Rebound effect related to retrofit solutions for residential housing – monitoring data from a field test

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Summary

A large number of buildings constructed in the second half of the twentieth century consume a big amount of energy due to marginal insulation standard and inefficient and obsolete heating systems. The housing society “Volkswohnung Karlsruhe” has 35 residential buildings in the area of Karlsruhe-Rintheim with more than 1.000 apartments built in the 1950s and 1960s. In this work the complete refurbishment of three buildings, each containing thirty apartments of 72 m² over three entrances (ten apartments per entrance), is presented.

In cooperation with “Volkswohnung Karlsruhe” and the University of Applied Science Karlsruhe, a field test on energy modernization with different combinations of innovative solutions in the area of building’s physics and technical installations has been planned and realized, accompanied by an extensive monitoring process and simulations. Each entrance has a different retrofit scenario in terms of insulation, heat production and delivery, domestic hot water production and air-handling systems. In total six different retrofit configurations are realized and compared to the standard retrofit model of the Volkswohnung (implemented in the three entrances of the first building). Each retrofit solution is realized for ten apartments, an adequate number to evaluate the user-behavior.

For the evaluation of the efficiency of each retrofit solution a high resolution monitoring system for rooms, apartments and engineering system has been installed. In each room, for example, a monitoring module collects the relative humidity, window opening, CO_2 and VOC and the temperature of the air inside the room as well as the illumination of the ceiling in lux.

In the course of the working process both static and dynamic calculations are done. The evaluation of the results demonstrates how, depending on the retrofit solution, primary energy savings up to 90% are possible. In parallel, the comfort inside the apartments has been increased. Data from the monitoring system show that for those buildings the heat consumption for space heating is in average 25% higher than the heat demand calculated following the EnEV procedure [1]. This result points to the emergence of a rebound effect, where some of the users tend to increase their consumption levels, once more energy efficient systems are available.

Keywords: Building Refurbishment, Rebound Effect, Energy Flow, EnEV, Building Monitoring, District Heating

1. Introduction

A large number of buildings constructed in Germany in the second half of the twentieth century consume big amount of energy due to low insulation standards and obsolete heating systems.
Since 1970 there have been many developments in the building sector both on material side as well as engineering systems side. In 1979 the Federal Government of Germany implements the first Heat Insulation Ordinance (WSVO). Over the years, the critical acceptable levels for new buildings standards have been tightened. Today the orders are far-reaching. Everyone has to fulfil the EPBD 2010 - European Directive Energy Performance of Buildings.

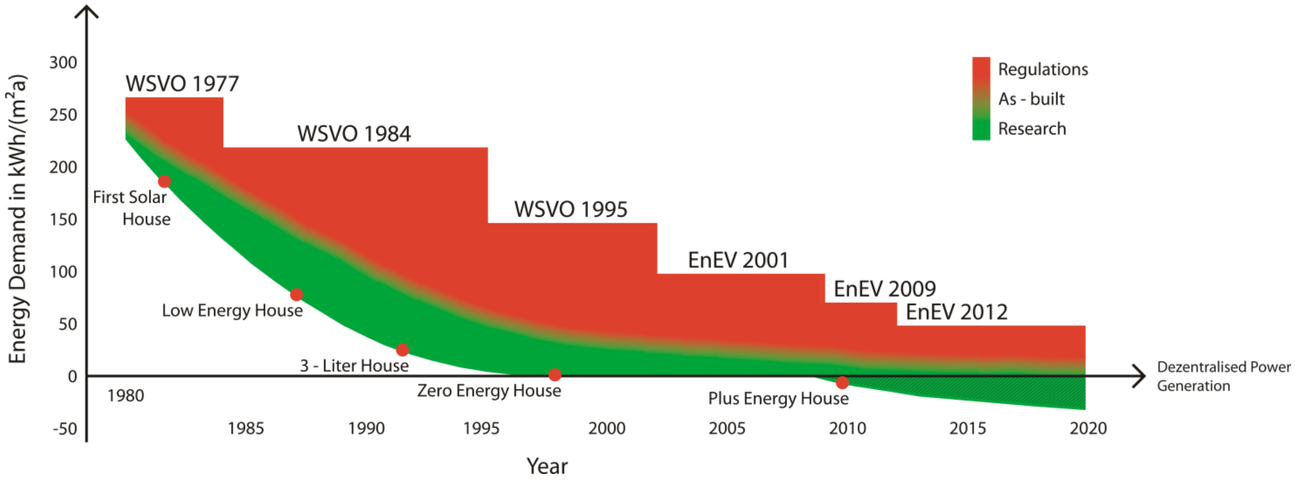


Figure 1 Development of the energy saving ordinance [source: inspired by Fraunhofer-Institute]

More than one fourth of the total energy consumption in Germany is originated in private households. A detailed analysis of this consumption points out that over 78% of the energy consumption of private households is used for space heating [1]. Depending on the age classes and building typologies, the energy consumptions of buildings vary significantly. Some regions particularly destroyed during the Second World War, have a lot of “more family houses” built between the 50’s and 60's (this is also one of the most strongly represented building group on the housing market in Germany). To a large extent these buildings were built and administered by building societies. Due to the restricted financial possibilities these buildings were built with qualitatively inferior materials.
The housing society “Volkswohnung Karlsruhe” has 35 residential buildings in the area of Karlsruhe-Rintheim with more than 1.000 apartments built in the 1950s and 1960s. In this work the retrofit solutions implemented in a field test in Karlsruhe in cooperation with the Volkswohnung are analysed and compared in order to better understand the importance of buildings’ retrofits in terms of primary energy saving per year and square meters. In parallel, the aim is to comprehend which retrofit solution is more effective, in terms of heat consumption and primary energy savings.
The buildings and buildings’ performances are compared through the specific heat demand per year and square meter of floor space (q_h) and the specific primary energy demand of the buildings per year and square meter floor space (q_P). Those parameters are calculated following the energy saving ordinance for buildings in Germany of the year 2007 (“Energieeinsparverordnung” EnEV 2007 [2], DIN V 4701-10 [3], DIN V 4801-06 [4]), using the procedure of the monthly energy balance.

2. Retrofit solutions

2.1 Building Description

Three equal aligned buildings with three entrances each and 10 housing units per entrance are considered. The west and the east front from each building have a length of 52 m and are aligned to the garden (Figure 2).

Figure 2 West façade (left picture) and south façade (right picture) of the first block, before refurbishment

To allow for an effective comparison of the different refurbishment solutions, the three buildings have been refurbished with increasing heat insulation standards. In each entrance several innovations are implemented in terms of engineering system: each building has an engineering system with increasing energy efficiency. As showed in the floor plan, each apartment has a kitchen, a bathroom, a living room, two sleeping rooms and a small central corridor, for a total floor space of 72 m².

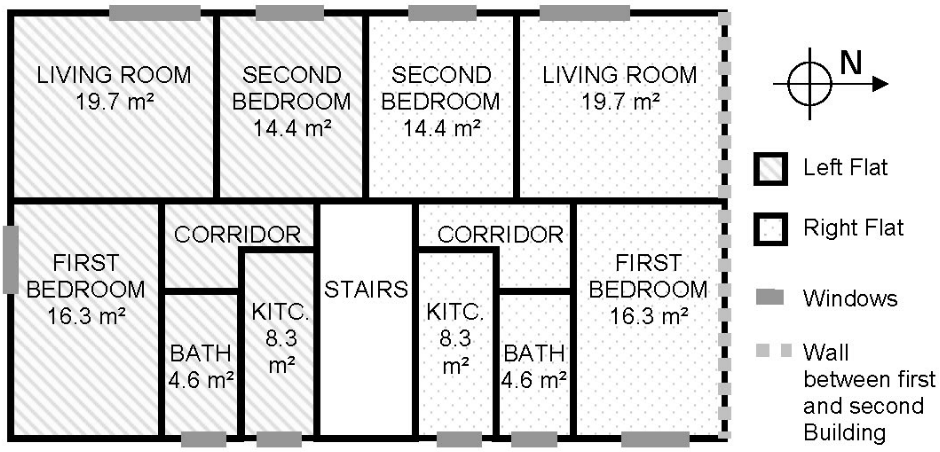


Figure 3.Qualitative layout of one floor of the first entrance of each building / KITC. is the Kitchen.

The total floor space of each entrance is 721m²; the envelope-surface is 1,097m² for the frontage-buildings, 959m² for the buildings in the middle.

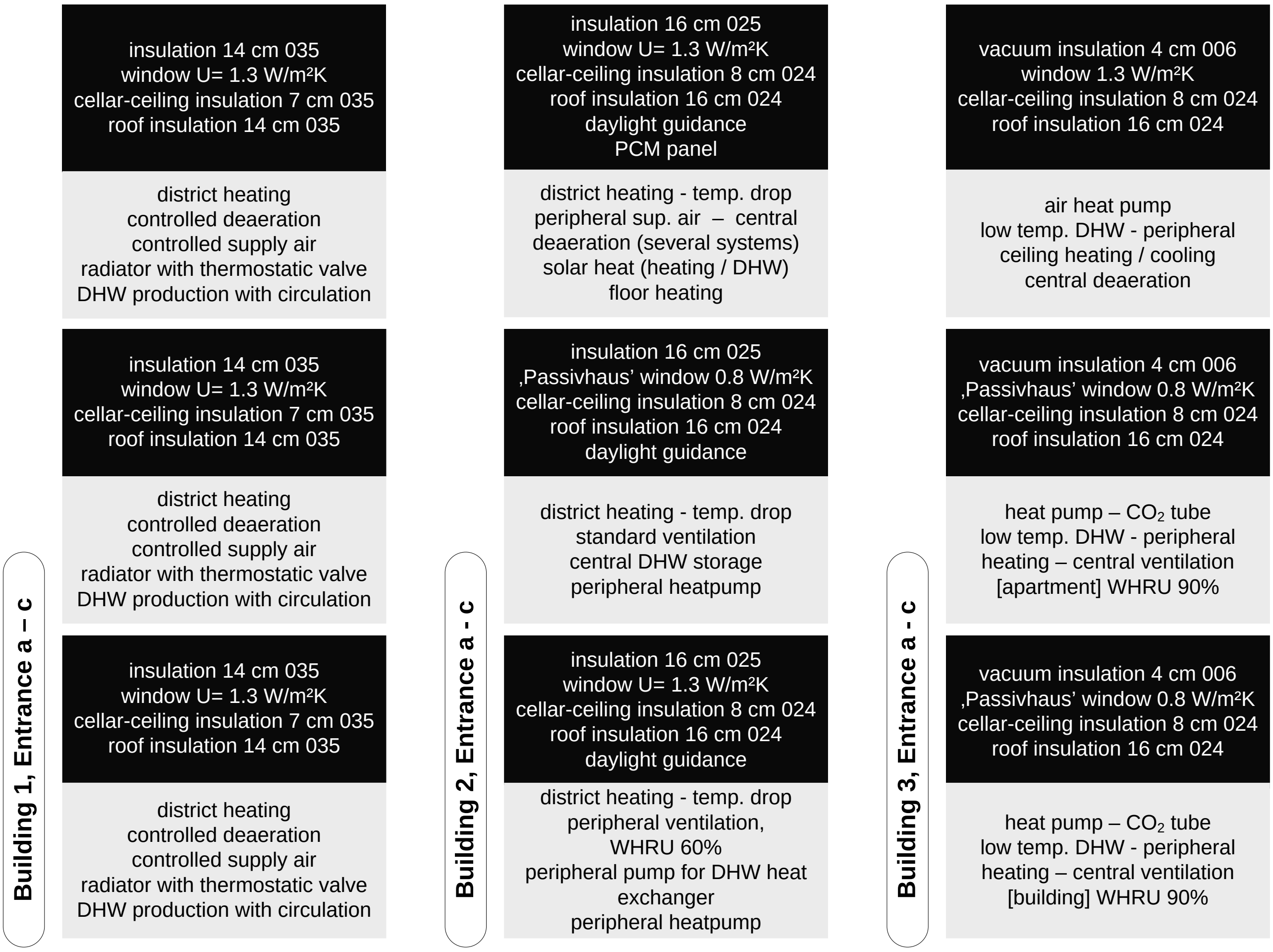
2.2 Building situation before retrofit

The buildings were built in 1955, originally without insulation and with single glass windows. The heat was provided by a cackle stove installed in each living room, domestic hot water (DHW) was supplied by electrical or gas circulatory type water heater. Later on the buildings had been lightly refurbished. At the beginning of the study, the buildings were in the following condition:

- double glass windows with an overall heat transfer coefficient U equal to 3.1 W/(m²K), (those windows have been installed during a previous refurbishment process in the 80's)
- only the south and the north façades were insulated with 4 cm insulation with λ=0.04 W/(m²K), the U-values for the external walls were between 1.22 and 0.55 W/(m²K),
- the ceiling of the last floor, under the pitched roof space, had a U-value of 2.58W/(m²K),
- the floor between basement and ground floor had a U-value of 1.93 W/(m²K).
- the walls between the flats and the stairs had a U-value of 1.25 W/(m²K).

The specific heat demand per year and square meter floor space q_h amounted to 190 kWh/m² with small differences for each entrance. This was a result of small geometric variations of the entrances, for example the windows orientation. The heating system, as well as the DHW system, were the same for each entrance: as consequence, q_h and q_P are proportional. The specific primary energy demand of the buildings q_h per year and square meter floor space q_P amounted to about 350 kWh/m².

2.3 Retrofit solutions



Building 1, Entrance a – c	Building 2, Entrance a - c	Building 3, Entrance a - c
insulation 14 cm 035 window U= 1.3 W/m²K cellar-ceiling insulation 7 cm 035 roof insulation 14 cm 035	insulation 16 cm 025 window U= 1.3 W/m²K cellar-ceiling insulation 8 cm 024 roof insulation 16 cm 024 daylight guidance PCM panel	vacuum insulation 4 cm 006 window 1.3 W/m²K cellar-ceiling insulation 8 cm 024 roof insulation 16 cm 024
district heating controlled deaeration controlled supply air radiator with thermostatic valve DHW production with circulation	district heating - temp. drop peripheral sup. air – central deaeration (several systems) solar heat (heating / DHW) floor heating	air heat pump low temp. DHW - peripheral ceiling heating / cooling central deaeration
insulation 14 cm 035 window U= 1.3 W/m²K cellar-ceiling insulation 7 cm 035 roof insulation 14 cm 035	insulation 16 cm 025 ‚Passivhaus’ window 0.8 W/m²K cellar-ceiling insulation 8 cm 024 roof insulation 16 cm 024 daylight guidance	vacuum insulation 4 cm 006 ‚Passivhaus’ window 0.8 W/m²K cellar-ceiling insulation 8 cm 024 roof insulation 16 cm 024
district heating controlled deaeration controlled supply air radiator with thermostatic valve DHW production with circulation	district heating - temp. drop standard ventilation central DHW storage peripheral heatpump	heat pump – CO_2 tube low temp. DHW - peripheral heating – central ventilation [apartment] WHRU 90%
insulation 14 cm 035 window U= 1.3 W/m²K cellar-ceiling insulation 7 cm 035 roof insulation 14 cm 035	insulation 16 cm 025 window U= 1.3 W/m²K cellar-ceiling insulation 8 cm 024 roof insulation 16 cm 024 daylight guidance	vacuum insulation 4 cm 006 ‚Passivhaus’ window 0.8 W/m²K cellar-ceiling insulation 8 cm 024 roof insulation 16 cm 024
district heating controlled deaeration controlled supply air radiator with thermostatic valve DHW production with circulation	district heating - temp. drop peripheral ventilation, WHRU 60% peripheral pump for DHW heat exchanger peripheral heatpump	heat pump – CO_2 tube low temp. DHW - peripheral heating – central ventilation [building] WHRU 90%

Figure 4. Refurbishment solutions: the white text on dark background is related to the thermal insulation, the dark text on the grey background is related to the engineering system solutions

The first building will be considered as reference case and represents the standard refurbishment solution of the Volkswohnung. This means that every entrance of the first building is equal in terms of thermal insulation and engineering system with common standard products available on the market. The retrofit of the second building makes use of state of the art insulation and a more advanced engineering system technology, which are as well to be found on the market. The most advanced refurbishment solutions are realized for the third building with the use of vacuum panels together with high efficiency heat pumps and waste heat recovery units. The third block is designed to reach the lowest primary energy demand. In Figure 4 the refurbishment solution are described. WHRU indicate waste heat recovery units, the number in percent next to WHRU is the efficiency of the heat exchange process. The thermal conductivity λ of the insulation is indicated by a number in each box, for example 035 means λ = 0.035 W/(mK).

3. Results from the static calculation

The first building has already been completely refurbished and is now inhabited. All the three entrances are supplied by district heating and have exactly the same engineering system; however, the connection to the district heating as well as the hot water storages for heating and DHW are built in the third entrance (so that for this entrance there is a smaller amount of heat

losses through the hot water pipes installed in the cellar, compared to the other entrances).
The second building has already been refurbished and almost all of its apartments have been occupied from February 2010 onwards. Also for this building the connection to the district heating is in the third entrance, but in this case each entrance has its own storage for heating water and its own storage for DHW.
The third building presents the most advanced refurbishment solutions and has been finished at the end of 2010. Each entrance has a separate engineering system. Looking at the third building it is obvious that the CO_2 tubes heat pumps installed in the first entrance and in the entrance in the middle ensure better energy performances than the air heat pump.

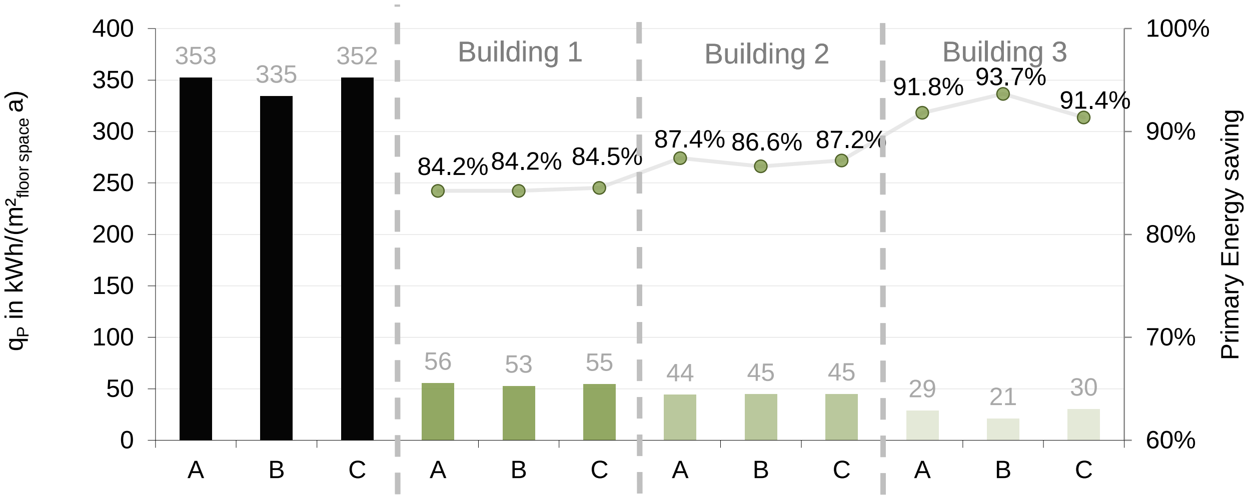


Figure 5. Primary Energy demand per square meter of floor space and year, of the buildings before and after refurbishment. In per cent, the primary energy saving of the retrofit solutions, compared to the primary energy demand of the buildings before the retrofit.

One of the objectives of this work is to outline the possible savings in terms of primary energy in the field of building refurbishment. The second objective of this work is to evaluate which of the refurbishment measures is more effective: the q_P of each refurbished building and, in per cent, the amount of primary energy saving brought through the relative refurbishment solution compared to the standard refurbishment of the first block have been calculated (following the EnEV regulation, monthly balance procedure MBP). Static calculation results showing the q_P and the primary energy savings are presented in Figure 5 (more details on the static calculations, primary energy balances and CO2 balances for this field test are presented in [5]).

4. Measurement technique

For the evaluation of the efficiency of each retrofit solution a high resolution monitoring system for rooms, apartments and engineering system (heat production, storage, distribution and delivery) has been installed. The installed measuring technique and the detectable measured variables were selected in such a way that the influence of the building construction and technical components on energy consumption and the space comfort can be determined. The collection of the room climate data in the apartment is made via a bus system (M2-Bus) developed at the University for Applied Science of Karlsruhe, with which the data of the individual apartment are obtained (The topology of the measurement system is described in Figure 6).
In each room a monitoring module collects the relative humidity, window opening, CO_2 and VOC, the temperatures of the air inside the room, and supplied to the room.
In each apartment (of the second and of the third building) a volume flow meter measures the volume flow through the heating system: flow and return water temperatures are measured as well. Also the consumption of DHW is monitored through flow meters and temperature sensors. In four apartments per entrance a heat meter has been installed for each heater device.
A weather station has been installed on the top of the roof (two meters high of the roof) in order to monitor ambient temperature, global solar irradiation, light intensity, wind intensity and wind direction.

All the monitored parameters are saved in a server each day in one csv-file per M-Bus module, and have a time step of 60 seconds. Every day about six millions values are saved in the server prepared by the University for Applied Science of Karlsruhe. Python scripts have been developed at the RWTH Aachen E.ON ERC EBC with the aim of converting the single csv-files into one single HDF5 file.

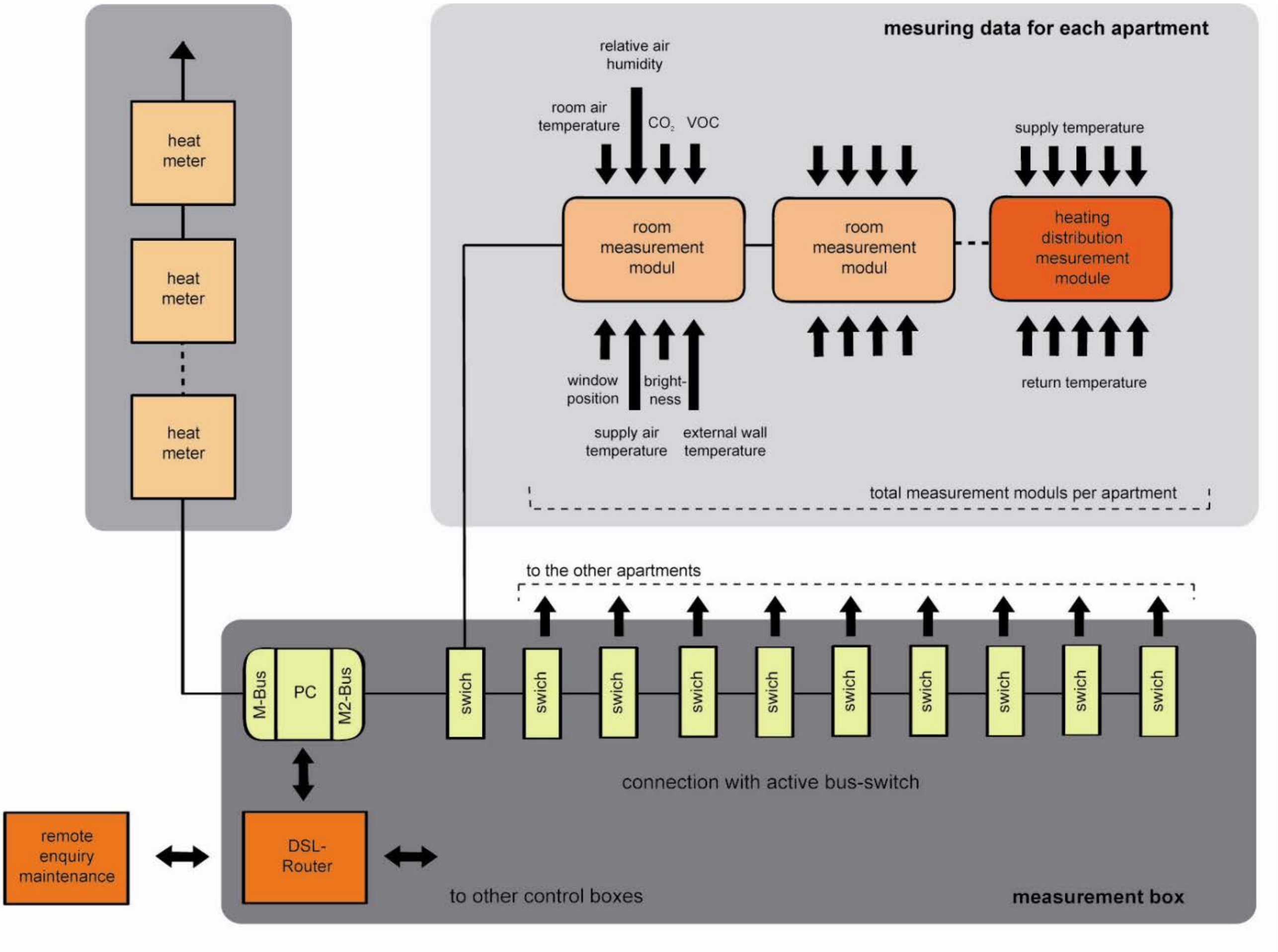


Figure 6. Overview of the topology of the measuring system

5. Preliminary evaluation of the measured data

5.1 Evaluation method

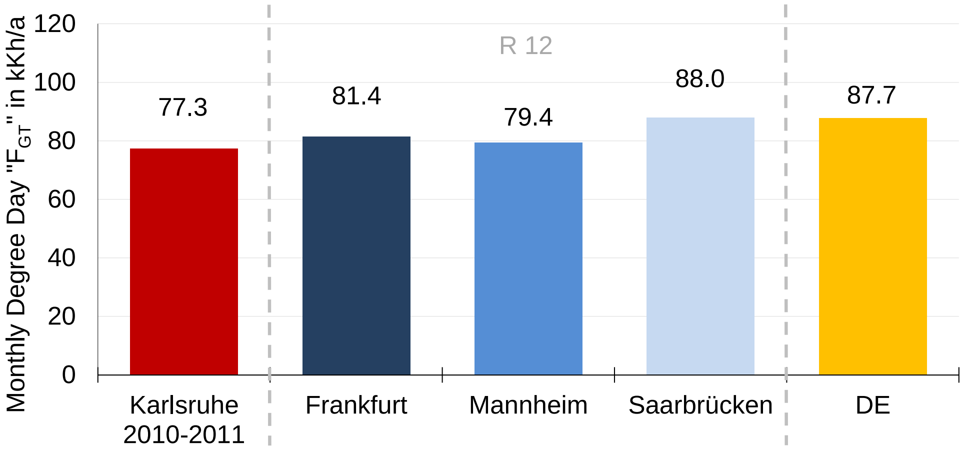


Figure 7. Monthly degree day calculated for Karlsruhe, compared to the values of the Monthly Balance Procedure for the climate region 12 (R12), and compared to the average value for Germany (DE).

While in chapter 3, *Figure 5*, the primary energy demand of the building calculated following the EnEV – monthly balance procedure (MBP) and using standard German weather boundary conditions suggested by the DIN norm [4] has been shown and commented, in this chapter the specific heat demand q_H of the buildings has been calculated with actual measured weather conditions.

An important role in the determination of the heat demand q_h, is played in the MBP by the monthly based “degree day” F_{GT}. According to the MBP, Germany is divided into 15 climate regions (Karlsruhe is in region 12) and for each region average values of ambient temperature are provided (average regional values and average major cities values), so that it is possible to calculate a regional F_{GT} (Figure 7). Thanks to the F_{GT} the specifics of the buildings can be evaluated in the desired climate region of Germany. In Figure 8 the q_P calculated with the F_{GT} based on real measured ambient temperature values is shown.

Figure 8. Primary Energy demand per square meter of floor space and year, of the buildings before and after refurbishment, calculated with F_{GT} based on measured ambient temperatures.

5.2 Preliminary analysis of heat consumption of each apartment

Since most of the apartments have been only recently occupied, only data for the last few months are available. In this work a preliminary evaluation of the specific heat demand (q_H) compared to the real specific heat energy consumption of each apartment is presented. As reference period, the time between October 2010 and March 2011 has been choosen for the second building, and the time between November 2010 and March 2011 has been choosen for the third building.

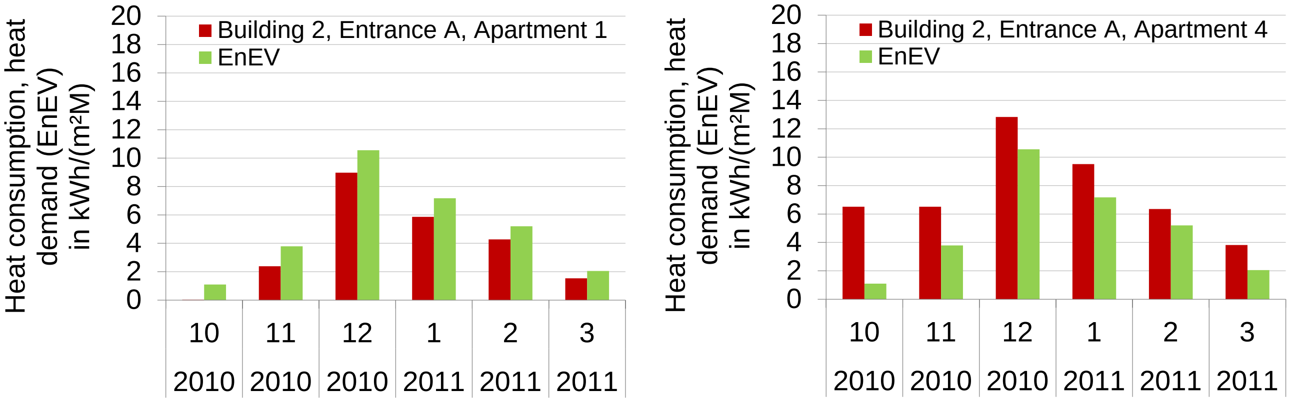


Figure 9. Building “2”, entrance “A”, apartment 1 (left) and apartment 4 (right): specific heat demand and specific heat consumption per month.

In the two graphics of Figure 9 the specific heat demand and the specific heat consumption of two apartments of the second building, entrance A, are presented. Analysing these data it appears that the occupants play a very big role in the energy consumption of the apartments. The inhabitants of apartment one have for example a heat energy consumption lower than the demand calculated by EnEV: it is interesting to see that on the other hand, in apartment 4 the situation is radically different. In order to compare the user behaviours for each refurbishment solutions, the heat consumption of each apartment has been divided through the specific heat demand and multiplied by 100% (C/D ratio). In this way, apartments with percentage lower than 100% show that the users need less energy than what predicted through EnEV.

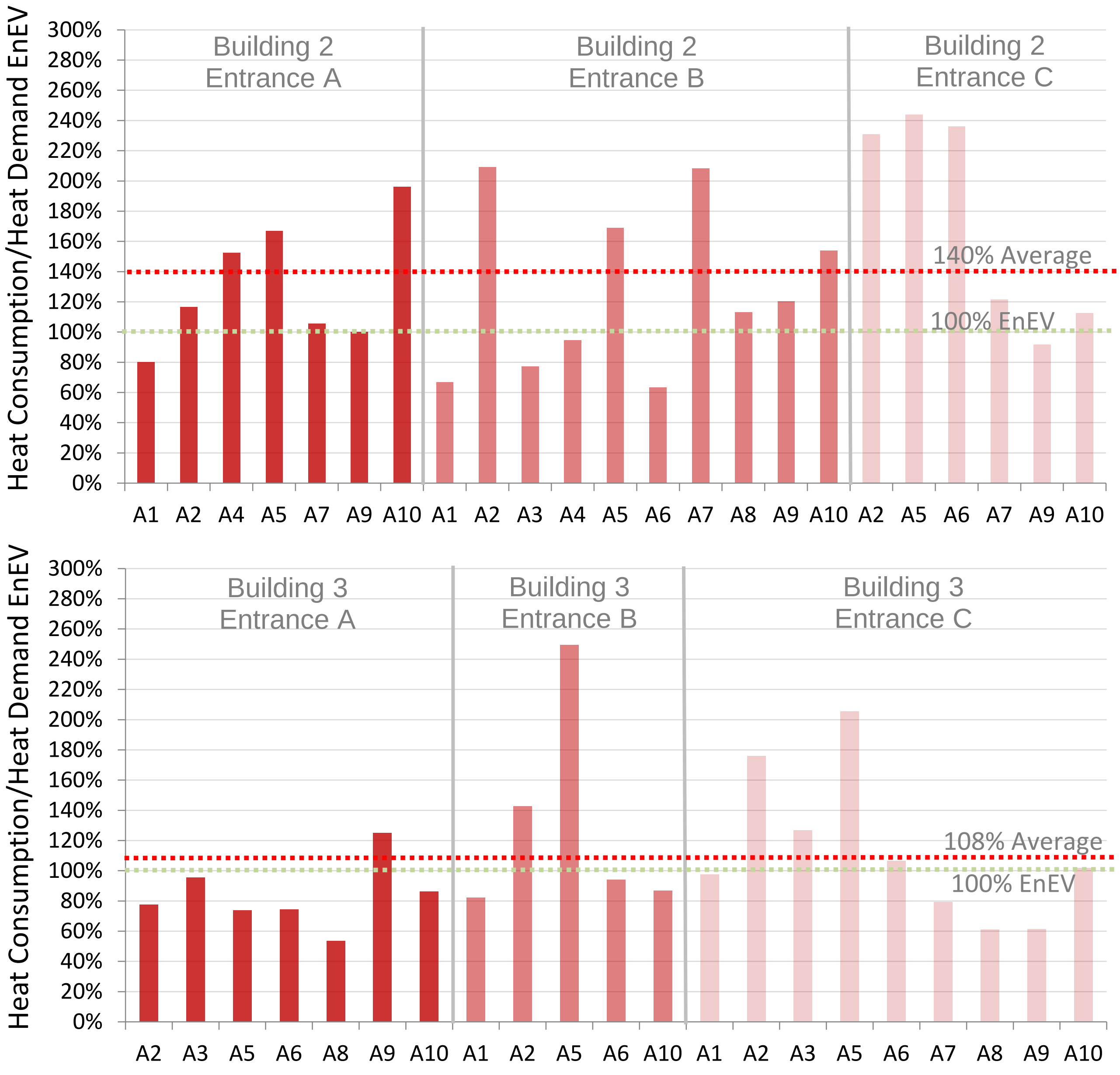


Figure 10. Ratio between heat consumption and heat demand for building 2 (up) and building 3 (bottom). “A”-Apartment. Some apartments have not been considered because not yet occupied.

In average, the energy consumption, monitored through the heat meters installed in each apartments, exceeds the heat demand calculated through EnEV with about 40% for building two, and 8% for building three. Comparing the user behaviours of each entrance it can be observed that the C/D ratio varies between 80% and 240%. In the two buildings we can observe the so called rebound effect [7] [8] for many apartments. In this study only heating energy has been taken into account. In future works the rebound effect will be analysed in more detail and also for the domestic hot water. It can also be interesting to research if (and if yes, which probably is the case, why) there are technologies that are more likely than others to lead the users to rebound effect.

The heat consumption will also be compared to the heat demand of each apartment obtained through dynamic simulations of models developed in the language Modelica.

5.3 Outlook

Dynamic simulation results and perspectives in terms of exergy flows will be analysed and presented in future works: an exergy comparison could offer different perspectives because of the difference between “primary energy efficiency factor” and “exergetic efficiency factor” [6]. On the basis of simulation results, exergy-flows will be taken into account and evaluated. The simulations will also work as a tool used to elaborate new control strategies for the buildings’ engineering system.

5.4 Acknowledgement

Grateful acknowledgement is made for financial support by BMWi (German Federal Ministry of Economics and Technology), promotional reference 0327400G.

5.5 References

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