	2,00	4,90	-
	Ex POST	0,26	-	0,24	2,00	1,40	0,30
Multi-family house	Ex ANTE	1,15	1,70	1,65	1,30	4,90	-
	Ex POST	0,26	0,43	0,24	1,30	1,40	0,20

2.2. Users and comfort expectations

In the framework of simulations, users are characterized by the number of persons in the household and the presence time per day. Households up to 5 members are considered since they represent the 99% of Italian households

[11].
Three different presence schedule are considered:

A. Always present. It is representative of households with retired, handicapped or sick people as well as housewives, teleworkers or unemployed.
B. Absence in weekday mornings (6 hours). It is representative of households with part-time workers or students.
C. Absence in weekday mornings and afternoons (12 hours). It is representative of households with only full-time workers.

During the weekend, an absence in the afternoon (4 hours) is assumed for schedule B and C.

Comfort expectations are outlined by the three different comfort categories of indoor environment defined in European standard EN 15251, namely:

I. High level of expectation. It is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons.
II. Normal level of expectation.
III. An acceptable, moderate level of expectation.

The standard recommends criteria for thermal environment and indoor air quality based on predicted mean vote (or predicted percentage of dissatisfied) and ventilation rates. For residential buildings, such specifications are illustrated in Table 3 concerning thermal comfort, while the airflow rate (q_v) is obtained by the following equation:

$$q_v = Max\left(A_f \cdot \alpha; N_{oc} \cdot \beta\right) \cdot 10^{-3} \tag{1}$$

Where:

- A_f is the useful area
- N_{oc} is the number of occupants
- α and β are the parameters illustrated in Table 4.

Table 3. PMV and PPD ranges for categories of indoor environment.

Category	PMV	PPD
I	-0,2 < PMV < +0,2	< 6 %
II	-0,5 < PMV < +0,5	< 10 %
III	-0,7 < PMV < +0,7	< 15 %

Table 4. Air change rate for categories of indoor environment.

Category	α [l/s pers]	β [l/s m^2]
I	10	0,49
II	7	0,42
III	4	0,35

2.3. Energy calculation hypotheses and parameters

For every one of the considered users three simulations are conducted, one for each of the comfort categories defined in EN 15251 (Table 3). In presence periods, the dry bulb temperature of the air-node is set in order to comply with the selected comfort category. So, in each thermal zone, the set-point temperature is adjusted in order to have a PMV in the desired range. In no presence periods, a set-back temperature of 18°C is set during the heating season, while no constrain is imposed during the cooling season. Ideal heating and cooling systems with unlimited thermal power are assumed. Air change rate are set in order to comply with the selected comfort category during the occupancy periods. In no occupancy periods infiltration rate based on ISO 13789 is assumed. The metabolic equivalent of task (MET) follows a schedule that assume a value of 0,7 met during the night (between 23h00 and 7h00) and 1.2 met during the day (form 7h00 to 23h00). The Clothing factor is set as a function of the running mean of ambient (external air) temperature: a maximum value of 1.2 clo for values lower than 12 °C, a minimum value of 0.5 clo for temperatures higher than 26 °C and a linear interpolation in between. Air velocity in the thermal zones is assumed to be negligible. Internal gains are set in accordance to ISO 13790, taking into account the effective number of occupants, presence periods, dwelling area and building typology. The building internal thermal capacitances per unit of useful floor area are set to 165 kJ/m^{2}K (medium “weight” building in accordance to ISO 13790).

In order to have a common benchmark, a further simulation is run for each building assuming the default user, i.e. the one used for Italian energy performance certificate. So, such additional simulations are not driven by comfort constraints but energy need is calculated imposing, all day long, an operative temperature of 20 °C and 26 °C, respectively, during heating and cooling periods. Air change rate are fixed to 0.3 h^{-1} and internal gain (Φ_{int}) are determined by the following equation (2):

$$\Phi_{int} = 7.987 \cdot A_f - 0.0353 \cdot {A_f}^2 \tag{2}$$

where A_f is useful floor area. Used time step for all simulations is set to 6 minutes; for this reason weather data in the form of a typical year is required: for this purpose ASHRAE International Weather for Energy Calculation (IWEC) data are used (Venice).

3. Simulation results and discussion

Thermal energy need for space heating is shown as a function of number of occupants, presence schedule and comfort expectations. Results for the single family house, both ex-ante and ex-post values (i.e. starting situation and after building renovation), are reported in Table 5, together with consequent energy savings; for the multi-family building in Table 6. Furthermore, ex-ante and ex-post thermal energy need as well as energy saving for default user are shown in Table 7.

Table 5. Thermal energy need and savings for space heating[kWh/m^{2}a]. Single family house.

Number of occupants	Presence schedule	Ex-ante			Ex-post			Energy Saving Q_H [kWh/m^{2}a]		
		Comfort category			Comfort category			Comfort category		
		I	II	III	I	II	III	I	II	III
1	A	220	181	157	78	62	52	142	119	106
1	B	213	177	156	71	58	50	141	119	107
1	C	201	170	154	66	54	48	135	116	106
2	A	217	178	155	76	60	50	142	119	105
2	B	211	175	155	70	56	48	141	119	106
2	C	199	168	152	65	53	47	134	115	106
3	A	215	176	153	74	58	48	141	118	105
3	B	209	173	153	68	55	47	140	118	106
3	C	197	166	151	63	51	45	134	115	105
4	A	213	174	151	72	56	47	141	117	104
4	B	206	171	151	67	53	45	140	118	106
4	C	195	165	149	62	50	44	134	115	105
5	A	210	172	149	70	55	45	140	117	104
5	B	204	169	149	65	52	44	139	117	105
5	C	193	163	147	60	49	43	133	114	105

Table 6. Thermal energy need and savings for space heating [kWh/m^{2}a]. Flat in a multi-family building.

Number of occupants	Presence schedule	Ex-ante Comfort category			Ex-post Comfort category			Energy Savings Q_H [kWh/m^{2}a] Comfort category		
		I	II	III	I	II	III	I	II	III
1	A	102	82	70	19	12	9	83	69	61
1	B	96	79	69	15	10	8	82	68	60
1	C	91	75	67	12	9	8	79	66	60
2	A	97	77	66	16	10	8	81	67	58
2	B	92	75	65	12	8	7	80	66	58
2	C	87	72	64	10	8	6	77	64	58
3	A	92	73	62	13	8	7	79	65	55
3	B	88	71	61	10	7	6	78	63	55
3	C	83	68	61	8	6	5	75	62	56
4	A	92	69	58	13	7	5	79	62	52
4	B	87	67	58	10	6	4	77	61	53
4	C	81	65	57	8	5	4	74	60	54
5	A	95	68	54	16	7	4	79	61	50
5	B	88	66	54	11	6	3	77	60	51
5	C	81	63	54	8	5	3	73	59	52

Table 7. Thermal energy need and saving [kWh/m^{2}a] for default user.

Building	Ex-ante	Ex-post	Savings
Single-family house	201	66	135
Flat in a multi-family building	91	12	79

Figure 2 shows thermal energy need for space heating correlation with building typologies and construction type, expected comfort category, number of occupants and presence schedule. As lot of studies already noticed, energy need determined for the standard user as defined in UNI/TS 11300 are overestimated. From this study it results that standard user consumptions are comparable to users with high level of comfort expectations.

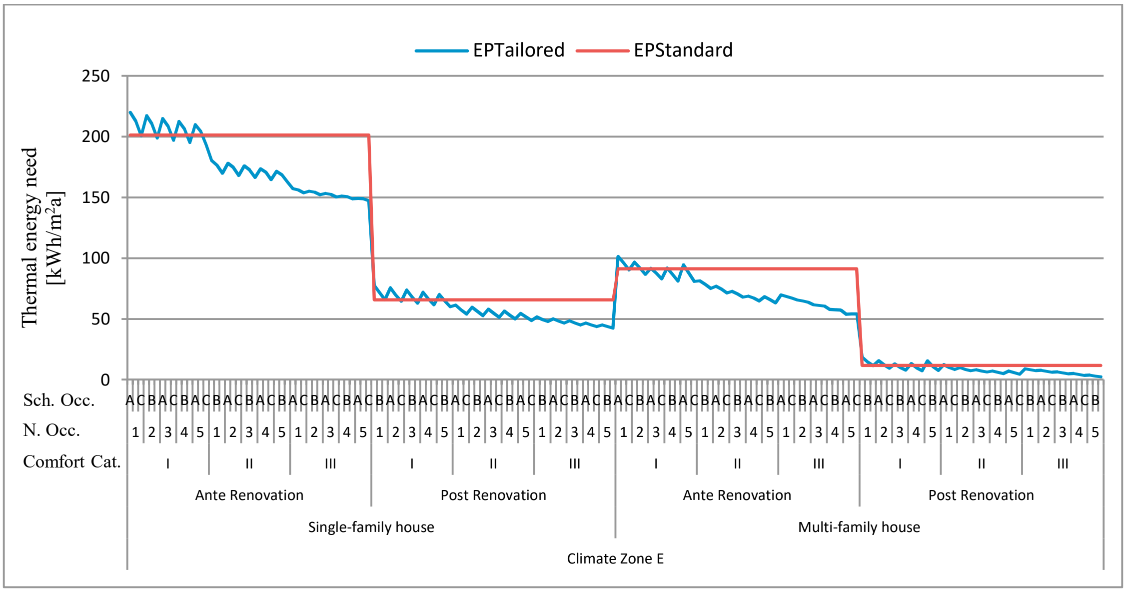

Figure 2 - Building thermal energy need for space heating operation in Venice: standard and tailored users

3.1. Influence of users on building energy need

The number of occupants affects thermal energy need via internal gains and air change rate. According to our assumptions, internal gains are a monotonically increasing function of the number of occupants: more people, more internal gains. The consequence of an increase in internal gain is a reduction of the thermal energy need for space heating.

As shown in equation (1), the air flow rate is obtained as the maximum between an evaluation based on the useful area and an evaluation based on the number of occupants. For the selected buildings, Table 8 shows the threshold in terms of number of occupants for switching between the two evaluations. Having considered households up to 5 persons, in the single-family house always prevails the constraint based on useful area and so air change rate does not depends on the number of occupant. In the flat, instead, for comfort categories I and II, air change rate depends on the number of occupants. The effect of higher air change rate is an increase in thermal energy need.

Table 8. Threshold in terms of number of occupants for switching between the evaluation based on useful area and the evaluation based on number of occupants.

Building	Comfort category		
	I	II	III
Single-family house	7.9	9.7	14.2
Flat in a multi-family building	3.4	4.1	6.0

Combining the effect of internal gain and air change rate, in the single family house, the thermal energy need for space heating is a monotonically decreasing function of the number of occupants for all occupancy schedules and comfort categories. This trend is confirmed in the flat only for the lowest comfort category; in the other cases, if the number of occupants exceeds the threshold of Table 8, the thermal energy need increases (Figure 3).

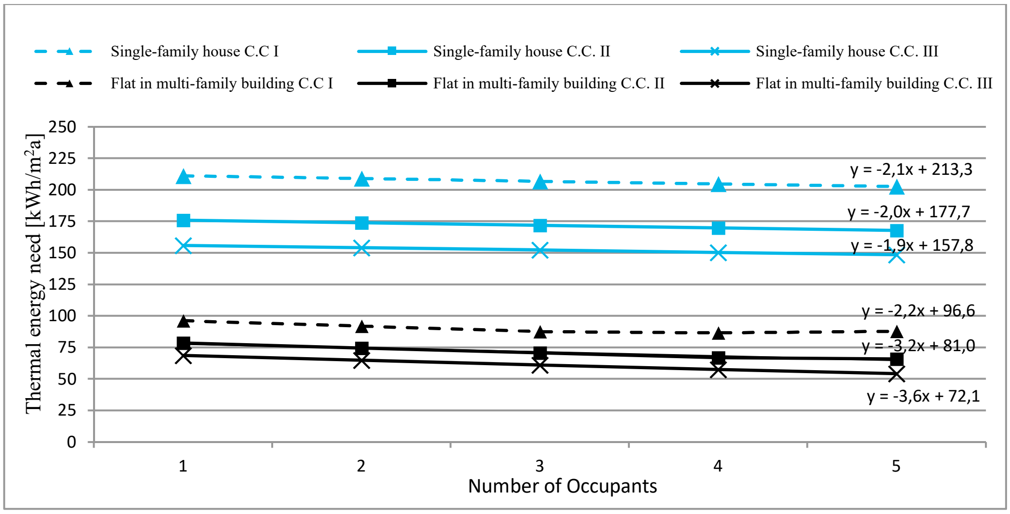

Figure 3. Thermal energy need as a function of the number of occupants and comfort category (occupancy schedule A, ex-ante buildings).

In any case, as it can be observed in Figure 3, number of occupants lightly affected building space heating consumptions. Comfort category expectation, instead, influences substantially, as represented in Figure 4, particularly in not renovated buildings.

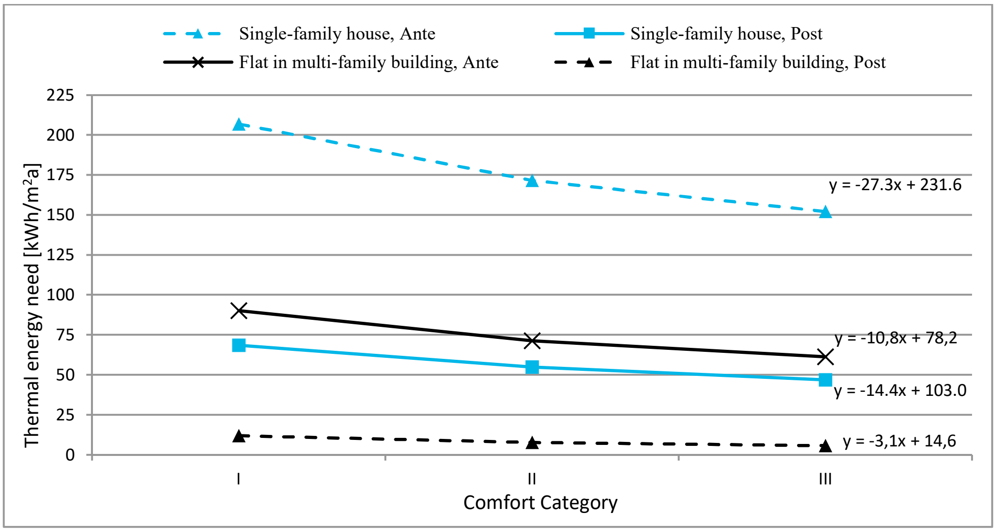

Figure 4. - Thermal energy need as a function of comfort category and renovation condition, climate zone E

3.2. Correlation between thermal comfort expectation, occupants concentration rate index and thermal energy need

It is defined IA, the building occupant concentration rate index (3), which figure out the number of components living in the building, per meter square of the useful floor area of the building.

To control comfort conditions through simulations, the operative temperature of a specified point in the building is monitored in TRNBUILD model, as described in paragraph 2.3. Operative temperature in this coordinates is calculated by the model as function of air temperature, mean radiant temperature, air velocity and relative humidity. Having defined a metabolic rate and a clothing resistance for each season, related to external air temperature, PMV could be calculated depending on room and user conditions, as EN 15251 defined. Using the three comfort category defined in CEN standards, three different operative temperatures resulted for the specified conditions (Table 9).

Table 9. Comfort categories operative temperatures

Comfort category		I	II	III
Operative Temperature	$T_{o,Eff}$	20.3 °C	18.6 °C	17.5 °C

ΔT_o is specified as the difference between effective operative temperature $T_{o,Eff}$ calculated for all three expected comfort levels and standard operative temperature $T_{o,STD}$ (4), fixed by normative to 20 °C.

$$IA = \frac{N_{oc}}{A_f} \quad [m^{-2}] \tag{3}$$

$$\Delta T_o = \left(T_{o,Eff} - T_{o,STD}\right) \quad [°C] \tag{4}$$

Simulations were ran or climate zone E, 2 building typologies, 3 levels of comfort expectation, 3 presence schedule for 1 to 5 family components: in total 90 outcomes of energy needs for space heating.

Equation (5) is the result of multiple regression using kWh/m^{2}a consumption as y, IA and ΔT_o as x. Coefficients α and β are results of multiple regression. In equation (7) building occupant concentration rate indexes as defined in EN ISO 13790 are reported.

$$EP_{Eff} = EP_{STD} \cdot \left[1 + \alpha \cdot \left(\frac{IA_{Eff} - IA_{STD}}{IA_{STD}}\right) + \beta \cdot \Delta T_o\right] \qquad \left[\frac{kWh}{m^2 a}\right] \tag{5}$$

Where:

$$IA_{Eff} = \frac{N_{oc}}{A_f} \quad [m^{-2}] \tag{6}$$

$$IA_{STD} = \frac{N_{oc,STD}}{A_{f,STD}} = \frac{1}{40}\ if\ regards\ multi\_family\ buildings;\ \frac{1}{60}\ if\ regards\ single\_family\ buildings \tag{7}$$

Equation (5) multiple regression is characterized by an R^2 of 0.845, and so well represents building energy need for space heating operation in relation with comfort expectations.

3.3. Rebound effect analysis

Numerous definitions of rebound effect, even contrasting, were founded in literature. In this study, as for the majority of papers, the rebound effect is defined as the reduction in expected savings as a result of behavioural responses to new technologies, in our case building renovation, that increases energy efficiency and reduces energy consumptions [12]. Three different behavioural changes has been studied, switching from a lower comfort category to a superior one, pushed by a reduced cost of use. In Table 10 percent reduction in expected savings caused by a behavioural response to building renovation is presented. It results that rebound effect influence is quite small.

Table 10. Rebound effect: Percent increased energy need for space heating, after a deep renovation, in case of three different behavioural changes

Number of occupants	Presence schedule	Energy Saving Q_H, Single-family house [%]			Energy Saving Q_H, Flat in a Multi-family house [%]		
		Comfort category			Comfort category		
		3→1	2→1	3→2	3→1	2→1	3→2
1	A	24%	14%	9%	16%	9%	5%
1	B	20%	12%	7%	11%	7%	3%
1	C	17%	10%	6%	7%	5%	2%
2	A	24%	13%	9%	13%	8%	4%
2	B	20%	12%	7%	9%	6%	2%
2	C	17%	10%	6%	6%	3%	2%
3	A	24%	13%	9%	12%	7%	3%
3	B	20%	11%	7%	8%	4%	3%
3	C	17%	10%	6%	6%	3%	2%
4	A	24%	13%	9%	15%	10%	4%
4	B	20%	11%	7%	10%	6%	3%
4	C	17%	10%	6%	7%	4%	3%
5	A	24%	13%	9%	24%	14%	7%
5	B	20%	11%	8%	15%	8%	5%
5	C	17%	10%	6%	10%	5%	4%

CONCLUSION

Aim of this paper is to investigate how comfort categories and user characteristics affect building energy need and to quantify rebound effect on energy savings after a deep renovation.

Two building typologies, representing Italian climate zone E building stock, were modelled in TRNSYS 17 and their thermal energy needs during a year were examined through case studies.

Energy savings for space heating operations after a deep renovation ranges between 66% and 70% for a single-family house, using Venice typical meteorological year, between 84% and 93% for a flat in a multi-family building.

The effect of building and user characteristics is evaluated too. Users are differentiated by number of persons and occupancy schedule. Their behaviour influence air change rate, air zone temperature, internal gains.

It results that occupant behavior is a key factor, being the most influential factor at same building conditions.

It also results that rebound effect after a deep renovation affects in sensible way building consumption, but it doesn't represent great changes. In the single-family house mean loss of energy savings, assuming a comfort improvement of one category, is lower than 12%, while in flat in multi-family house it is lower than 7%, for both cases with a standard deviation approximately equal to 3%. This results underline that rebound effect in case of a deep renovation does not frustrate lower energy consumptions and improvements in thermal comfort for final users.

Nomenclature	
A_f	Floor area, m^2
A_w	Wall area, m^2
A_{env}	Building envelope area, m^2
EP_{Eff}	Effective specific yearly primary energy consumption, kWh/m^2a
EP_{Std}	Standard specific yearly primary energy consumption, kWh/m^2a
IA	Building occupant concentration rate, m^{-2}
N_{oc}	Number of occupants, ND
PMV	Predicted mean vote index, ND
PPD	Predicted percentage of dissatisfied users index, %
q_v	Airflow rate, 1/h
T_o	Operative temperature, °C
V_g	Overall building volume, m^3

Acknowledgements

This work has been financed by the Research Fund for the Italian Electrical System under the Contract Agreement between RSE S.p.A. and the Ministry of Economic Development - General Directorate for Nuclear Energy, Renewable Energy and Energy Efficiency stipulated on July 29, 2009 in compliance with the Decree of March 19, 2009.

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