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The Rebound Effect after the Energy Refurbishment of Residential Buildings towards High Performances

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ABSTRACT

In the last decades, governments worldwide have promoted energy efficiency improvements in order to reduce the building energy consumptions and CO_2 emissions.
In many geographical contexts, the largest and most cost-effective energy saving potential is in the existing housing stock renovation. For this reason, many energy efficiency policies are focused on the energy refurbishment of the existing buildings.
Though the energy consumption of buildings is supposed to decrease after a retrofit, several studies show that the energy performance does not increase as much as it would be expected and that a significant gap between the estimated and the real energy savings - called ñrebound effectò - occurs.
This deviation can partly depend on the model used for the energy performance evaluation, but changes in the occupantsô behavior after a thermal retrofit of an existing dwelling are also revealed.
The present paper examines the influences of occupant behavior on the energy savings for some retrofitted Italian residential representative buildings. Some typical use patterns are defined according to statistics of the national census of population and dwellings and the expectations of the building occupants are specified before and after the retrofit. The main objective is to investigate the elasticity of the energy consumption in function of the occupancy parameters before and after the application of high energy efficiency improvements.
The analysis is carried out by means of a simplified energy performance assessment model. The outcomes of this study consist in defining synthetic indicators for the quantitative assessment of the rebound effect.

1 INTRODUCTION

In the last decades, governments worldwide have promoted energy efficiency improvements in order to reduce the building energy consumptions and CO_2 emissions.
In many geographical contexts, as in Italy, the largest and most cost-effective energy saving potential is in the existing housing stock renovation. For this reason, many energy efficiency policies are focused on the energy refurbishment of the existing buildings.
Though the energy consumption of buildings is supposed to decrease after a retrofit, several studies show that the energy performance does not increase as much as it would be expected and that a significant gap between the estimated and the real energy savings - called ñrebound effectò ï occurs (Haas and Biermayr, 2000).
This deviation can partly depend on the model used for the energy performance evaluation (Tronchin and Fabbri, 2008), but changes in the occupantsô behavior after a thermal retrofit of an existing dwelling are also revealed (Oreszczyn *et al.*, 2006).
In the nineteenth century the rebound effect was identified in the so called ñJevons paradoxò, that pointed out the higher consumption of coal resulting from an increase of the efficiency of the steam engines. After the first oil shock in 1973-1974 and the resulting energy efficiency targets this notion revived and both the economists Khazzoom and Brookes, working independently, observed that in fact energy efficiency improvements, which were aimed to

produce savings in energy consumption, had the opposite effect and led to increase the consumption of energy services.
In the midst of the intense discussion among economists over the last two decades of the twentieth century the terms ñrebound effectò and ñbackfireò became mainstream in academic literature. ñBackfireò was the preferred term to describe the cases where energy efficiency improvements led to an increase in energy consumption, whereas ñrebound effectò came to be used to describe and quantify the shortfalls in expected energy savings.
By the mid-2000s a lot of definitions of the rebound effect and approaches to quantify this phenomenon were used in literature ever since, and some relevant differences in the values for the rebound effect were observed (Galvin, 2015). Among the others, Hans e Biermayr (2000) defined the rebound effect as the increase in energy demand which results from an increase in service demand due to decreasing prices for energy service. They quantified it for some retrofitted dwellings in Austria as the shortfall in energy savings as percentage of the expected energy savings.
According to the previous analysis of Greening *et al*. (2000), Sorrell and Dimitropoulos (2008) delineated the effects of the rebound in three categories, in economics terms: direct, indirect and economy-wide effects.
The present paper concerns the direct rebound effect according to which improved energy efficiency for a particular energy service will decrease the effective price of that service and should therefore lead to an increase in consumption of that service. In terms of occupantsô behavior, the direct rebound effect can be exemplified as follows: occupants take back the benefits of energy savings after a thermal retrofit as improved thermal comfort (e.g. higher indoor temperature, more hours of heating).
In the same way Herring and Roy (2007) used the term rebound effect to describe the effect that the lower costs in energy services has on consumer behavior, due to the increased energy efficiency. They also called this phenomenon ñtake-back effectò because of consumers take back some of the energy savings due to the improved energy efficiency in the form of higher levels of energy services.
Hens *et al.* (2010) estimated the rebound effect in some residential buildings by dividing the difference between the calculated reference consumption and the normalized measured consumption by that reference. References were estimated using the methodology imposed by the energy performance regulation, based on EN ISO 13790.
Sunikka-Blank and Galvin (2012) clarified the different impact of the occupant behavior on the energy consumption of buildings before and after the refurbishment and highlighted that the rebound effect occurs when a proportion of the energy savings after a retrofit is consumed by additional energy use.
Furthermore, Galvin (2014) identified the classic definition of the rebound effect as the energy efficiency elasticity of energy consumption and two further definition of the rebound effect, which can be useful when there is not enough information to calculate an elasticity rebound effect. Galvin named these two further definitions as follows:

- energy performance gap: the ratio between over-consumption and expected consumption;
- energy savings deficit: shortfalls in energy savings as a proportion of expected energy savings.

In the present research, the rebound effect is defined as the difference between expected and actual post-retrofit energy savings taking account of the occupantsôbehavior change after a retrofit, in absolute terms.
The influence of the occupant behavior on the energy savings for some retrofitted Italian residential representative buildings is examined. Some typical use patterns are defined according to statistics of the national census of population and dwellings and the expectations of the building occupants are specified before and after the retrofit. The main objective is to investigate the elasticity of the energy consumption in function of the occupancy parameters before and after the application of high energy efficiency measures.

2 METHODOLOGY

It is generally recognized in literature that user behavior is related to some building properties, for instance period of construction, roof insulation, wall type and required energy consumption to maintain a steady state temperature (Oreszczyn *et al.*, 2006). Moreover, it is observed that occupant behavior changes after retrofitting and that this change is related to the adoption of energy efficiency measures (Oreszczyn *et al.*, 2006).
For this reason, in the present research it is defined a rebound correlation matrix among energy efficiency measures, energy services and user parameters as shown in Figure 1.
Each energy efficiency measure has an influence on the consumptions related to one or more energy services and at the same time each energy service is related to one or more parameters that the user can control according to his preferences (e.g. temperature set point for heating and cooling, ventilation rate). These parameters can change after retrofitting if a rebound effect occurs.

ENERGY SERVICES: Heating	Cooling	Domestic Hot Water	Ventilation	Lighting	ENERGY EFFICIENCY MEASURES	
X	X				External wall insulation	Thermal envelope insulation
X	X				Wall vs. unconditioned spaces insulation	Thermal envelope insulation
X	X				Roof insulation	Thermal envelope insulation
X	X				Floor insulation	Thermal envelope insulation
X	X				Window replacement	Thermal envelope insulation
	X			X	Solar shading devices	Solar control
X					Heat recovery unit	Ventilation heat recovery
X					Room temperature PI-controller	Improving heating control
	X				Chiller	Installation of high effiiciency generator
X					Space heating generator	Installation of high effiiciency generator
		X			DHW generator	Installation of high effiiciency generator
X		X			Combined heating and DHW generator	Installation of high effiiciency generator
X	X	X			Heat pump for heating, DHW and cooling	Installation of high effiiciency generator
		X			Thermal solar system	Energy form renewable sources
(*)	X	(*)		X	PV system	Energy form renewable sources
				X	High efficiency luminaries	Improving lighting efficiency
				X	Automatic lighting control	Improving lighting efficiency

Heating	Cooling	Domestic Hot Water	Ventilation	Lighting	USER PARAMETERS
X					Temperature set point for heating
X					Temperature set back for heating
X					Daily heating period
X			X		Ventilation rate
	X				Temperature set point for cooling
	X				Daily cooling period
		X			Daily water consumption
				X	Daily lighting period

(*) in presence of heat pumps

Figure 1: Rebound correlation matrix among energy efficiency measures, energy services and user parameters

In order to investigate the influence of occupant behavior changes, the building energy consumption was evaluated after the implementation of the the same energy efficiency measure by considering the variables of the user behavior both before and after the refurbishment, when the occupant behavior is affected by rebound.

In the present research, the rebound effect is defined as the difference between expected (ΔEP) and actual post-retrofit energy savings (ΔEP_{RB}) taking account of the occupants' behavior change after a retrofit, in absolute terms as listed in equation (1).

$$RB = \Delta EP - \Delta EP_{RB} = EP_{EB} - EP_{REF} - (EP_{EB} - EP_{REF,RB}) = EP_{REF,RB} - EP_{REF} \quad (1)$$

Inspired by Galvin's analysis (2014), the follow indicators, based on rebound effect and estimated energy savings, were determined:

- $I_{RB,1}$ represents the size of the rebound effect as proportion of the building energy performance after retrofit without changes in occupant behavior, as expressed in equation (2):

$$I_{RB,1} = \frac{RB}{EP_{REF}} = \frac{EP_{REF,RB} - EP_{REF}}{EP_{REF}} \quad (2)$$

- $I_{RB,2}$ estimates the percentage of the expected energy savings, which are not frustrated by the phenomenon of the rebound effect, as formulated in equation (3):

$$I_{RB,2} = \frac{\Delta EP_{RB}}{\Delta EP} = \frac{EP_{EB} - EP_{REF,RB}}{EP_{EB} - EP_{REF}} \quad (3)$$

3 CALCULATION

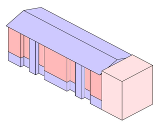
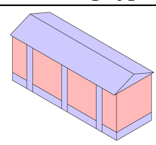
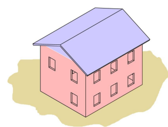
3.1 Case studies

According to academic literature, the occupant behavior is influenced by a whole string of variables such as user characteristics, lifestyle, personal background and perception of comfort (Guerra Santin, 2011).
In accordance with previous studies, the user characteristics that could affect the building energy use are: household size, age of occupants, education, income, main occupation (Guerra Santin, 2011).
In order to define some typical occupants, the statistics of the last Italian census of population and dwellings were analyzed. Some of the resultant typical householders are presented in Table 1. Each user was then related with a specific building typology for his characteristics. The pictures and the main geometrical and technological data of the building type are shown in Table 2.

Table 1: Household characteristics

# User	Description of family	N. of components	Age	Income	Education level	Ecological awareness	Building typology
U1	Elderly single	1	70	Low	Low	Low	Apartment blocks
U2	Young couple with children	3 or 4	42, 38, 5, (2)	Middle	High	High	Multi-family house
U3	Adult couple with teenagers	3 or 4	53, 48, 18, (16)	High	Middle	Middle	Single-family house

Table 2: Main data of the buildings

				Building type		
				 Apartment blocks (AB)	 Multi-family house (MF)	 Single-family house (SF)
Geometry	Whole building	V_g	(m^3)	5949	3076	584
		$A_{f,n}$	(m^2)	1552	827	162
		A_{env}/V_g	(m^{-1})	0.46	0.51	0.73
		A_w	(m^2)	217	150	20.26
		no. of floors	(ï)	4	3	2
		no. of units	(ï)	24	12	1
Construction	Opaque envelope	U_{wl}	(W m^{-2}K^{-1})	1.15	1.48	1.48
		$U_{wl,u}$	(W m^{-2}K^{-1})	2.32	1.70	-
		$U_{fl,up}$	(W m^{-2}K^{-1})	1.65	1.65	1.65
		$U_{fl,lw}$	(W m^{-2}K^{-1})	1.30	1.30	2.00
	Windows	U_w	(W m^{-2}K^{-1})	4.90	4.90	4.90
		$g_{gl,n}$	(ï)	0.85	0.85	0.85
Technical systems efficiency (mean yearly/seasonal values)	Radiators	$\eta_{H,e}$	(ï)	0.90	0.90	0.88
	Room temperature control	$\eta_{H,c}$	(ï)	0.85	0.85	0.85
	Central distribution	$\eta_{H,d}$	(ï)	0.901	0.889	0.876
	Natural gas standard generator	$\eta_{H,gn}$	(ï)	0.85	0.85	0.85
	Electric water heater	$\eta_{W,gn}$	(ï)	0.75	0.75	0.80
	Indoor units split systems	$\eta_{C,e}$	(ï)	0.97	0.97	0.97

The reference existing buildings were selected among those included in the Italian National Building Typology of the IEE-TABULA research project (Ballarini *et al*., 2014), as belonging to the age class ranging from 1946 to 1960. The location of the buildings is Milan (Italy, 2404 HDD): this city belongs to the climatic zone (E), which includes most of the municipalities and of the Italian population.

The energy efficiency measures applied to the reference buildings were gathered in four packages: thermal envelope insulation, installation of solar shading devices, replacement of the generator for space heating and domestic hot water, and the building transformation into nZEB, as defined by the national and European legislation (European Directive 2010/31/EU).

The above-mentioned packages include the following energy efficiency measures:

a) insulation of the opaque envelope enclosing the heated space, replacement of the existent windows with new ones with double low-e glass and PVC frame, improvement of heating control with room temperature PI-controllers,
b) installation of external movable solar shading devices,
c) replacement of natural gas standard generator for space heating and electric water heater with a condensing boiler and installation of room control temperature PI-controllers,
d) insulation of the opaque envelope, replacement of the existent windows with new ones with double low-e glass and PVC frame, improvement of the heating control with new room temperature PI-controllers, replacement of the natural gas generator for space heating and electric water heater with a heat pump for heating, DHW and cooling (and associated radiant panels), installation of PV panels.

Each energy efficiency measure was identified by an appropriate parameter (e.g. *U*-value of the building envelope component, efficiency of the heat generator) and its value meets the requirements fixed by the Italian legislation in force (Ministerial Decree of 26 June 2015). The packages of the energy efficiency measures applied to the case studies are listed in Table 3.

Table 3: Energy efficiency measures and options

Retrofit measures	*Existing building*			Thermal envelope insulation*			Solar shading devices			Thermal system*			Major renovation		
Building type	AB	MF	SF	AB	MF	SF	AB	MF	SF	AB	MF	SF	AB	MF	SF
U_{wl} (W m^{-2}K^{-1})	*1.15*	*1.48*	*1.48*	0.28	0.28	0.28	*1.15*	*1.48*	*1.48*	*1.15*	*1.48*	*1.48*	0.26	0.26	0.26
$U_{wl,u}$ (W m^{-2}K^{-1})	*2.32*	*1.70*		0.56	0.47		*2.32*	*1.70*		*2.32*	*1.70*		0.58	0.43	
$U_{fl,up}$ (W m^{-2}K^{-1})	*1.65*	*1.65*	*1.65*	0.27	0.27	0.27	*1.65*	*1.65*	*1.65*	*1.65*	*1.65*	*1.65*	0.24	0.24	0.24
$U_{fl,lw}$ (W m^{-2}K^{-1})	*1.30*	*1.30*	*2.00*	0.58	0.58	0.29	*1.30*	*1.30*	*2.00*	*1.30*	*1.30*	*2.00*	0.52	0.52	0.26
U_w (W m^{-2}K^{-1})	*4.90*	*4.90*	*4.90*	1.40	1.40	1.40	*4.90*	*4.90*	*4.90*	*4.90*	*4.90*	*4.90*	1.40	1.40	1.40
τ_{sol} (ï)	-	-	-	-	-	-	0.57	0.55	0.55	-	-	-	0.30	0.20	0.30
$\eta_{H,c}$ (ï)	*0.85*	*0.85*	*0.85*	0.995	0.995	0.995	*0.85*	*0.85*	*0.85*	0.995	0.995	0.995	0.995	0.995	0.995
EER (ï)	*2.35*	*2.35*	*2.35*	*2.35*	*2.35*	*2.35*	*2.35*	*2.35*	*2.35*	*2.35*	*2.35*	*2.35*			
$\eta_{H,gn}$, COP_H (ï)	*0.85*	*0.85*		*0.85*	*0.85*		*0.85*	*0.85*		1.10	1.10				
$\eta_{W,gn}$, COP_W (ï)	*0.75*	*0.75*		*0.75*	*0.75*		*0.75*	*0.75*		0.95	0.95				
$\eta_{H+W,gn}$, COP_{H+W} (ï)			*0.80*			*0.80*			*0.80*			1.10			
EER; COP_{H+W} (ï)													2.50; 3.00	2.50; 3.00	2.50; 3.00
$W_{PV,p}$ (kW)													25	10	3
*plus improved heating system control															

The user behavior is characterized by the parameters that influence the energy uses and that can be controlled by the occupants. The value of these parameters was defined in accordance with the level of occupantsô expectation and the household characteristics. The European Standard EN 15251 (2007) specifies the values of the indoor environmental parameters for three categories of expectation according to the building properties (new construction, renovation, existing building) and the occupants conditions (sick, children, elderly people).
Combining the household characteristics with the typical level of expectation of each category, the user behaviorôs variables were identified as listed in Table 4.

Table 4: User parameters in connection with retrofit measures

Retrofit measures	*Existing building*			Thermal envelope insulation*			Solar shading devices			Thermal system*			Major renovation		
User ID	U1	U2	U3	U1	U2	U3	U1	U2	U3	U1	U2	U3	U1	U2	U3
$\theta_{\mathrm{H,set\ point}}$ (°C)	*21*	*18*	*20*	22	20	21	21	18	20	22	20	21	22	20	21
$\theta_{\mathrm{H,set\ back}}$ (°C)	*16*	*16*	*16*	16	16	16	16	16	16	16	16	16	16	16	16
d_{H} (h/d)	*14*	*13*	*14*	14	13	14	14	13	14	14	13	14	14	13	14
n (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
$\theta_{\mathrm{C,set\ point}}$ (°C)	*27*	*27*	*26*	26	26	25.5	26	26	25.5	27	27	26	26	26	25.5
d_{C} (h/d)	*14*	*13*	*14*	14	13	14	14	13	14	14	13	14	14	13	14
V_{DHW} (l/d unit)	*30*	*175*	*245*	30	175	245	30	175	245	50	245	438	50	245	438
*plus improved heating system control															

3.2 Calculation options and boundary conditions

The energy performance of the case studies was calculated by means of the quasi-steady-state calculation method, as specified by the Italian technical specification UNI/TS 11300, based on the standard EN ISO 13790. To determine the net energy need for space heating and cooling, it analyses the steady state balance of heat losses (transmission and ventilation) and of heat gains (solar and internal) evaluated in average monthly conditions. The dynamic effects on the net heating and cooling energy needs are considered by introducing dynamic parameters, such as the utilization factors, that accounts for the mismatch between transmission plus ventilation heat losses and solar plus internal heat gains; and an adjustment of the set point temperature for intermittent heating/cooling or set-back.
According to the calculation model, the following assumptions and simplifications were applied:

- climatic data of Milan obtained from the national technical standard UNI 10349-1 (2016),
- simplified approach to calculate internal heat gains, building internal heat capacity, temperature of unconditioned spaces, according to the assumptions defined in the Italian technical specifications UNI/TS 11300-1 (2014),
- value of shading reduction factor for external obstacles fixed at 0.8,
- simplified calculation of the mean monthly values of the technical subsystem efficiencies,
- primary energy factors fixed at 2.42 (1.95 non-renewable plus 0.47 renewable) for electricity, at 1.05 for fossil fuels (entirely non-renewable), at 1.00 for both electricity from photovoltaic system and heat energy from outdoor with heat pump (completely renewable in both cases).

3.3 Results and discussion

From Figure 2 to Figure 7 the net energy need for space heating and cooling and the non-renewable primary energy normalized by the heated floor area are shown for the considered case studies. In each figure the existing building is compared with the different retrofit options, both with and without the rebound effect.
Results show that the major renovation toward the nearly zero-energy target reach the lowest non-renewable primary energy consumption, but also that the thermal insulation of the envelope is a very efficient retrofit measure when the building stock is characterized by high *U*-values.
Considering the rebound effect, the net energy need for space heating decreases of about 70-75% either after the thermal envelope insulation or the building transformation into nZEB, for all the analyzed users; anyway, the energy savings would be 5-10% higher without considering a change in the user behavior after the retrofit. The replacement of the heat generator for space heating and domestic hot water causes 10-30% increase of the net energy need for

space heating, due to a different user behavior in the set-point temperature control and in the ventilation of the building. As regards the net energy need for cooling and considering the rebound effect, the results are not so uniform among the different users and the considered packages of measures: for user 1 and user 2, the thermal envelope insulation makes worse the cooling energy performance on the order of 25-40%; for user 3, the same retrofit measures provide energy savings of about 10% in the cooling period. The reduction of the net energy need for cooling would be significant (about 25-30%) after the installation of solar shading devices, but the changes in the user behavior after the retrofit frustrate it almost completely. The major renovation determines the decrease of the net energy need for cooling for all the users but especially for the user 2 and the user 3 on the order of 25-45%.
As concerns the non-renewable global primary energy, the energy savings result considerable for all the users after the thermal envelope insulation (45-70%) and the building upgrading into nZEB (80-85%), whereas they are limited after the adoption of thermal system retrofit measures singularly (10-20%). On the contrary after the installation of solar shading devices, the non-renewable global primary energy slightly increases (2%). As far as the energy services are concerned, the non-renewable primary energy for space heating is the most sensitive at the analyzed retrofit actions.

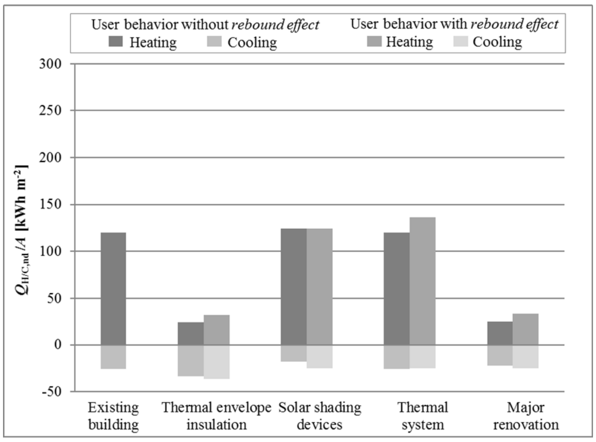


Figure 2: Net energy need for heating and cooling normalized by the heated floor area ï User 1

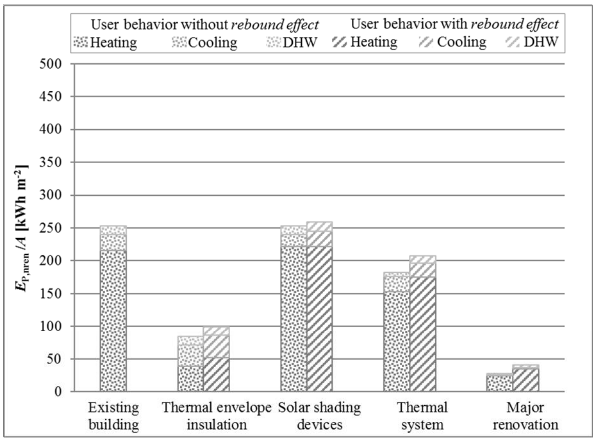


Figure 3: Non-renewable primary energy normalized by the heated floor area ï User 1

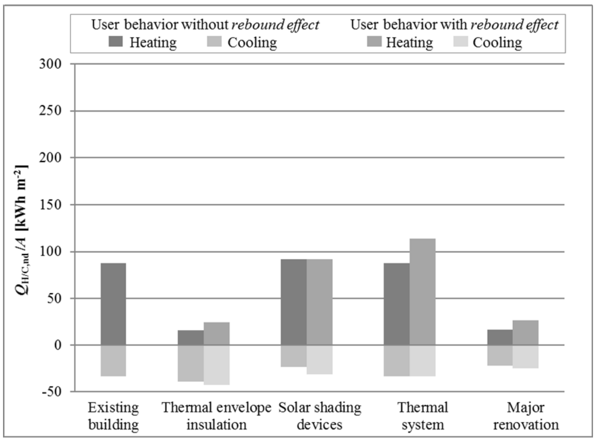


Figure 4: Net energy need for heating and cooling normalized by the heated floor area ï User 2

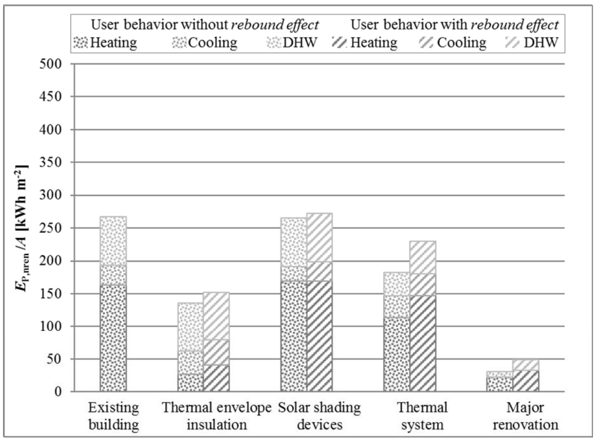


Figure 5: Non-renewable primary energy normalized by the heated floor area ï User 2

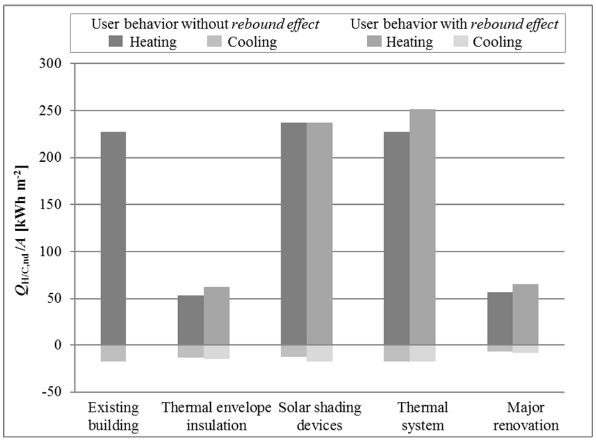


Figure 6: Net energy need for heating and cooling normalized by the heated floor area ï User 3

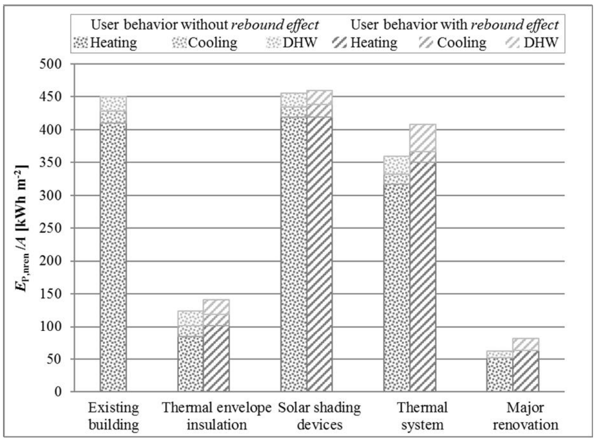


Figure 7: Non-renewable primary energy normalized by the heated floor area ï User 3

The rebound effect and the rebound indicators of the case studies are presented in Table 5.
The highest values of the index $I_{RB,1}$ stress that significant energy savings only occur when a major renovation into a nearly zero-energy building is considered.
Looking to the values of the index $I_{RB,2}$, the gap between the real and the expected energy saving is higher for retrofit measures concerning the thermal systems (35-55%). On the opposite, when the energy efficiency improvements concern the thermal envelope insulation or both the envelope and the thermal systems, approximately 10% of expected energy savings are frustrated by the rebound effect.
Moreover, the single installation of solar shading devices is always inefficient: the energy savings thanks to solar shading devices are little or donôt come true given that the energy savings due to lower solar gains during cooling period are frustrated by the higher heating demand due to lower solar gains during heating period. In this context, the higher expectations of the occupant after the retrofit can determine negative values of ΔEP_{RB}.

Table 5: Energy efficiency measures and options

Retrofit measures	Thermal envelope insulation*			Solar shading devices			Thermal system*			Major renovation		
User ID	U1	U2	U3	U1	U2	U3	U1	U2	U3	U1	U2	U3
RB (kWh m^{-2})	14.79	16.52	17.36	6.03	6.59	4.13	25.05	47.21	48.87	12.57	17.59	19.18
ΔEP_{RB} (kWh m^{-2})	154.16	114.89	309.51	*-5.60*	*-4.67*	*-9.43*	45.91	37.87	42.30	212.79	218.94	369.06
$I_{RB,1}$ (%)	17.5%	12.2%	14.0%	2.4%	2.5%	0.9%	13.7%	25.9%	13.6%	44.9%	57.1%	30.8%
$I_{RB,2}$ (%)	91.2%	87.4%	94.7%	*-1297.4%*	*-243.7%*	*177.8%*	64.7%	44.5%	46.4%	94.4%	92.6%	95.1%
*plus improved heating system control												

4 CONCLUSIONS

The present work aims to investigate the ñrebound effectò, defined as the gap between the real and the expected energy saving due to the influence of the occupant behavior on the energy consumption of retrofitted buildings.
For this purpose, three typical users and associated Italian building types were considered, and the expectations of the building occupants were modeled before and after the retrofit.
A correlation matrix among the energy efficiency measures adopted in the refurbishment process, the energy services and the user parameters affected the building energy consumption (e.g. temperature set point for heating and cooling, ventilation rate) was defined. Finally, two indexes ($I_{RB,1}$ and $I_{RB,2}$) were used in order to estimate the real energy saving due to the application of some retrofit measures, and the influence of the modified behavior of the occupants on the energy consumption after the building refurbishment.
The results show that the energy efficiency measures lead to the highest benefits when these are mutually reinforced, that is the case of the major renovation into a nZEB. In contrast, single energy efficiency measures may lead to the

opposite goal of increasing the energy consumption of the building, that is the case of the solar shading devices installation.
Moreover, the results point out that the rebound effect does exist: it especially occurs when the users modify their behavior in favor of a higher thermal comfort as a result of the thermal system renovation (35-55%), while in case of the major renovation of the building toward the nearly zero-energy target, the rebound effect decreases to the 10%.

NOMENCLATURE

A	area	(m^2)
COP	coefficient of performance	(ï)
E	energy	(kWh)
EER	energy efficiency ratio	(ï)
EP	energy performance	(kWh m^{-2})
g	total solar energy transmittance	(ï)
HDD	heating degree days	(°C d))
n	ventilation rate	(h^{-1})
I	indicator	(-)
Q	quantity of heat	(kWh)
RB	absolute rebound effect	(kWh m^{-2})
U	thermal transmittance	(W $m^{-2}K^{-1}$)
V	volume	(m^3)
W	power	(kW)
Δ	variation	(ï)
η	efficiency	(ï)

Subscript

C	cooling
c	control (subsystem)
d	distribution (subsystem)
e	emission (subsystem)
env	envelope
EX	existing building
f	floor
fl	slab
g	gross
gl	glass
gn	generation (subsystem)
H	heating
lw	lower
n	normal
nd	need (energy)
nren	non-renewable (energy)
P	primary (energy)
p	peak (PV system)
PV	photovoltaic (system)
RB	rebound effect
REF	refurbished
sh	solar shading
u	unheated
up	upper
W	domestic hot water
w	window
wl	wall

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