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Energy performance gap in refurbished German dwellings: Lesson learned from a field test

Davide Calì*, Tanja Osterhage, Rita Streblow, Dirk Müller

RWTH Aachen University, E.ON Energy Research Center, Institute for Energy Efficient Buildings and Indoor Climate, Mathieustr. 10, 52074 Aachen, Germany

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ABSTRACT

Low insulation standards and obsolete heating systems of a large amount of buildings in Europe account for disproportional energy consumption. Within this project, the holistic renovation and the results from the monitoring activity of buildings from a field test, located in Southern Germany, are presented. The buildings, built at the end of the 1950s, have been retrofitted with seven different refurbishment layouts. The layouts differ in insulation and engineering system. An installed monitoring system collects thermal indoor environmental conditions and air quality conditions in rooms, as well as data about energy flows at delivery, distribution, storage and generation level, at high time resolution. The monitoring system allows a comparison between the real and the expected energy consumption of the buildings. The energy performance gap was identified and quantified for each refurbishment solution (with values up to 287% based on calculated savings): on average, the energy performance gap of the entire field test varied from 117% in 2011, 107% in 2012, 41% in 2013 and 60% in 2014. The occupants' behavior has been identified as one of the causes for the energy performance gap. Further causes are mistakes in the installation, and malfunctioning of the engineering system. The importance of a monitoring system for buildings with a complex engineering system was confirmed.

1. Introduction

The real energy consumption of buildings often differs significantly from the expected, calculated consumption, even if this is obtained using advanced, complex dynamic building energy performance simulation software. This phenomenon is well known and has been recently identified as the "Energy Performance Gap" [1] (EPG). In addition, the tendency of users of determinate products, to increase needs and elevate expectations when technology improvements are reached, is called "Rebound Effect".

The term "Rebound Effect", also known in the literature as the "Jevons Paradox", was coined by William Stanley Jevons and used in his book "The Coal Question: An Enquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal-mines" [2] already in the middle of the nineteenth century. In his book, Jevons asserts: "It is wholly a confusion of ideas to suppose that the economic use of fuel is equivalent to a diminished consumption. The very contrary is the truth".

A detailed discussion about the rebound effect and its impact on society, as well as a literature review of the rebound effect since Jevons definition, can be found in Polimeni et al. [3]. In general, the rebound effect distinguishes between direct and indirect. The direct rebound effect implies that an energy service becomes more efficient and therefore cheaper for a user, hence this service will be in higher demand than before. The indirect rebound effect implies that a user saves money for a certain energy service that became cheaper thanks to a technology development that makes this service more efficient. The user therefore utilizes the saved money for a new service that also requires energy. Within this work only the direct rebound effect is of interest.

A first use of the concept of the direct rebound effect for the building sector, as well as the introduction of the index "rebound share", was proposed by Haas et al. [4,5]. In their work, the authors defined (1):

$$Rebound\ Share = \frac{100\,(Calculated\ \ savings - Actual\ \ savings)}{Calculated\ \ savings}\% \qquad (1)$$

The "calculated savings" of Eq. (1) express the amount of saved energy through a specific efficiency change in an existing building; however, in their works, the authors do not specify how this term should be calculated. There are two options to estimate this value, since this can be calculated as:

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* Corresponding author.
E-mail address: dcali@eonerc.rwth-aachen.de (D. Calì).

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- the difference between the calculated consumption before the retrofit and the calculated consumption after the retrofit,
- the difference between the measured consumption before the retrofit and the calculated consumption after the retrofit.

Furthermore, the use of the term “Rebound” is critical: in literature [1,3], the rebound is mainly connected to a change (direct or indirect [6]) of user behavior. But the definition in Eq. (1) does not distinguish whether the gap between expectations and observation is really caused by a change in behavior or by failures of the engineering system. This index could hence rather be called “energy saving deficit” (ESD), as proposed by Galvin [1], or “unachieved energy conservation share” as proposed by Haas and Biermayr [4] (see Section 3.3).

Evidence of the energy performance gap for new or retrofitted buildings is presented in the literature since the end of the 1990s, when Haas et al. [5] identified a gap between predicted (expected) and observed energy performances of buildings. The authors based their analysis on observations of about 400 retrofitted dwellings, and concluded that the rebound share, due to the retrofit, was between 15 and 30%. Two years later, Haas and Biermayr [4] calculated this index for approximately 500 dwellings, finding a rebound share between 20 and 30%. In both studies, the authors mainly concluded that “energy savings achieved in practice (and thus the reduction in CO_2 emissions) due to building retrofit measures will be lower than those calculated in engineering conservation studies”.

Based on a field test data analysis of the German Energy Agency (DENA), Erhorn [7] showed a discrepancy of up to 300% between calculated and observed energy consumption for residential buildings.

More recently, Tronchin and Fabbri [8] tested three different computational methods to calculate the energy consumption of a single-family house located in Italy, and showed consistent differences between the predictions and the real consumption. They also pointed out that different calculation methods (static and dynamic) may lead to very different results.

Hens [9] illustrated the results of a “step-wise” retrofitting of the end of a row house located in Belgium, built in 1957 and monitored since 1978. For each retrofit action on the building (a.o. insulation, new windows, solar boiler) the author compared its calculated and its monitored energy performance and concluded that:

- the measured data show a net decrease of energy consumption by each improvement/retrofit,
- the decrease in energy consumption is consistently lower than predicted,
- wall insulation, new windows and better air tightness generate higher benefits than solar boiler and photo-voltaic panels.

Hens et al. [10] compared the observed and the calculated energy consumption of 964 dwellings finding a consistent discrepancy between expectations and observations.

In 2012 Sunnika-Blank and Galvin introduced the term “Prebound effect” [11] to evaluate the discrepancy between observed and calculated consumption of existing non-retrofitted buildings: they noted that the existing, not refurbished building stock, tends to consume less energy than expected (evaluating the buildings through calculation methods used for the energy pass certification procedures). They therefore advised scientists and policy makers that, when calculating the benefits of a retrofit of the existing building stock, the real consumption of non-retrofitted buildings should be used as a reference figure, instead of the calculated one. They argue that it is not possible to make energy savings, on energy that has not been consumed previously (before the retrofit).

Menezes et al. [12] analyzed the gap for a new office building, after what they called “a twelve month liability period” (they used the first year to optimize the building performance and reduce rough failures of the engineering system). They concluded that “There is significant evidence that buildings do not perform as well as predicted”.

Dall’O et al. [13] compared the observed and expected (based on the calculation from energy pass certification procedures) consumption of 196 similar apartments in two residential “new high performance” buildings. They conclude that the consumption data are not homogeneous (due to occupants’ behavior) and observed consumption may be higher than calculated.

Galvin [1] compared several studies on the rebound effect in the building sector concluding that there is no shared approach among scientists for evaluating building performances and discrepancies between observations and expectations. He also noted that in some of the analyzed literature, “rebound indexes” computed with different approaches were wrongly compared between each other. Further, the author introduced new indexes and new calculation methods to evaluate the discrepancies between observations and expectations and to compute the rebound effect.

deWilde [14] proposes a framework for investigation of the gap between predicted and measured performances of buildings and offers a relevant literature review on the topic. His pilot study showed that “the performance gap changes with external conditions (example given: outdoor temperature), and with the temporal resolution of the energy measure in use” (i.e. if the collected data are annual based or have a higher time resolution).

Further studies confirm the existence of a gap between expected and observed energy performances for cooling systems [15,16], heating systems and domestic hot water engineering systems [17–19].

In a nutshell, it can be concluded that previous studies confirm the presence of a gap between expected and observed energy performances of new and retrofitted buildings. This gap is caused by engineering systems that are not performing as expected, and by occupants’ behavioral issues.

Within this work, the refurbishment of a field test with three demonstration buildings with 30 apartments each is described. The buildings have been retrofitted with different strategies and are monitored since 2011 in high time resolution.

The objectives of this work are:

1. Discuss existing indexes and define new indexes to evaluate the performances of both new and refurbished buildings;
2. Based on the collected data, verify the existence of the energy performance gap for the demonstration buildings and quantify this;
3. Evaluate the level of success of each retrofit layout (based on the analysis of the primary energy consumption of the buildings);
4. Evaluate the causes for the identified energy performance gap;
5. Analyze occupants’ diversity in big apartment buildings.

The description of the buildings and of the monitored system is presented in Section 2. In Section 3 the methods for the evaluation of the buildings’ retrofit are illustrated, and in Section 4 the results are explained and commented. Finally, the reasons for the gap between observations and expectations are analyzed and discussed.

2. Description of the demonstration buildings and monitoring system

Three demonstration buildings located in southern Germany have been selected for a field test. The buildings were built at the

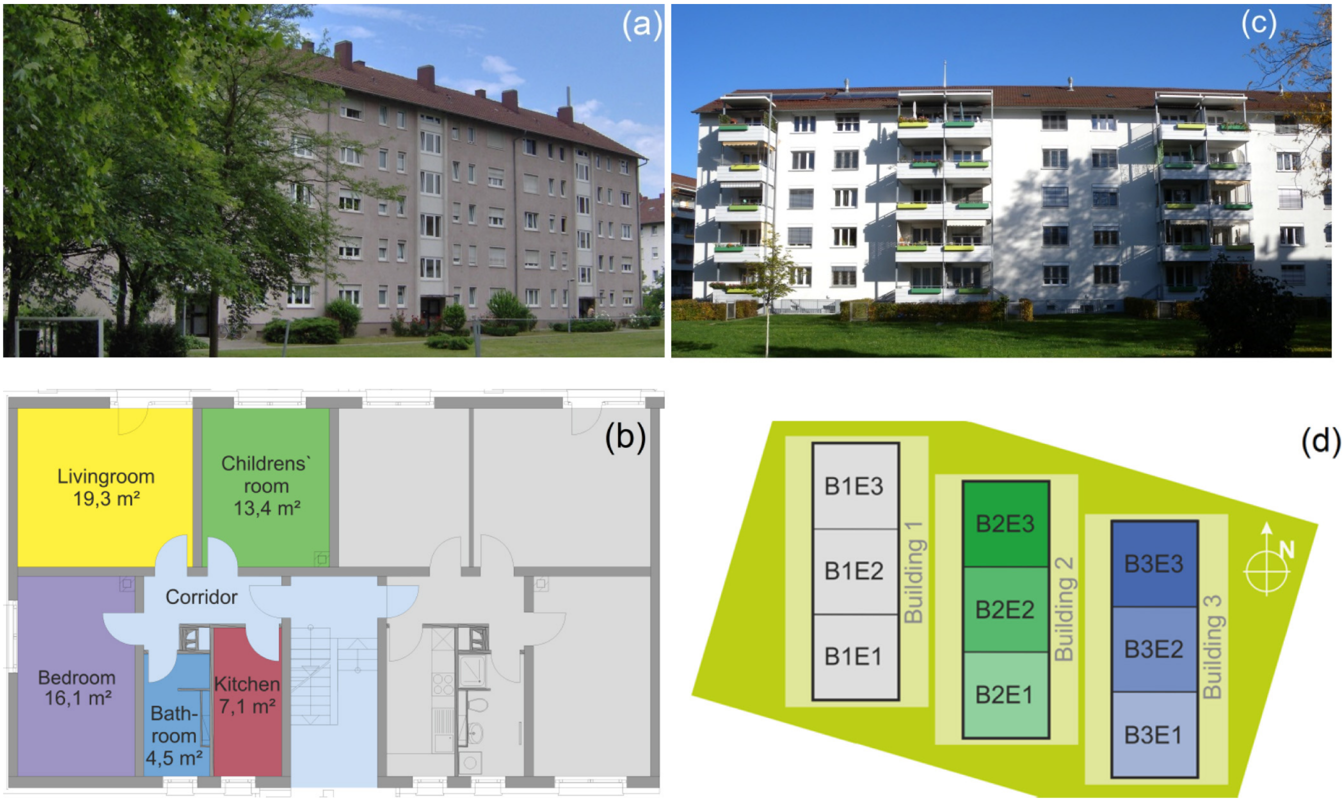


Fig. 1. One building façade before retrofit (a). one back façade after the retrofit (c). floor space of the apartments, for one entrance with south-gable (b). relative position and orientation of the buildings (d).

end of the 1950's, with relatively poor materials and primitive engineering systems (the façade of one building is illustrated in Fig. 1). The three buildings are located next to each other and are geometrically identical. They all have three entrances, each of which provides access to 10 apartments over five floors. Altogether there are 90 apartments. The apartments have the same ground floor (specular to the stairs, illustrated in Fig. 1), a kitchen, a bathroom, three additional rooms and a corridor. In this paper, the following nomenclature will be used: "B" for Building, "E" for Entrance, e.g. "B2E1" refers to the group of the 10 apartments in building 2, entrance 1. The buildings are 52 m wide and 10 m long.

At the end of the 1970s, some changes to the building envelope and the engineering system had been done: on the gables, 4 cm insulation material was installed, and the original windows were replaced with double glazing windows. Roof, floor to the cellar and façade were not insulated. The apartments were originally heated by tiled stoves and later by gas stoves installed in each living room. Domestic hot water was produced through gas flow heaters installed in each apartment.

2.1. The retrofit of the buildings

Between 2008 and 2010 the demonstration buildings have been retrofitted: the retrofit layouts have been designed by the authors, in cooperation with the municipal society that owns the buildings. Various engineering system components and various building insulation materials have been selected and combined, to generate seven different retrofit layouts, one for building 2 (standard retrofit layout), and one for each entrance of building 2 and building 3. The retrofit layouts can be compared, and useful knowledge about optimal retrofit can be gained. Building 1 and building 2 are connected to the district heating, while building 3 is heated by different typologies of heat pumps (HP). Depending on the entrance, radiators, ceiling heating, floor heating and ventilation heating have been installed to deliver the heating energy to the heated spaces. Standard water heaters and low temperature peripheral domestic hot water (DHW) heaters have been installed: in the peripheral solution (apartment-wise) the DHW is generated through so called fresh water heat exchanger stations (FWHX). The fresh water stations produce hot water by heating fresh water on demand, and using heating water as a source: in this way there are no issues of legionella since the hot water is not stored, and the overall system temperature can be minimized. The seven retrofit layouts are schematically described in Table 1. More information about the buildings and the retrofit layout can be found in [20–23].

2.2. The monitoring system

To evaluate the energy performances of the refurbished buildings, a comprehensive high time resolution monitoring system (the tenants agreed to be monitored) has been designed and installed (by the University of Applied Sciences Karlsruhe). The monitoring system collects the energy flows in the generation, the storage and the distribution system of both domestic hot water and heating. In building 2 and building 3 each room of the 60 apartments is monitored in terms of temperature relative humidity, CO_2, volatile organic compounds (VOC), light on the ceiling (Lux), Infrared/visible light ratio (to recognize the light source), window opening sensors (open/closed) through a room monitoring unit (RMU) Fig. 2. The electronics installed in the RMU generates heat: a laboratory test (executed by the University of Applied Sciences Karlsruhe) showed that this heat affects the temperature measurement by 2.5 K. Therefore, the temperature values illustrated within this work are corrected by −2.5 K. Further information about the monitoring system can be found in [25]. In building 1, only 7 apartments are equipped with RMUs. The monitoring started in 2009, the

Table 1
Description of each retrofit layout.

Building code	Floor space and no. Of apartments	Insulation	Ø Walls U-Value, W/(m2 K)	Windows U-Value, W/(m2 K)	Heating and ventilation system	Domestic hot water
B1	2160 m^2, 30 apartments	14 cm 0.035	0.2	1.3	District heating, exhaust air ventilation, radiators	Central fresh water heat exchanger (T > 60 °C)
B2E1	720 m^2, 10 Apartments	16 cm 0.021 W/(m2 K)	0.11	1.3	District heating, exhaust air ventilation, window frame ventilation with heat recovery, radiators	Apartment fresh water heat exchanger (T < 60 °C)
B2E2	721 m^2 10 Apartments			0.8	District heating, exhaust air ventilation, Radiators	Central fresh water heat exchanger (T > 60 °C)
B2E3	722 m^2 10 Apartments			1.3		
B3E1	722 m^2 10 Apartments	Vakuum + Polystyrene: 4 cm 0.008 W/(m2 K) 4 cm 0.021 W/(m2 K)	0.11	0.8	CO_2-Probe HP, central ventilation, heat recovery in each apartment, floor heating	Apartment fresh water heat exchanger (T < 60 °C)
B3E2	722 m^2 10 Apartments			0.8	CO_2-Probe master HP + slave HP, ventilation heating, heat recovery centralized	
B3E3	722 m^2 10 Apartments			1.3	AirHP + exhaust air HP, ceiling heating	

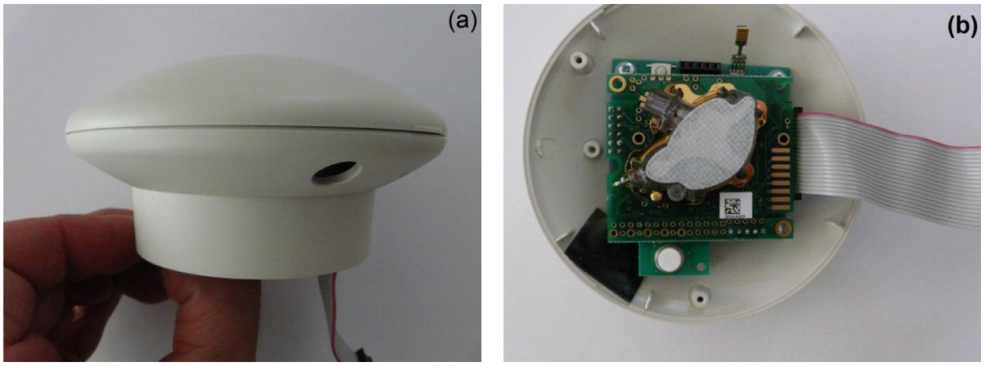


Fig. 2. (a) RMU ready for plugging. The border on the bottom of the RMU is attached to the wall. The circular opening permits the light penetration. (b) Upper part of an open RMU: VOC sensor (bottom), CO2 sensor (in the center), temperature and relative humidity sensor (top right outside the board), and illuminance sensor (behind the black tape, bottom left).

time step for the measurements is 60 s, and the data are collected in HDF5 files.

2.3. The retrofit process and the communication with the tenants

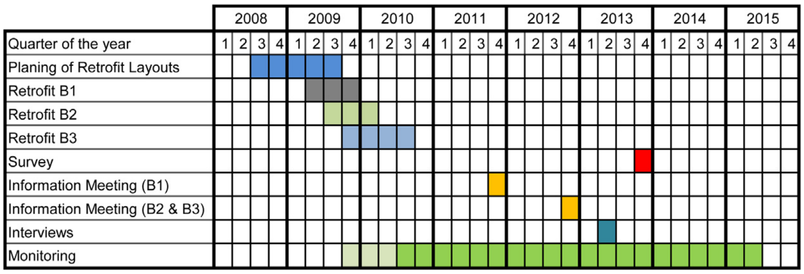
The retrofit layouts of the buildings were developed from the authors of this manuscript together with the owner of the buildings (a municipal real estate company): the tenants were not involved in this process. To permit the realization of the retrofit process, the tenants had to leave their apartments. Most of the tenants of the refurbished buildings were not living in these buildings prior to the retrofit. The technical manuals of the installed technologies have been provided to the tenants when they entered their apartments. No further information about the optimal way to manage the engineering system (e.g. heating set points, ventilation settings) was provided to the tenants of B2 and B3 until autumn 2012 (the tenants of B1 were informed about the correct way to operate the system in autumn 2011). In autumn 2012, all the tenants of B2 and B3 were invited to an information event, and were informed about the correct way to operate the engineering system and the right way to ventilate their apartments (most of the tenants participated in this meeting). Surveys and Interviews were conducted in 2013 (Occupants from 36 apartments participated in the survey). Table 2 shows the timeline of the project.

3. Evaluation methodologies

3.1. Procedure for the prediction of the energy consumption

The predicted energy figures for the demonstration buildings are calculated in accordance with the “Energieeinsparverordnung 2009” (EnEV) [26], the German energy saving ordinance for the building sector, and in particular the monthly balance procedure proposed in the German standards [27,28]. The monthly balance procedure allows for the calculation of the expected heating energy and the expected primary energy consumption under the standard German weather, and under regional standard weather profiles. The expected heating energy consumption q_h is defined in (2) as the ideal quantity of energy needed, in order to keep the heated spaces at a constant temperature of 19 °C. The term $Q_{l,M}$ represents the heat losses for each month, which depend on the specific heat transmission and heat ventilation losses of the buildings (those depend on the building structure, on the air tightness of the buildings and on the ventilation system), and the weather (the weather data provided for the calculation comprises the monthly average ambient temperature as well as the monthly average direct solar radiation on the surfaces, oriented in the four cardinal points, under several tilt angles). The terms $\eta_M \times Q_{g,M}$ represent respectively the usability degree of the heat gains, and the solar and internal heat gains of each month. The expected heating energy does not account for both distribution and delivery losses. All the energy figures illustrated

Table 2
Project Timeline.



	2008				2009				2010				2011				2012				2013				2014				2015			
Quarter of the year	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Planing of Retrofit Layouts			🟦	🟦	🟦	🟦	🟦																									
Retrofit B1						⬛	⬛	⬛																								
Retrofit B2							🟩	🟩	🟩																							
Retrofit B3								🟦	🟦	🟦	🟦																					
Survey																								🟥								
Information Meeting (B1)																🟨																
Information Meeting (B2 & B3)																				🟨												
Interviews																						🟦										
Monitoring								🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		

within this work refer to the "fictive floor space" of the buildings, as defined by the EnEV (A_{FFS}). The fictive floor space of a building is calculated by multiplying the factor 0.32 to the outer volume of the heated spaces of the buildings (including the volume of the construction elements). This allows for a comparison of energy figures of buildings with differently heated volumes/surfaces. The fictive floor space of each apartment is equal to 72 m^2, against a net floor space equal to 65 m^2.

So defined, the q_h is a reliable index to evaluate the buildings' envelope and the buildings' ventilation system, under the provided weather conditions.

$$q_h = \frac{\sum Q_{h,M|Positive}}{A_{FFS}} = \frac{\sum \left(Q_{l,M} - \eta_M \times Q_{g,M}\right)}{V_{H,B} \cdot 0.32} \qquad (2)$$

The expected primary energy consumption q_P (3) is calculated based on the expected heating energy consumption, the expected energy consumption for the production of DHW q_{DHW}, assumed 12.5 kWh/(m2FFSa), and on the "energy $e_P$effort factor" of the engineering system. This takes into account all the losses involved in the ventilation, heating and domestic hot water production process, up to the extraction of primary energy carriers (losses for: delivery/controlling, distribution, storage, conversion, extraction) and the auxiliary energy consumption (e.g. circulation pumps, fans electricity consumption, etc.). Detailed specifications $q_P$of the engineering system are therefore required for the calculation of q_P. The expected specific primary energy consumption of the buildings includes the transmission losses, the ventilation losses and the energy needed by the engineering system (including auxiliary energy). The primary energy conversion factor is 1.8 for electricity, 0.7 for district heating, and 1.1 for gas.

$$q_P = e_P \times (q_h + q_{DHW}) = e_P \times (q_h + 12.5) \qquad (3)$$

The expected energy performances are compared to the observed energy performances to prove the success of every implemented retrofit. However, to compare the observed consumption directly to the expected, calculated one, is not correct. In fact, the expected consumption is calculated using a standard weather dataset for Germany, which strongly differs from the real, observed weather. Usually, the observed consumption is adjusted to the standard reference weather using "weather factors" (e.g. through the guidelines VDI 3807-1 [29]): this has the advantage to make consumption values of different buildings in different climate zones comparable through very simple arithmetic; nevertheless, the procedure is imprecise (e.g. it doesn't take into account the solar radiation). The procedure for the calculation of the expected heating and primary energy consumption was implemented using the authors' own visual basic software that allows for the input of real weather conditions: the monthly average outdoor temperature and the solar global radiation (this is used to rescale the direct radiation on the windows). This way, every observed consumption figure could be compared to the expected figure under the real, observed weather conditions.

3.3. Definition of the energy performance gap

In [1], the energy performance gap is computed using Eq. (4), where $q_{h,obs}$ indicates the observed heating energy consumption during a certain year, while $q_{h,exp,OW}$ indicates the expected consumption under real, observed weather conditions, taking into account the heat recovery of the ventilation system, where present.

$$EPG = \frac{\left(q_{h,obs} - q_{h,exp,OW}\right)}{q_{h,exp,OW}} \qquad (4)$$

When used in this work, the EPG is used always referred to the heating energy (the observed value is the heating consumption measured at apartment level). For this reason, the EPG does not account for transportation, storage, and conversion losses of the heating energy. It does however account for the heat recovery system, where installed. The EPG is therefore a good index to reveal how occupants behave and how good the heat recovery ventilation system is working (although it is not possible to discern the two effects). In this sense, the energy performance gap can be used both for existing and new buildings.

3.4. Definition of the primary energy saving indexes

The expected and the observed primary energy saving indexes are expressed in Eqs. (5) and (6) respectively. Where:

- $q_{P,Exp,OW,New}$ indicates the expected primary energy consumption of the retrofit building, under observed weather conditions,
- $q_{P,Obs,Old}$ indicates the observed primary energy consumption of the building before the retrofit,
- $q_{P,Obs,New}$ indicates the observed primary energy consumption of the building after the retrofit,

The indexes are related to the primary energy and therefore take into account all the energy flows contributing to the heating of the building (from extraction of the primary energy source to heat generation, storage and distribution). The expected primary energy saving index is a useful figure to predict the potential of a certain retrofit action on an existing building. The observed primary energy saving index indicates the real effect of a certain retrofit action on an existing building. Hence, if the two indexes are in the same range, the retrofit action can be defined as successful.

$$S_{Exp,OW} = 1 - \frac{Q_{P,Exp,OW,New}}{Q_{P,Obs,Old}} \qquad (5),$$

$$S_{Obs} = 1 - \frac{Q_{P,Obs,\ New}}{Q_{P,Obs,\ Old}} \qquad (6)$$

The "energy savings deficit" (ESD, defined in [1], previously introduced by Haas and Biermayr as the unachieved energy conservation share [4]) and the related "energy savings achievement" (ESA, defined as achieved energy conservation share in [4]) are described in Eqs. (7) and (8). As discussed in the introduction, the ESD was introduced by Haas [4,5] under the name "Rebound share". Furthermore, Haas didnot specify whether the "calculated savings" are based on the observed or on the calculated energy consumption of a building before a retrofit process. The ESD is based on the observed consumption before the retrofit, not on the calculated one. Thus, energy savings of 100% indicate that a certain retrofitted building completely meets energy performance expectations.

$$ESD = \frac{\left(Q_{P,Obs,Old} - Q_{P,Exp,OW,New}\right) - \left(Q_{P,Obs,Old} - Q_{P,Obs,New}\right)}{\left(Q_{P,Obs,Old} - Q_{P,Exp,OW,New}\right)} \tag{7}$$

$$ESA = 1 - ESD \tag{8}$$

The primary energy saving index, the ESD and the ESA are strongly affected by occupants' behavior. These indexes are therefore not recommended for evaluating the degree of success of the retrofit process of single and double family houses, for which the tenants changed after the renovation process Those indexes should only be used when the tenants of a building are the same before and after a renovation process, or when the number of dwellings within a building is high enough (equal or greater than 10), to prevent that the behavior of a particular occupant strongly affects the results.

3.5. Dynamic evaluation of the heat shift between apartments

Following the hypothesis that non insulated inner walls may lead to an undesired heat shift between the apartments, a dynamic model of the buildings was implemented in Dymola [30] (Modelica [31]). The air room temperature of each room, measured every minute, and the weather conditions (Outdoor temperature, solar radiation, wind speed) were provided to the model as an input: an ideal heating system kept the temperature of the room at the measured level. The walls in the model accurately represent the actual heat capacity, density, and thermal conductivity of each layer of material (e.g. for an outer wall: plastering, insulation, bricks, inner plastering); thus, the heat flows through the walls (interior and exterior) were analyzed in detail [32,33]. An extract of the results of this study is presented at the end of Section 4.5.

4. Evaluation of the demonstration buildings retrofit

4.1. Expected energy figures under standard conditions

Fig. 3 illustrates the expected heating energy consumption of each entrance of the buildings, before and after the retrofit, and the related expected heating energy saving. In this evaluation, the buildings are evaluated under standard German reference weather.

B1 has energy savings of 80%, the middle entrance has a lower energy consumption since it has less transmission surface exposed to the outside, compared to the other entrances. The expected heating energy consumption of B1E1 is lower than the one of B1E3 due to the orientation of the windows in the sleeping rooms, with B1E1 facing south and B1E3 facing east.

The savings for B2 vary between 81 and 85%. B2E1 has the highest expected specific heating energy consumption. This is due to the fact that, following the DIN 4108-6, a total air change rate per hour of 0.6 1/h has to be assumed, if a ventilation system with return and supply air is installed; Where only exhaust air ventilation systems are installed, a value of 0.55 1/h is used (heat recovery is not included). The higher heating energy savings of B2E2 compared to the other entrances are due to the triple glazing of the installed windows and less external envelope surface. The difference between B2E1 and B3E1 is also due to the triple glazing windows (installed in B3E1). The slightly higher expected specific heating energy consumption of B3E2, compared to the one of B2E2, is due to the different typology of the ventilation system (respectively supply/return and exhaust ventilation). Finally, as predicted, B2E3 and B3E3 have the same expected primary energy consumption.

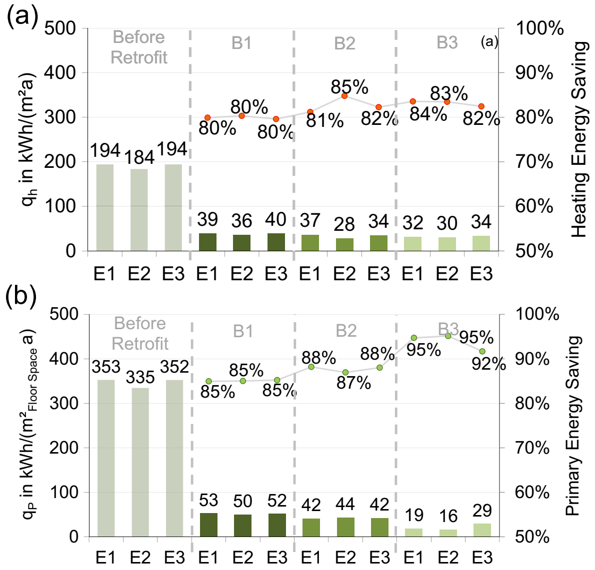


Fig. 3. Expected specific energy consumption per square meter of floor space and year, of the buildings before and after refurbishment: calculated heating energy consumption q_h (a), calculated primary energy consumption q_P (b). The energy saving of each retrofit solution, in comparison to the calculated energy consumption of the buildings before the retrofit, is shown in percent.

The evaluation of the expected specific primary energy consumption shown in Fig. 3 reveals that, in building 1, B1E2 has the lowest expected specific primary energy consumption, since it has the lowest transmission surface exposed to the outside. B1E3 has a slightly lower expected specific primary energy consumption compared to entrance 1, since the supply station of the district heating is situated in this entrance, therefore the distribution losses are lower. In building 2, B2E1 has the lowest q_P because of the installed heat recovery ventilation system, B2E3 has a lower q_P if compared to entrance 2, because of the solar heating system for DHW. In building 3, B3E2 has the lowest q_P because of the installed heat recovery ventilation system and due to having less transmission surface exposed to the outside, B3E3 has the highest q_P of the building since no heat recovery is installed and since the windows are only double glazed.

4.2. Observed vs. expected energy performances: EPG

The EPG is presented for the years 2011–2014 respectively. B3 has been occupied since spring 2011, therefore the 2011 values of this building are not relevant.

Depending on the retrofit layout, the EPG strongly varies over the several years. The EPG is consistently lower in 2013 than in 2011 or 2012, and grows mostly up again in 2014. On average (B2 and B3), the EPG is lower in 2014, and in 2013, than in 2012. The occupants' interviews and surveys, and the consequential feedback to the occupants about the correct behavior and use of the heating system provided in 2012, contributed to these positive results. In B2E1 the EPG varies between 95% in 2011, 51% in 2012, −2% in 2013 and 32% in 2014. The change between 2013 and 2014 could perhaps be explained by a change in the occupants' behavior. A similar situation can be observed in B2E2 and B2E3 (with EPG equal to or below 0% in 2014). For these entrances the occupants learned how to optimally use the system and this is reflected in the EPG being equal or smaller than 0%.

A comparison of the EPG calculated for the years 2012, 2013 and 2014 also reveals a reduction of the heating energy consumption in building 3. However, each year the EPGs of building 3 are much higher than those of building 2.

In B3E1 the EPG first decreases and then increases again during the four observed years. The apartments located in this entrance are heated by floor heating and the ventilation system has a central heat recovery unit in each apartment. It seems that either the occupants do not use the ventilation system constantly, or the heat recovery system does not recover as much heat as declared in the specifications (in the calculation of the expected heating energy the heat recovery factor η_{HR} has a value of 80%, and an air change per hour of 0.33 1/h is considered to flow through the recovery system).

An even worse situation than in B3E1 can be observed in B3E2: the EPG varies between 287% in 2012, 190% in 2013, and 200% in 2014 (slight increase). The apartments located in this entrance are heated only by the ventilation system (there are no radiant surfaces except for the low temperature towel radiator installed in the bathroom). The ventilation system has one central heat recovery unit for the entire entrance, which is installed on the roof. It seems that the occupants do not use the ventilation system properly and/or that the heat recovery system does not recover as much heat as declared in the specifications (in the calculation of the expected heating energy, the heat recovery factor η_{HR} has a value of 80%, and an air change per hour of 0.33 1/h is considered to flow through the recovery system).

In B3E1 and B3E2 there is an acceptance problem: the tenants were not involved in the decision process for the refurbishment of the buildings, and it is known from the interviews that many occupants were not satisfied with the new ventilation system: some of them switched it off (renouncing the heat recovery system). In general, there are building owners that deliberately install a ventilation system with heat recovery for their own dwelling: they will probably use it and save energy and consequently money. In this case the misuse of the ventilation system is in part responsible for the mismatch in B3.

In B3E3 the EPG is lowest one in 2012, further decreases in 2013, increases again in 2014. Still, this entrance has the lowest EPG of building 3.

Although the energy performance gap of the entrances located in building 3 is higher than that of the entrances located in building 2, Fig. 4 still reveals that these entrances (in B3) generally have the lowest observed heating energy consumption.

4.3. *Observed vs. expected energy performances: primary energy savings and energy savings deficit*

As explained in Section 3, the primary energy saving index and the energy savings deficit (and achievement) reflect the building as a whole, accounting for the building's construction, the occupants' behavior, the engineering system and the primary energy carriers. The primary energy saving index and the energy savings deficit allow for an evaluation of the effectiveness of a building retrofit. Due to failures when monitoring the engineering system (at production and storage level) in 2011 and again in 2014, in this section only the monitored years (2012 and 2013) can be evaluated. Furthermore, between September and December 2013, some of the data related to building 2 are missing: those data are substituted with consumption values of other months with similar weather.

The green (continuous) line of Fig. 5 indicates the expected primary energy savings: the line for year 2012 differs from the line for 2013 since the weather conditions are different. 2013 was, as measured by the installed weather station, the coldest and least sunny year monitored (Table 3): the expected primary energy saving for 2013 is lower than for 2012.

It is important to consider that the observed energy consumption of the buildings before the retrofit (used as reference for the calculation of the indexes) was measured between 2005 and 2007, and no weather station had been installed at that time. Before the retrofit, the observed energy consumption for all the buildings was, on average, equal to 171 kWh/(m^{2}a), despite a calculated primary energy consumption of 347 kWh/(m^{2}a), for the 3-year period. In this case, the calculated primary energy consumption impressively overestimated the observed consumption by factor 2.

The expected primary energy saving indexes show, as previously discussed in Section 4.1, that building 1 has the lowest primary energy saving, and building 3 the highest. The observed savings show an opposite situation for the year 2012: this could be an indication for failures of the engineering systems of building 2 and building 3, or an issue of the occupants' acceptance, connected to difficulties of occupants with operating the system correctly. Again, as for the EPG, the situation changes slightly during 2013: adjustments to the engineering system of building 2, as well as the feedback provided to the tenants in the form of a "tenant information day", could be reasons for this change. Still, for building 3 the gap between expectations and achievements is big.

Building 3 has the highest observed primary energy consumption of the demonstration buildings both for 2012 and 2013 even though it has the lowest observed heating energy consumption (Fig. 4). A reason for this discrepancy can only be connected to issues in the engineering system. It is not possible, based on the available data, to distinguish in how far the occupants' behavior, responsible for the EPG of this building, also negatively impacts the observed primary energy consumption. For example, a wrong occupants' behavior concerning the natural ventilation can strongly affect the seasonal performance factor of the heat pumps. This phenomenon will be partly analyzed in other works.

The energy savings deficit and the energy savings achievement are illustrated in Fig. 5: The energy savings deficit is very low for building 1 (in the accuracy range of the measurement equipment). For building 2, the energy savings deficit varies between 13% in 2012 and 7% in 2013, showing a slight improvement of the efficiency of the engineering system. Building 3 has the same positive trend as building 2, but also has a high (23%) energy savings deficit for 2013.

An analysis of the data for 2014 would have been very valuable, but it is not possible due to the previously mentioned lack of data for this year. Based on the analyzed data, it can be concluded that the retrofit of building 1 and building 2 was successful, especially after the feedback provided to the occupants. The discrepancies between expected and observed consumption lie within the typical accuracy of the measurement equipment, and reveal a relatively small negative occupants' impact on the energy consumption figures. For building 3 the situation is different, and the discrepancies between observations and expectations may be due to both technical issues and occupants' behavior issues. It should be noted that the technology installed in building 3 was state of the art (in 2008), and not yet on the market. This project offered a framework to test those new technologies and further develop them. Some of this technology may work, at time of writing, much better than 8 years ago.

4.4. *Engineering system issues*

The occupants' complaints about discomfort in parallel to an analysis of the monitored data for B2E1 and the entire building 3 revealed a malfunctioning of the DHW FWHX stations, due to rapid calcification in the heat exchangers. As a first reaction, the overall system temperature was increased, with a negative impact on the overall efficiency of the system, especially for the heat pumps of building 3. The heat exchangers were cleaned at the end of 2012

Fig. 4. Expected (under monitored weather) and observed heating energy consumption of the buildings for the year 2011 ((a), some of the bars are brighter to indicate that the buildings were not occupied for the entire year), 2012 (b), 2013 (c), and 2014 (d).

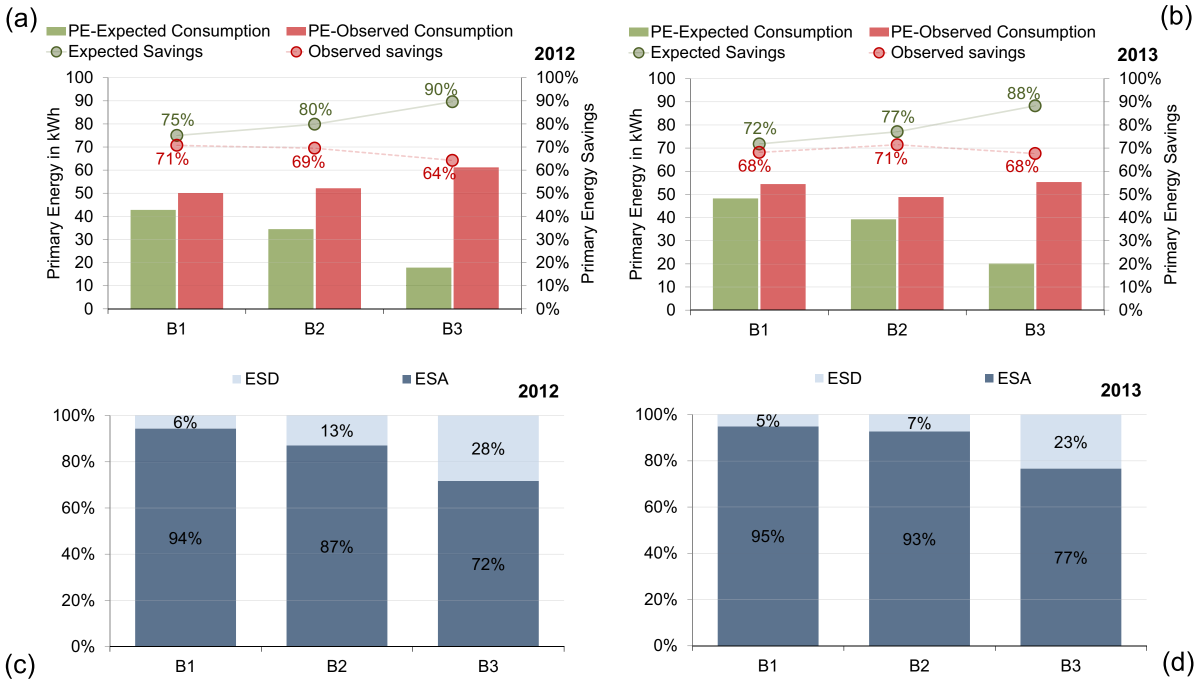


Fig. 5. Expected (under monitored weather, green) and observed primary energy consumption (red) of the demonstration buildings for 2012 (a) and 2013 (b). ESD and ESA of each building for 2012 (c) and 2013 (d). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

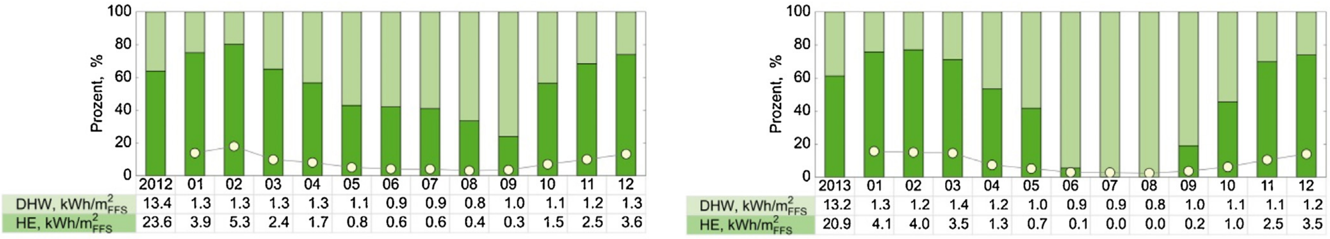
and since 2013 building 2 and building 3 are equipped with a system for fresh water de-calcification, to prevent future calcification issues of the heat exchangers. Further, an over-consumption of DHW was monitored at distribution level in the cellar, in those entrances where the DHW FWHX stations are installed: the distribution losses of the DHW were surprisingly high, varying from 19% up to 66% in 2012.

In 2011 and 2012, the measured data showed a consumption of heating energy also during the summer time. Since 2013, the heating system has been switched off during summer time (Fig. 6). Although 2013 was colder and less sunny than 2012, there is a heating energy saving of over 11%.

A meticulous analysis of the heat meter data in building 2 revealed a malfunctioning of the installed heating circulation pumps. In B2E1, B2E2 and in two apartments of B2E3, the circulation of the heating water through the heating surfaces (radiators and floor heating) is realized through peripheral heating circulation pumps. The pumps were built without a valve preventing reverse-flow. As a result, the “return heating water” from a heated room (for example the living room) flowed backwards into the radiator of another room. This effect would not have been noticed by

Table 3
Monthly average outdoor temperature and global solar radiation on the horizontal surface for the standard German weather (EnEV) and as measured during the 4 monitoring years.

	$T_{a,\,DE,\,EnEV}$ in °C	$T_{a,\,2011}$ in °C	$T_{a,\,2012}$ in °C	$T_{a,\,2013}$ in °C	$T_{a,\,2014}$ in °C	$G_{DE,\,EnEV}$ kWh/m^2	G_{2011} kWh/m^2	G_{2012} kWh/m^2	G_{2013} kWh/m^2	G_{2014} kWh/m^2
Jan	−1.3	2.4	3.2	1.6	4.6	24.6	25.1	24.3	23.3	24.8
Feb	0.6	3.5	−1.8	0.2	5.8	34.9	40.6	51.0	32.8	42.5
Mar	4.1	7.6	8.9	2.9	9.0	61.0	102.7	103.1	77.8	94.6
Apr	9.5	14.1	10.0	10.2	13.1	136.8	160.9	115.4	104.1	121.1
May	12.9	17.0	16.5	12.4	14.5	157.0	192.7	171.1	113.3	147.8
Jun	15.7	18.8	18.5	18.2	18.7	184.3	153.2	151.4	162.2	157.2
Jul	18.0	17.9	19.6	22.4	20.5	189.7	153.3	149.0	176.9	132.2
Aug	18.3	20.3	21.5	20.0	18.0	133.2	145.7	142.8	135.2	119.7
Sep	14.4	17.6	15.7	15.4	16.3	97.2	107.4	107.4	86.8	84.5
Oct	9.1	10.7	9.9	11.9	13.4	55.8	75.2	58.5	54.6	58.2
Nov	4.7	5.4	6.0	5.3	7.3	28.1	32.9	27.5	23.5	26.6
Dec	1.3	5.0	3.6	3.8	3.9	16.4	17.8	19.7	19.2	14.5
Year	8.9	11.7	11.0	10.4	12.1	1119.0	1207.5	1121.3	1009.7	1023.7



	2012	01	02	03	04	05	06	07	08	09	10	11	12
DHW, kWh/m$^2_{FFS}$	13.4	1.3	1.3	1.3	1.3	1.1	0.9	0.9	0.8	1.0	1.1	1.2	1.3
HE, kWh/m$^2_{FFS}$	23.6	3.9	5.3	2.4	1.7	0.8	0.6	0.6	0.4	0.3	1.5	2.5	3.6

	2013	01	02	03	04	05	06	07	08	09	10	11	12
DHW, kWh/m$^2_{FFS}$	13.2	1.3	1.2	1.4	1.2	1.0	0.9	0.9	0.8	1.0	1.1	1.1	1.2
HE, kWh/m$^2_{FFS}$	20.9	4.1	4.0	3.5	1.3	0.7	0.1	0.0	0.0	0.2	1.0	2.5	3.5

Fig. 6. Observed heating energy and DHW energy consumption for B2E1 for 2012 and 2013. The tables show the specific consumption values for DHW and heating, in relation to the fictive floor space. The dots in the bars indicate the weight of each month on the year balance.

merely looking at the energy flows, since the installed heat meters only measure the volume flow in "flow direction". An analysis of the flow and return temperature of the system, as well as the increasing indoor temperature in those rooms while the heating system was switched off, revealed this issue. The heating circulation pumps have been improved by the producer and, in 2012, were substituted, free of charge.

In Fig. 7, the seasonal performance factors (SPF) of the installed heat pumps are illustrated for 2012 and 2013. The boundaries of the seasonal performance factors described in this section are circumscribed only to the heat pumps, and do not comprehend storage, nor distribution losses. The heat pumps installed in building 3 are, at least in part, responsible for the primary energy over-consumption. The change in SPF, since November 2012, is mainly due to a new software configuration of the heat pumps installed by the producers. The heat pump installed in B3E1 has the highest SPF over the two evaluated years, with a value of 3.5 in 2013.

The two heat pumps installed in B3E2 have a lower SPF than the heat pump of B3E1. The modulated heat pump (Master) has, as expected, a higher SPF than the non-modulated one (Slave): this happens since the slave heat pump is only activated when the heat and DHW demand is high and higher supply temperatures are requested. The overall SPF for B3E2 is surprisingly low (around 2.5 in the monitored period).

In B3E3, there is an evident problem with the exhaust air to water heat pump (ExA2W HP): the SPF is around 1 in 2012. This heat pump had been wrongly installed, and in November 2012 the installation was corrected. Still, the average SPF for 2013 is below 2. At the end of 2014, the heat pump was switched off and only the air to water heat pump is still in use.

The air to water heat pump (A2W HP) of B3E3 has already been substituted two times, in January 2012 and in February 2013. In January 2012, and in January and February 2013, the heat pump was replaced by heating rods, installed in the storages. The heat pump has an average seasonal performance factor of 3 (this SPF value includes the energy used by the heating rods).

4.5. Considerations on the occupants' behavior

In Section 4.2, the analysis of the EPG revealed that occupants do have an impact on the heating energy consumption of an entire building entrance. However, occupants are different from each other and may impact the energy performance of buildings differently. The results illustrated in Section 4.2 are therefore attenuated by the number of apartments behind each building entrance (10 apartments). In this section, an overview of the occupants' behavior is provided, in order to demonstrate the diversity of occupants' behavior in similar apartments.

An analysis of the monitoring data at apartment level confirms the inhomogeneity of occupants' behavior encountered in [13]. Fig. 8 illustrates the distribution of the observed energy consumption for heating and domestic hot water production, measured in the apartments from 2011 to 2014.

The distribution of the observed energy consumption for the heating considers 60 apartments located in building 2 and building 3, while the distribution for DHW considers only 40 apartments located in B2E1 and in building 3. Due to missing data, it was not always possible to represent all of the apartments in the yearly distribution figures. The heating energy is distributed widely (as seen in Fig. 8) for all measured years. Six apartments consumed more than 50 kWh/(m^{2}a) in 2012 and 2013, while only four apartments exceeded this value in 2014. 2014 was the warmest and sunniest year monitored: this is reflected in the distribution of the observed heating energy, and resulted in a shift to a lower consumption level. In this year, 14 apartments (23%) used less than 5 kWh/(m^{2}a) for heating, and almost half of the apartments used less than 15 kWh/(m^{2}a).

The energy consumption for domestic hot water production is almost normally distributed. The consumption may strongly correlate with the number of occupants in the apartments (unfortunately, the number of occupants in each apartment is unknown).

Fig. 9 shows a chromatic view of the facade of building 2, during a winter month. Four apartments clearly use more energy than the others, while their neighbors, on average, use less. Focusing on

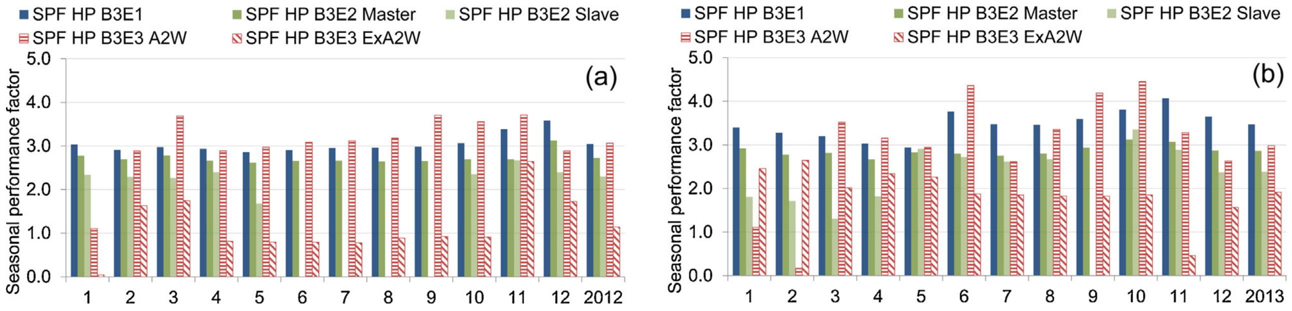


Fig. 7. Seasonal performance factor of the heat pumps for 2012 (a) and 2013 (b).

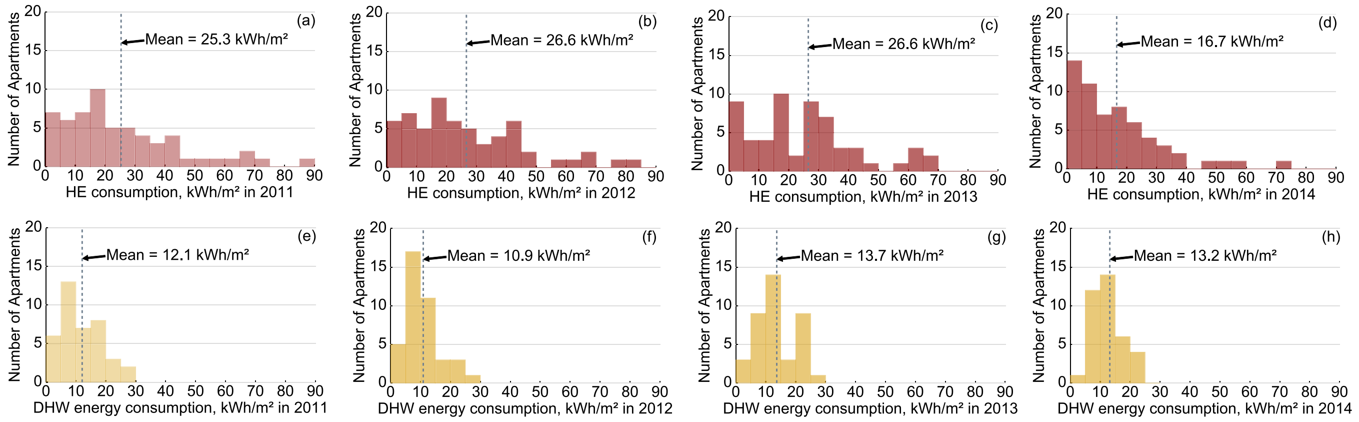
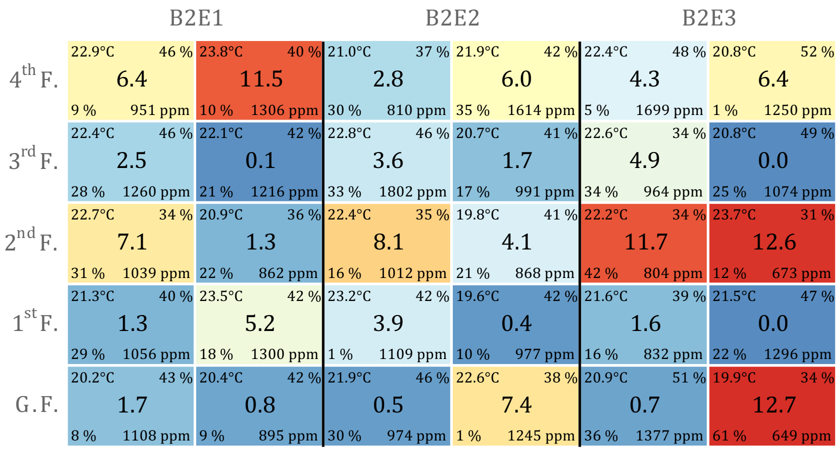


Fig. 8. Distribution of the observed energy consumption for heating (a–d) and domestic hot water production (e–h), measured in the apartments, during the four year monitoring time. The apartments located in building 3 have been occupied since spring 2011. The graphics for 2011 use brighter colors, since not all apartments were occupied by the beginning of that year, and the distribution is therefore less meaningful than that of the other years.



	B2E1		B2E2		B2E3	
4th F.	22.9°C 46 % 6.4 9 % 951 ppm	23.8°C 40 % 11.5 10 % 1306 ppm	21.0°C 37 % 2.8 30 % 810 ppm	21.9°C 42 % 6.0 35 % 1614 ppm	22.4°C 48 % 4.3 5 % 1699 ppm	20.8°C 52 % 6.4 1 % 1250 ppm
3rd F.	22.4°C 46 % 2.5 28 % 1260 ppm	22.1°C 42 % 0.1 21 % 1216 ppm	22.8°C 46 % 3.6 33 % 1802 ppm	20.7°C 41 % 1.7 17 % 991 ppm	22.6°C 34 % 4.9 34 % 964 ppm	20.8°C 49 % 0.0 25 % 1074 ppm
2nd F.	22.7°C 34 % 7.1 31 % 1039 ppm	20.9°C 36 % 1.3 22 % 862 ppm	22.4°C 35 % 8.1 16 % 1012 ppm	19.8°C 41 % 4.1 21 % 868 ppm	22.2°C 34 % 11.7 42 % 804 ppm	23.7°C 31 % 12.6 12 % 673 ppm
1st F.	21.3°C 40 % 1.3 29 % 1056 ppm	23.5°C 42 % 5.2 18 % 1300 ppm	23.2°C 42 % 3.9 1 % 1109 ppm	19.6°C 42 % 0.4 10 % 977 ppm	21.6°C 39 % 1.6 16 % 832 ppm	21.5°C 47 % 0.0 22 % 1296 ppm
G.F.	20.2°C 43 % 1.7 8 % 1108 ppm	20.4°C 42 % 0.8 9 % 895 ppm	21.9°C 46 % 0.5 30 % 974 ppm	22.6°C 38 % 7.4 1 % 1245 ppm	20.9°C 51 % 0.7 36 % 1377 ppm	19.9°C 34 % 12.7 61 % 649 ppm

Fig. 9. Schematic view of the facade of building 2, based on observations from December 2012. The boxes represent the apartments. In each box, the number in the middle indicates the specific heating energy consumption of the given apartment for the given month; the number on the top left represents the average temperature; the number on the top right the average relative humidity; the number on the bottom left the average windows opening time; the number on the bottom right the average carbon dioxide concentration. The chromatic scale of the figure reflects the heating energy consumption of the apartments (high in red, low in blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Correlation indexes (Pearson) between the heating energy consumption of the apartments and the average indoor air temperature per month, over the four monitored years.

		Jan	Feb	Mar	Apr	Oct	Nov	Dec
2011	Heating energy - AART	0.485	0.465	0.427	0.161	0.193	0.329	0.239
2012	Heating energy - AART	0.284	0.343	0.420	0.411	0.152	0.310	0.206
2013	Heating energy - AART	0.310	0.315	0.373	0.183	0.133	0.292	0.335
2014	Heating energy - AART	0.336	0.389	0.340	0.257	0.252	0.360	0.362

Table 5
Correlation indexes (Pearson) between the heating energy consumption of the apartments and the average window position per month, over the four monitored years.

		Jan	Feb	Mar	Apr	Oct	Nov	Dec
2011	Heating energy - AWP	-0.133	0.024	0.034	0.119	0.074	0.125	0.055
2012	Heating energy - AWP	0.109	0.080	0.125	-0.064	0.132	0.138	0.136
2013	Heating energy - AWP	0.076	0.041	0.037	0.003	0.086	0.079	-0.082
2014	Heating energy - AWP	-0.185	-0.204	-0.219	-0.023	-0.026	0.008	-0.026

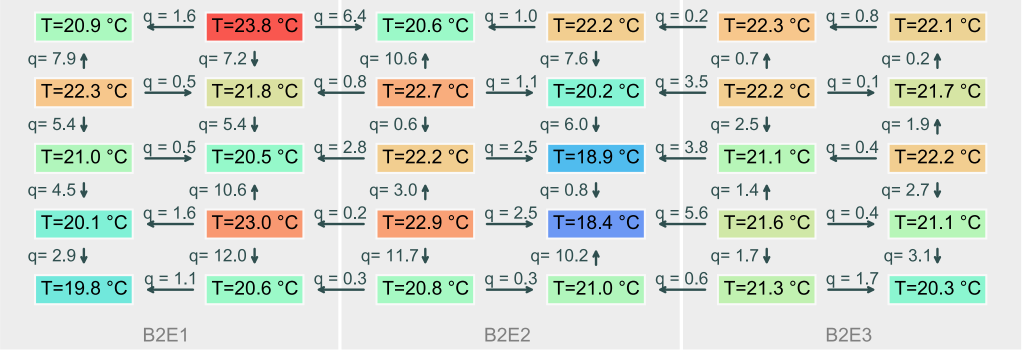


Fig. 10. Heat shift between the apartments in the heating period 2012–2013. Each block represents one apartment of building 2. The number in the boxes indicates the average air temperature of each apartment during the heating period; the number on the arrows the energy flows between the apartments, obtained through a dynamic simulation (input data with one minute time interval).

the apartments located in entrance 3, three apartments are colored red and consume about 12 kWh/(m^2a). Further, two apartments located on the right side of the entrance, on the ground floor and on the second floor, contribute to the heating of the neighboring apartments, especially of those on the floor above. The values in this figure are only average values for each entire apartment over a long period (one month): however, it can be seen, that often apartments with higher average indoor temperatures or windows open for longer times, consume more energy than others (An evaluation of the drivers for window opening and closing actions, based on the data from this field test, is proposed in [25]). In entrance 3, ground floor, the apartment on the right has the highest energy consumption, but only an average room temperature of 19.9 °C. In this apartment, on average, the windows are open for 61% of the time. In the same entrance, the two apartments on the second floor have the second and third highest energy consumption in this building. The one on the left has an average indoor temperature of 22.2 °C and opened windows for 42% of the time, while the one on the right has an average indoor temperature of 23.7 °C and open windows for 12% of the time.

The correlation indexes of the monthly heating energy consumption of the 60 apartments, with the indoor air average temperature for each month of the heating period (October–April), and with the average window position for each month of the heating period, for the four monitored years, are illustrated in Table 4 and in Table 5 respectively. The correlation between heating energy and the average apartment air temperature is mostly very weak for warmer months, and weak to moderate for colder periods. This result is expected: The average temperature in one apartment depends not only on the set points of the heating system and on the weather conditions (which are equal for all the apartments), but also strongly on the internal gains and on ventilation habits (duration of windows completely open or tilted at different outdoor temperatures). Cali et al. [34] proposed a sensitivity analysis of the heating energy consumption (of the buildings of this field test), using those variables as inputs. However, surprisingly, there is no correlation between heating energy and the average window position of the apartments. This result shows that the window opening behavior alone does not directly influence the consumption of each dwelling. Rather, the combination of factors such as heating set points, window opening cycles and internal gains, is responsible for the final energy consumption of each dwelling.

There is another aspect that can strongly impact the room temperature of the apartments and their heating energy consumption in big buildings: the heat shift between dwellings (and rooms in general). As explained in Section 2, the buildings were insulated on the outer walls, but internal walls were left non-insulated. An analysis of Fig. 9 suggests the existence of heat shift between dwellings with higher temperatures and dwellings with lower temperatures.

The results of the dynamic simulation of heat shift between internal walls (introduced in Section 3.4), and the scale of this phenomenon compared to the overall transmission losses of the buildings, are illustrated for building 2, for the heating period 2012–2013 (October to December, January to April), in Fig. 10 and Fig. 11 respectively. There are apartments that only lose heating energy to the neighbors, and apartments that only get heating energy from neighbors. The losses to neighbors can represent up to 50% of the total transmission losses of one apartment. In other cases, the gains from neighbors allow to completely cover the transmission losses to the outside and to the staircase.

5. Conclusions and outlook

The discrepancy between expected and observed energy figures has been analyzed through existing (EPG, ESD and ESA) and newly introduced indexes (primary energy savings S_{exp}, S_{Obs}). It has been shown how reality may differ from one's expectations. In addition, the causes for the discrepancy between the predicted and the observed energy figures were analyzed: they are mainly connected to engineering system issues, and occupants' behavior issues.

Fig. 12 shows expected and observed primary energy consumption of buildings before and after a retrofit process: the differences between expected and observed primary energy consumption of non-refurbished buildings can be caused by a comfort gap and by wrong assumptions about a building's substance and engi-

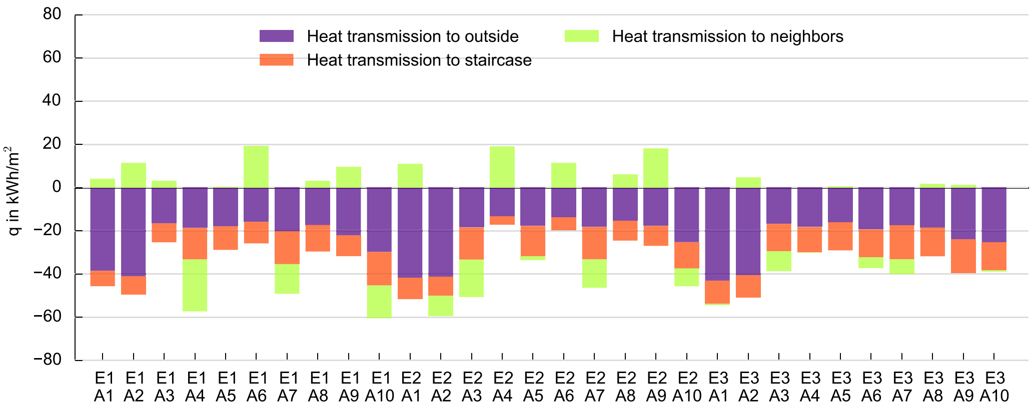


Fig. 11. Total heat transmission losses to the outside and to the staircase, heat transmission losses/gains to/from neighbors.

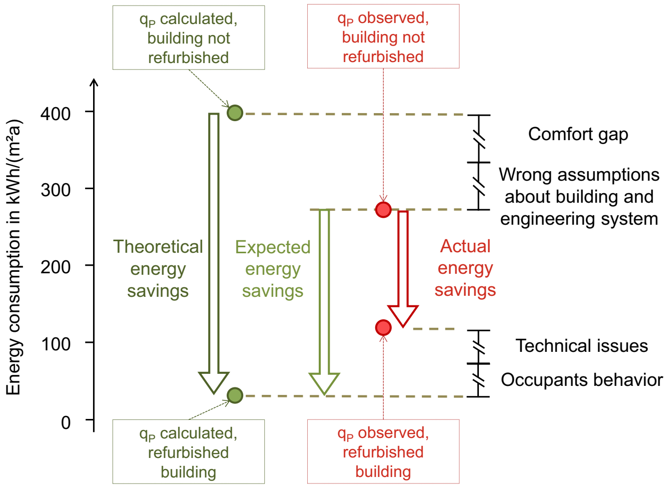


Fig. 12. Qualitative expected and observed energy figures of buildings before and after retrofit process. New elaboration of the graphic of Galvin [1].

neering system. The comfort gap in non-refurbished buildings can be arbitrary, since the occupants choose to reduce their comfort to save money, and/or are limited by the status of the building and its engineering system. The expected energy savings due to a retrofit process have to be calculated based on the real, observed energy consumption of the building before the retrofit: it is in fact not possible to save energy, which was previously not consumed. However, a retrofit process should eliminate the comfort gap. For the demonstration buildings before the retrofit process, despite an expected energy consumption of 347 kWh/(m^{2}a), the observed energy consumption was in average, for all the buildings (over 3 years), equal to 171 kWh/(m^{2}a). The discrepancy between expected and observed primary energy consumption of new or refurbished buildings can be both related to technical issues and occupants' behavioral issues. Technical issues are not a general effect and should be considered case by case (the technical failures encountered in this field test, discussed in Section 4.4, were identified through the monitoring system, and a monitoring system is therefore recommended for buildings with complex engineering systems. The main issues with the system were, first, the rapid calcification in the DHW FWHR stations, fixed through the installation of a water de-calcification system, second, the high distribution losses of the DHW system for some of the buildings, and third, technical problems with the heat pumps installed in B3E3.

The energy savings deficit is considerably high only for building 3 (28% in 2012, 23% in 2013), a building particularly affected by technical issues. Further, B3E1 and B3E2 have ventilation systems with heat recovery, but the ventilation rate of the system was set at a very low level, and the air change was compensated by natural ventilation. The occupants' acceptance of a system is a key factor for reaching energy saving goals. Moreover, the occupants wished to have a higher DHW temperature than planned (the maximum temperature for the tap was 42 °C at first but was later increased to 60 °C at the occupants' request), which led to much higher distribution losses of the DHW system, and a lower performance of the heat pumps.

With the collected data, it is not yet possible to separate the role of occupants' behavior and that of technical issues due to the discrepancies between expectations and reality. Occupants' behavior may substantially differ from expectations, and occupants are very different from each other. While in some cases, the building still reaches the energy goals, in other cases, the influence of the occupants seems to be so substantial that energy goals cannot be reached. The results of this work therefore confirm the main findings of the previously illustrated literature review, showing that occupants' behavior can affect a building's energy performance, as demonstrated by the calculated EPG indexes and in Section 4.5 (realistic occupants' behavior models could lead to better predictions of a building's energy performance [35]). We also conclude that there should be further research on which technologies are most likely to be negatively impacted by occupants' behavior, and which are most robust.

Acknowledgments

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