Application of Dynamic Numerical Simulation to Investigate the Effects of Occupant Behaviour Changes in Retrofitted Buildings

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Abstract

The term *rebound effect* is commonly used in literature to identify the gap between the estimated and the real energy savings due to changes in the occupant behaviour after a building energy retrofit. In the present article, the rebound effect for some Italian residential building types is investigated through dynamic simulation. The energy efficiency measures determining the highest rebound effect are identified and discussed. The results point out that the major renovation generally leads to the highest benefits as the efficiency measures are mutually reinforced. In contrast, single measures may lead to the opposite goal of increasing the energy consumption.

Introduction

Rebound effect

The energy consumption of existing buildings is supposed to decrease after an energy refurbishment. Anyway several studies, like those of Haas and Biermayr (2000), and Ben and Steemers (2014), show that the energy performance of retrofitted buildings does not increase as much as it would be expected. A significant gap between the estimated and the real energy savings is revealed, due to changes in the occupant behaviour. Indeed, the increased efficiency of new technologies leads a reduction of the energy bill for the consumers that comes down to a reduction of the price of the energy services. This reduction consequently involves an increasing use of such a service or of other commodities that require energy use.

The term *rebound effect* commonly identify this phenomenon. During decades, several definitions of rebound effect have been provided in literature. Khazzoom (1980) firstly called "backfire" the failing of the mid-'70s regulations in reducing the energy consumption during the oil crises. Berkhout et al. (2000) expressed the rebound as a percentage of the energy efficiency improvement potential, predicted by the engineer, representing the lost part of the saving. Sorrell (2007) identifies the rebound effect as the energy efficiency elasticity of energy services. Moreover, other terms were coined, like "*take-back effect*" that was used by Herring and Roy (2007) to empathize the effect of the lower costs in energy services on the consumer behaviour, or "*prebound*" that identifies the gap between the calculated consumption and the actual values, highlighting that if no consumption occurs, no energy saving is possible (Sunikka-Blank and Galvin, 2012).

Objectives of the work

In the present article, the influence of the user behaviour on energy savings for some Italian residential building types is investigated. The rebound effect, defined as the difference between the expected and the actual post-retrofit energy savings taking account the occupant behaviour change, is determined through dynamic simulation.

As Galvin (2016) reminds, there are at least four different forms of rebound effect: direct, indirect, economy-wide and transformational. In the present paper, only the direct effects of the rebound are considered, i.e. when the consumer increases the energy services uses in the same sector in which he previously obtained a higher energy efficiency by means of a building retrofit.

The purpose of the work is to quantify the rebound effect for different residential building sizes and considering the most widespread Italian households. The energy performance, in terms of annual net energy needs for space heating and space cooling of the buildings, before and after the energy refurbishment, is assessed through dynamic simulation.

The rebound effect needs to be investigated, also in the prospective of the EU goal up to 2020, as energy savings lower than expected could betray the objectives of the national energy policies.

Simulation

Definition of users and occupant behaviour

According to Guerra Santin (2011), the socio-economic aspects that influence the user behaviour and the energy use in residential buildings are household size, age of occupants, education, income, main occupation. Starting from these variables, three types of households are defined (elderly single, young couple with children and adult couple with teenagers) according to statistics of the Italian population census carried out in 2011 (Italian National Institute of Statistics, 2011). The main characteristics of these households are reported in Table 1.

Table 1: Households characteristics.

# User	Description of family	N. of components	Age	Income	Education level	Ecological awareness	Building type
U_1	Elderly single	1	70	Low	Low	Low	Apartment block
U_2	Young couple with children	3 or 4	42, 38, 5, (2)	Middle	High	High	Multi-family house
U_3	Adult couple with teenagers	3 or 4	53, 48, 18, (16)	High	Middle	Middle	Single-family house

The occupancy parameters for each household type have been derived from national time use surveys, carried out since the late 1990s from the Italian National Institute of Statistics (ISTAT), according to the Harmonised European Time Use Survey (HETUS) project (Italian National Institute of Statistics, 2007). Another reference has been the ISO/DIS 18523-2 (International Organisation for standardisation, 2016).

The present paper examines three of the most common scenarios of household occupancy patterns in Italy:

- Scenario 1: the house is occupied all the day. This family consists of retired couples/single.
- Scenario 2: unoccupied period is from 09:00 to 16:00. The family of this type of household has children to look after when schools are closed.
- Scenario 3: unoccupied period is from 09:00 to 18:00. The occupants have full-time job.

The considered scenarios are representative of 65% of the Italian family units.

The occupancy pattern was taken separately for weekdays and weekends. The occupancy patterns influence the internal heat gain, the air change rate and the management of heating and cooling systems.

Figures 1 and 2 show the daily profiles (continuous lines) and the mean values (dashed lines) of the internal heat flow and of the air change rate respectively. The internal heat flow takes into account the presence of occupants and their activities, the use of domestic appliances and lighting in rooms and the preparation of meals. As regard the occupants, the internal heat gains are related to the most frequent activities, performed by each of them at home in the daytime, and to the gender and the age of the people, according to the literature (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2009). In the calculation, it is assumed that the maximum sensible heat gains from one adult male doing housework equals 90 W and the minimum sensible heat gains from one adult male sleeping is 50 W at 24 °C dry-bulb temperature. These values are adjusted assuming that the gain from an adult female is 85% of that from an adult male, and the gain from a child is 75% of that from an adult male. The internal heat gains due to domestic appliances and lighting are based on the data of the annual electricity use supplied by ISO 13790 (International Organisation for Standardisation, 2008) and on the typical hourly profile avaible in literature (Lubina and Nantka, 2008 and Yao and Steemers, 2005). Lastly, the internal heat gains produced during the preparations of the meals are based on national statical analyses about annual natural gas use for cooking. The air change rate is the sum of the natural ventilation rate and of the infiltration rate; the air change rate is maximum early in the morning and during cooking; in case of no occupancy, only the infiltrations are considered. Finally, there is a relationship between the occupancy patterns and the hourly profile of thermostat set point and set-back for heating and cooling systems.

The expectations of the occupants are specified before and after the retrofit according to the EN 15251 standard (European Committee for Standardization, 2007), which describes three levels of the indoor environmental parameters related to the building properties (new construction, renovation, existing building) and the occupant conditions (sick, children, elderly people). In the present study it was assumed that after the refurbishment the expectations of the occupants grow toward the next higher level of comfort. The parameters affected by the occupant expectations are: the temperature set point ($\theta_{H,set\ point}$) and the temperature set back for heating ($\theta_{H,set\ back}$), the temperature set point for cooling ($\theta_{C,set\ point}$), the daily period both for heating (d_H) and for cooling (d_C), the maximum (n_{max}) and the mean (n_{mean}) air change rate. According to the classification of the EN 15251 standard the user behaviour's variables are identified as listed in Table 2.

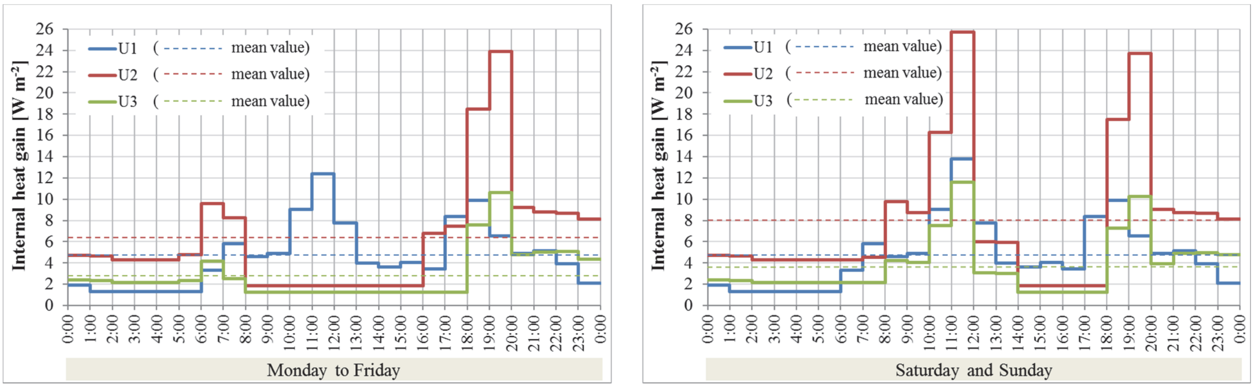

Figure 1: Daily profiles and mean values of the internal heat gain for weekdays (left) weekends (right).

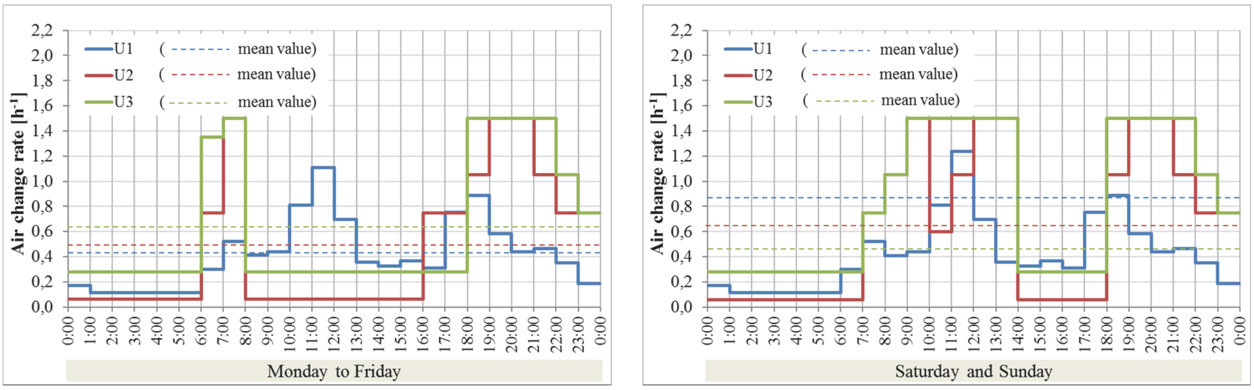

Figure 2: Daily profiles and mean values of the air change rate for weekdays (left) weekends (right).

Table 2: Actual user parameters in connection with energy refurbishment measures.

Parameter	Unit	WITHOUT REBOUND EFFECT			WITH REBOUND EFFECT											
					Thermal envelope insulation			Solar shading devices			Thermal system replacement			Major Renovation (nZEB)		
# User	-	U_1	U_2	U_3	U_1	U_2	U_3	U_1	U_2	U_3	U_1	U_2	U_3	U_1	U_2	U_3
$\theta_{H,set\ point}$	°C	21	18	20	22	20	21	21	18	20	22	20	21	22	20	21
$\theta_{H,set\ back}$	°C	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
d_H	h	14	13	14	14	13	14	14	13	14	14	13	14	14	13	14
n_{mean}	h^{-1}	0.42	0.50	0.59	0.50	0.59	0.70	0.42	0.50	0.59	0.50	0.59	0.70	0.50	0.59	0.70
n_{max}	h^{-1}	1.24	1.50	1.50	1.47	1.80	1.80	1.24	1.50	1.50	1.47	1.80	1.80	1.47	1.80	1.80
$\theta_{C,set\ point}$	°C	27	27	26	26	26	25.5	26	26	25.5	27	27	26	26	26	25.5
d_C	h	14	13	14	14	13	14	14	13	14	14	13	14	14	13	14

Case studies and energy efficiency measures

The analysed building types have been selected from the IEE-TABULA research project (Ballarini et al., 2014). They represent three building sizes, i.e. single-family house, multi-family house and apartment block, the construction period 1946–1960 and the Italian climatic zone having from 2100 to 3000 heating degree-days. These buildings were selected as they present a higher energy saving potential compared to buildings belonging to other construction periods, as highlighted in Ballarini et al. (2015) and Corrado et al. (2016b). The geometric and thermo-physical features of the case studies are shown in Table 3.

Table 3: Main data of the building types.

	Parameter	Symbol	Unit	BUILDING TYPE: Single-family house	BUILDING TYPE: Multi-family house	BUILDING TYPE: Apartment block
						
Geometric data	Gross conditioned volume	V_g	m^3	584	3076	5949
	Net floor area	$A_{f,net}$	m^2	162	827	1552
	Thermal envelope area	A_{env}	m^2	424	1576	2740
	Windows area	A_w	m^2	20.3	150	217
	Shape factor	A_{env}/V_g	m^{-1}	0.73	0.51	0.46
	Window to Wall Ratio	*WWR*	-	0.09	0.20	0.23
	Number of storeys	-	-	2	3	4
	Number of units	-	-	1	12	24
Construction data	Wall thermal transmittance	U_{wl}	W·m^{-2}K^{-1}	1.48	1.48	1.15
	Upper floor thermal transmittance	$U_{fl,up}$	W·m^{-2}K^{-1}	1.65*	1.65*	1.65*
	Lower floor thermal transmittance	$U_{fl,lw}$	W·m^{-2}K^{-1}	2.00	1.30*	1.30*
	Windows thermal transmittance	U_w	W·m^{-2}K^{-1}	4.90	4.90	4.90
	Total solar energy transmittance of glazing for normal incidence angle	$g_{gl,n}$	-	0.85	0.85	0.85
	Solar absorption coefficient of the external opaque surface	α_{sol}	-	0.60	0.60	0.60
* attached to an unconditioned space						

Table 4: U values [W·m^{-2}K^{-1}] of the energy refurbishment measures.

Energy efficiency measure	Parameter *	BUILDING TYPE: Single-family house	BUILDING TYPE: Multi-family house	BUILDING TYPE: Apartment block
Thermal envelope insulation (single efficiency measure)	U_{wl} (Δ%)	0.28 (-81%)	0.28 (-81%)	0.28 (-76%)
	$U_{fl,up}$ (Δ%)	0.27** (-84%)	0.27** (-84%)	0.27** (-84%)
	$U_{fl,lw}$ (Δ%)	0.29 (-86%)	0.58** (-55%)	0.58** (-55%)
	U_w (Δ%)	1.40 (-71%)	1.40 (-71%)	1.40 (-71%)
Thermal envelope insulation in major renovation (nZEB)	U_{wl} (Δ%)	0.26 (-82%)	0.26 (-82%)	0.26 (-77%)
	$U_{fl,up}$ (Δ%)	0.24** (-85%)	0.24** (-85%)	0.24** (-85%)
	$U_{fl,lw}$ (Δ%)	0.26 (-87%)	0.52** (-60%)	0.52** (-60%)
	U_w (Δ%)	1.40 (-71%)	1.40 (-71%)	1.40 (-71%)
* Δ% is calculated with respect to the existing state		** attached to an unconditioned space		

The following energy refurbishment measures are applied to the building types:

- thermal insulation of the building envelope,
- installation of solar shading systems, operating only in the cooling period when the hourly irradiance is greater than 300 W·m^{-2},
- replacement of the heat generator and improvement of the thermal system control,
- major renovation towards the nZEB target.

According to Italian legislation (Italian Ministry of Economic Development, 2015), major renovation is defined as the renovation of a building where more than 25% of the surface of the building envelope undergoes renovation. In this study major renovation includes the thermal insulation of the building envelope, the installation of solar shading devices, the thermal system replacement and the improvement of the thermal system control.

The properties of the above listed energy efficiency measures meet the requirements fixed by the Italian legislation (Italian Ministry of Economic Development, 2015). An example of requirement values for the building envelope components are listed in Table 4.

Calculation methodology and boundary conditions

The energy performance assessment of the building types was carried out by means of *EnergyPlus 8.5* and using the building geometry interface of *DesignBuilder*

5.0. The simulation engine is based on the air heat balance solution method. The following assumptions are done: the indoor air temperature of the thermal zone is uniform (perfect mixing), the surface temperature is uniform, the long and short-wave irradiation is uniform, the surfaces are perfectly diffusive and the heat conduction through the surface is one-dimensional. The indoor air heat balance is expressed as in Equation (1):

$$C_{\mathrm{ai}} \cdot \frac{dT_{\mathrm{ai}}}{d\tau} = \sum_{i=1}^{N} \Phi_{\mathrm{c,gn},i} + \sum_{i=1}^{N_s} h_{\mathrm{c},i} \cdot A_i \cdot \left(T_{\mathrm{s},i} - T_{\mathrm{ai}}\right) + \dot{m} \cdot c \cdot \left(T_{\mathrm{ae}} - T_{\mathrm{ai}}\right) + \Phi_{\mathrm{sys}} \tag{1}$$

The simulation was carried out with the climatic data of Milan, as it is the biggest city in the most populated Italian climatic zone (zone E, 2100 < HDD ≤ 3000). It has 2404 HDD. The average monthly temperature is 4.0 °C in January and 22.8 °C in July.

Indexes to quantify the rebound effect

The building energy performance (EP) was evaluated before (EP_{EB}) and after the implementation of the energy efficiency measure (EP_{REF}). The energy performance is expressed as the annual net energy need for space heating and space cooling of the building divided by the net conditioned floor area.

The influence of the occupant behaviour changes due to the retrofit has been investigated by considering the changes of the variables of the user behaviour after the refurbishment, when the occupant behaviour is affected by rebound ($EP_{\mathrm{REF,RB}}$).

In the present research, the rebound effect (RB) is defined as the difference between expected (ΔEP) and actual post-retrofit energy savings (ΔEP_{RB}), taking into account the occupants' behaviour change after the retrofit, in absolute terms, as shown in Equation (2).

$$\begin{aligned} RB &= \Delta EP_{\mathrm{REF}} - \Delta EP_{\mathrm{RB}} = \\ &= EP_{\mathrm{EB}} - EP_{\mathrm{REF}} - (EP_{\mathrm{EB}} - EP_{\mathrm{REF,RB}}) = \\ &= EP_{\mathrm{REF,RB}} - EP_{\mathrm{REF}} \end{aligned} \tag{2}$$

Two indexes, defined in Corrado et al. (2016a), are also used in the present work to quantify the rebound effect:

$$I_{\mathrm{RB,1}} = \frac{RB}{EP_{\mathrm{REF}}} = \frac{EP_{\mathrm{REF,RB}} - EP_{\mathrm{REF}}}{EP_{\mathrm{REF}}} \tag{3}$$

$$I_{\mathrm{RB,2}} = \frac{\Delta EP_{\mathrm{RB}}}{\Delta EP_{\mathrm{REF}}} = \frac{EP_{\mathrm{EB}} - EP_{\mathrm{REF,RB}}}{EP_{\mathrm{EB}} - EP_{\mathrm{REF}}} \tag{4}$$

$I_{\mathrm{RB,1}}$, calculated as in Equation (3), represents the rebound effect as fraction of the building energy performance post-retrofit without changes in occupant behaviour (EP_{REF}).

$I_{\mathrm{RB,2}}$, calculated as in Equation (4), estimates the percentage of the expected energy savings, which are not frustrated by the phenomenon of the rebound effect.

Results

Figures from 3 to 5 show the net energy performance for heating and cooling, before and after the energy retrofit of the selected reference buildings, with and without the occupant behaviour change. In case of multi-unit housing (i.e. multi-family house and apartment block), the results refer to a single apartment.

Before the refurbishment, the net energy need for heating is about 80-90 kWh·m^{-2}, while the net energy need for cooling is about 15-30 kWh·m^{-2}; the multi-family house shows lower $EP_{\mathrm{H,nd}}$ and higher $EP_{\mathrm{C,nd}}$ values due to the high internal heat gains (4 people) and solar heat gains (East-West orientation, high windows area, no shading devices).

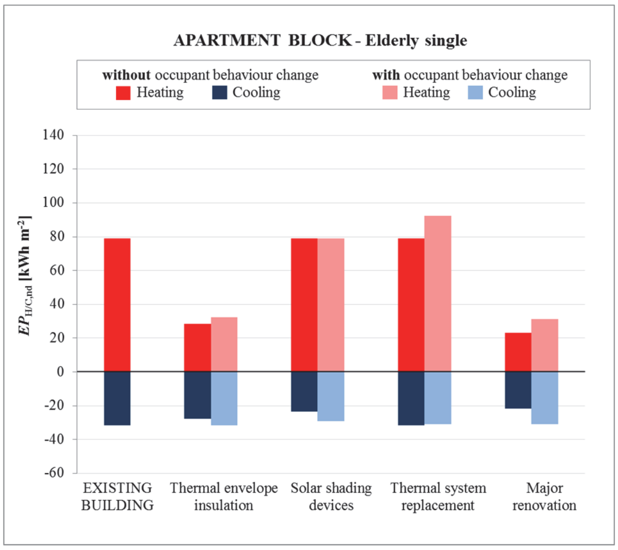

Figure 3: Net energy need for heating and cooling normalized by the conditioned floor area – User 1

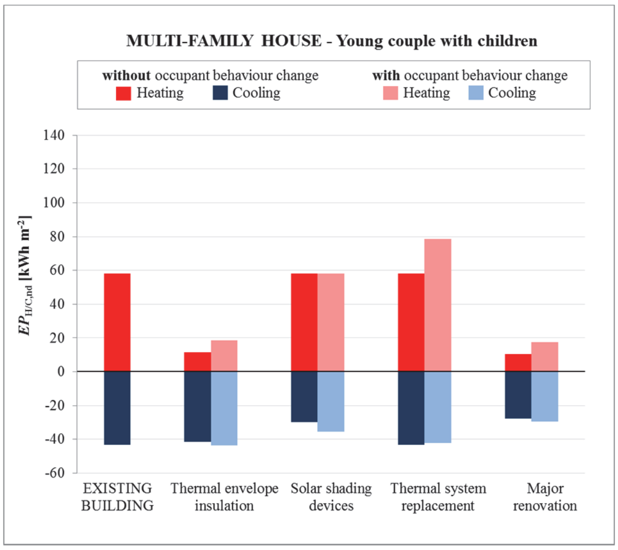

Figure 4: Net energy need for heating and cooling normalized by the conditioned floor area – User 2

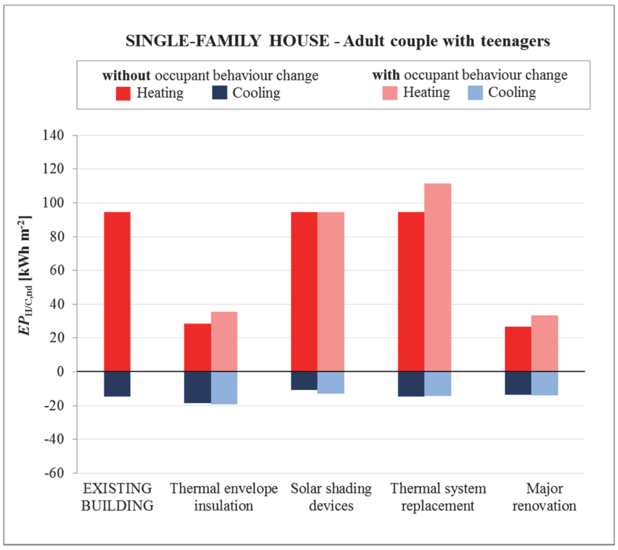

Figure 5: Net energy need for heating and cooling normalized by the conditioned floor area – User 3

The most effective retrofit measures are the thermal envelope insulation as regards the heating season, and the solar shading devices installation as regards the cooling season; the combined retrofit solutions in the major renovation allow to further reduce the net energy need, both for heating and cooling.

The thermal system replacement shows the highest deviation between the net energy need for heating respectively with and without change in the occupant behaviour; as regards the net energy need for cooling, the highest deviation refers to the solar shading devices installation.

In Table 5 the absolute rebound and the related indexes, as well as the real energy saving, for both the heating and the cooling season, are reported.

Table 5: Rebound effect and related indexes of the case studies.

Retrofit measures		Thermal envelope insulation			Solar shading devices			Thermal system replacement			Major renovation (nZEB)		
User ID		U_1	U_2	U_3	U_1	U_2	U_3	U_1	U_2	U_3	U_1	U_2	U_3
$\boldsymbol{RB_H}$	(kWh m^{-2})	4.15	7.35	6.98	-	-	-	13.61	20.49	16.99	8.28	7.08	6.68
$\boldsymbol{RB_C}$	(kWh m^{-2})	3.82	2.11	0.69	5.51	5.58	2.25	-	-	-	9.28	1.53	0.70
$\boldsymbol{\Delta EP_{RB,H}}$	(kWh m^{-2})	46.46	39.42	58.96	-0.07	-0.03	-0.02	-13.61	-20.49	-16.99	47.64	40.63	61.02
$\boldsymbol{\Delta EP_{RB,C}}$	(kWh m^{-2})	0.18	-0.45	-4.52	2.61	7.78	1.71	-	-	-	0.72	13.71	0.56
$\boldsymbol{I_{RB,1,H}}$	(%)	15%	65%	25%	0%	0%	0%	17%	35%	18%	36%	68%	25%
$\boldsymbol{I_{RB,1,C}}$	(%)	14%	5%	4%	23%	19%	21%	-	-	-	43%	5%	5%
$\boldsymbol{I_{RB,2,H}}$	(%)	92%	84%	89%	100%	100%	100%	-	-	-	85%	85%	90%
$\boldsymbol{I_{RB,2,C}}$	(%)	5%	-27%	118%	32%	58%	43%	-	-	-	7%	90%	44%

In Table 5, the negative values of the real energy saving ΔEP_{RB} mean that the retrofit measure is ineffective.

$I_{RB,1}$ indicates the increased energy consumption due to changes in the occupant behaviour after a building energy retrofit, with regard to the expected result. The highest values of this index refer to the refurbishment of the building towards the nearly zero-energy target; that means the higher the energy efficiency of the building, the higher is the importance of a correct management of the building.

$I_{RB,2}$ indicates the percentage deviation between the real and the expected energy saving, due to changes in the occupant behaviour after a building energy retrofit. The percentage of energy saving during the heating season that is frustrated by the occupants is around 10-15% when the retrofit measures concern the thermal envelope insulation. In contrast, values close to zero or negative refer to ineffective retrofit measures; that mainly happens in case of thermal envelope insulation with regard to the energy need for cooling.

Conclusion

The rebound effect, which is defined as the gap between the real and the expected energy saving due to the influence of the occupant behaviour on the energy consumption of retrofitted buildings, has been assessed for typical Italian residential buildings through dynamic simulation. Three types of households and their occupancy profiles have been defined according to statistics, literature and technical standards.

The results highlight that the change in the occupant behaviour might alter the effect of the energy efficiency measures on the building energy performance. In some cases, as for instance in case of thermal system replacement, the retrofit even determines an increment of the energy need for space heating compared to the situation before the refurbishment. This is due to a higher expectation of the user towards the thermal comfort, that determines higher indoor temperature and, consequently, higher ventilation rates in the heating season.

Therefore, the energy efficiency measures should be chosen accurately, as the energy savings might not be as high as expected. The results of this work point out that the major renovation generally leads to the highest benefits as the efficiency measures are mutually reinforced. In contrast, single measures may lead to the opposite goal of increasing the building energy consumption.

For every energy refurbishment measures, results show the same trend of the rebound regardless the considered users and building types.

In order to overcome the limitations related to the adoption of standard assumptions and to have more reliable user profiles, it is proposed to conduct further field surveys and targeted analyses.

Acknowledgement

This work springs from a research activity conducted in the project "Study of the elasticity of the buildings' energy consumptions", financed by RSE (Ricerca sul Sistema Energetico).

Nomenclature

Symbol	Quantity	Unit
A	area	m^2
C	heat capacity	$J\cdot K^{-1}$
c	specific heat	$J\cdot kg^{-1}K^{-1}$
d	duration, time	h
EP	energy performance	$kWh\cdot m^{-2}$
g	total solar energy transmittance (solar factor)	-
h	surface heat transfer coefficient	$W\cdot m^{-2}K^{-1}$
HDD	heating degree days	°C·d
I	index	-
$\dot{m}$	mass flow rate	$kg\cdot s^{-1}$
n	air change rate	h^{-1}
RB	absolute rebound effect	$kWh\cdot m^{-2}$
T	temperature	°C
U	thermal transmittance	$W\cdot m^{-2}K^{-1}$
V	volume	m^3
WWR	window to wall ratio	-
Greek symbols		
α	absorption coefficient	-
Δ	variation	-
θ	temperature	°C
τ	time	h
Φ	heat flow	W
Subscripts		
ae	external air	
ai	internal air	
C	space cooling	
c	convection	
EB	existing building	
env	building envelope	
f, fl	floor	
g	gross	
gl	glazing	
gn	gains	
H	space heating	
lw	lower	
n	normal	
nd	need (energy)	
RB	rebound effect	
REF	refurbishment	
sol	solar	
sys	thermal system	
up	upper	
w	window	
wl	wall	
Acronyms and abbreviations		
nZEB	nearly zero-energy building	
U	user	

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