Aalborg Universitet

Passive house renovation of a block of flats – Measured performance and energy signature analysis

Rose, Jørgen; Kragh, Jesper

Published in:
Energy and Buildings

DOI (link to publication from Publisher):
10.1016/j.enbuild.2021.111679

Creative Commons License
CC BY 4.0

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Rose, J., & Kragh, J. (2022). Passive house renovation of a block of flats – Measured performance and energy signature analysis. *Energy and Buildings*, *256*(1), [111679]. https://doi.org/10.1016/j.enbuild.2021.111679

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy
If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Energy & Buildings 256 (2022) 111679

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Passive house renovation of a block of flats – Measured performance and energy signature analysis

Jørgen Rose [a,*], Jesper Kragh [a], Kasper Furu Nielsen [b]

[a] Department of the Built Environment, Aalborg University, A C Meyers Vænge 15, DK-2450 Copenhagen SV, Denmark
[b] DEAS A/S, Dirch Passers Allé 76, DK-2000 Frederiksberg, Denmark

A R T I C L E   I N F O

Article history:
Received 23 September 2021
Revised 12 November 2021
Accepted 13 November 2021
Available online 24 November 2021

Keywords:
Energy renovation
Passivhaus renovation
Multi-story apartment buildings
EnerPHit
Retrofit
Energy signature
Rebound effect

A B S T R A C T

In order to reduce CO_2-emissions it is necessary to reduce the energy use in the existing building stock significantly. Gadehavegård – a social housing built-up area consisting of 19 similar blocks of flats with nearly 1000 dwellings situated in Denmark – needed renovation and therefore a block was selected for testing an ambitious renovation that would result in a significant reduction in energy use and CO_2 emissions. The ambition was to reach the German Passivhaus standard for the building, i.e. a very strict requirement, especially for a renovation project. The renovation included insulating the facades from the outside, replacing all windows, insulating the roof, installing decentralized mechanical ventilation systems with efficient heat recovery and a photovoltaic system on the roof. In addition, the balconies were included in the apartments by installing foldable glass façades. This paper gives a detailed description of the renovation project along with measurements of the energy use and indoor climate before and after renovation. Comparing the achieved results to the Passivhaus requirements show that the original goal is not achieved, however, the building fulfils the less strict requirements of the Passivhaus renovation certification EnerPHit and is still a very good example on how significant reductions in energy use can be achieved for these types of buildings. Results before and after renovation are compared using the energy signature and shows that heating energy consumption has been reduced by more than 50% even though indoor temperature on average has increased from 21.7 °C to 23.3 °C.
© 2022 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

In 2011, the Danish government published a strategy with an aim for Denmark to be fossil-free by 2050 [1]. In 2019, the present government set a new and ambitious intermediate target for national CO_2-emissions; by 2030 Denmark needs to reduce emissions by 70% in relation to a 1990 baseline [2].

Buildings account for approximately 40% of all energy use in Europe [3], and therefore reducing their energy use is key in reaching these ambitious goals. Calculations for the Danish building stock show, that in order to reach the overarching goal of a fossil-free society it is necessary to reduce the energy use of the existing building stock by up to 50% on average [4]. While a 50% reduction is relatively easy to achieve for some buildings, other buildings will never be able to reduce energy use that much, e.g. due to restrictions regarding preservation of heritage values etc. Therefore, those that can should, in connection with the general renovation, go much further than 50% to compensate, i.e. reducing the energy use to a level corresponding to that of new buildings or even more.

A more ambitious goal for an energy renovation of existing buildings is to meet the relatively recent Passivhaus requirement EnerPHit.[1] In [5] the modelled results of energy retrofit adaptations in historic buildings to EnerPHit standard shows energy and CO_2 emissions savings between 55% and 83%, but only when the thermal envelope is significantly improved, and the use of PV is included. Another retrofit study of a low-rise suburban dwelling in the southern Chinese town of Huilong to the Passivhaus EnerPHit standard shows that it was more difficult to reach the EnerPHit cooling energy demand criterion than the heating target, however the requirement was fulfilled by use of additional measures as solar shading and natural ventilation [6].

* Corresponding author.
E-mail address: jro@build.aau.dk (J. Rose).

[1] PHI has developed the "EnerPHit – Quality-Approved Energy Retrofit with Passive House Components". Certificate for the refurbishment of old buildings. Max heat 25 kWh/m^{2}a, max primary energy demand 120 kWh/m^{2}a.

https://doi.org/10.1016/j.enbuild.2021.111679
0378-7788/© 2022 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Similarly [7] presents a study that seeks to establish whether the EnerPHit standard can be a guideline for existing building retrofitting interventions and based on a pilot project study on houses erected between 1940 and 1960 [8] discussed and concluded that the Passivhaus standard represents a suitable solution for a holistic approach to retrofit existing houses. However, analysis performed in [9] also shows that retrofitting a non-domestic building to EnerPHit standard provides good energy performance but that the approach is not yet economically viable.

This paper describes a case study in which a multi-story apartment building underwent a very ambitious energy renovation with the goal of reaching the original Passivhaus standard [10] in effect at the time. The renovation was carried out in 2014 and included insulating the facades from the outside, replacing all windows, insulating the roof, installing decentralized mechanical ventilation systems with efficient heat recovery and including the balconies in the apartments by installing foldable glass façades. In order to be able to compare the situation before and after the renovation, two different blocks of flats have been monitored; a renovated block and a very similar block, that has not been renovated yet. Potentially, using two different blocks of flats for the analysis could lead to uncertainties in the analysis, e.g. number of tenants may be different etc., but relevant parameters were monitored carefully to make sure that there were no major discrepancies between the two measurement situations making comparisons possible.

The comparison of results before and after renovation is made using the energy signature, i.e. the correlation between monthly mean outdoor temperature and accumulated monthly heating energy consumption.

The mismatch between expected and actual energy savings has been documented in many renovation projects and usually the expected energy savings are not achieved. This discrepancy is typically referred to as the "performance gap" and it has been reported in numerous journal articles and conference proceedings. Shi et al. made a recent state-of-the-art review on the performance gap [11].

Most often the reason for the mismatch is related to user behaviour, or maybe more accurately, inconsistencies between calculation model input and actual circumstances. In Denmark, for instance, calculations are usually performed with an indoor temperature of 20 °C even though the mean indoor temperature is known to be around 22 °C in dwellings, see e.g. [12,13].

Kragh et al. [14] made a detailed investigation into explanations for the performance gap for new houses and came up with a list of possible explanations; most important were "indoor air temperature", "domestic hot water consumption" and "internal heat gains", all of which are related to the users and their behavior. Therefore, detailed knowledge of these parameters is necessary in order to increase the accuracy of energy saving predictions.

For deep energy renovations, where energy inefficient buildings are renovated to a theoretically high or very high energy efficiency level, there are two predominant reasons for overestimation of energy savings. Firstly, the building may use less heating before the renovation due to the so-called pre-bound effect [15] and secondly, the building may use more heating energy after the renovation due to the rebound effect [16]. Both of these have a negative effect on achieved energy savings and therefore overestimation of energy savings is very likely to occur. Whether the pre-bound effect is present can be investigated before the project starts, i.e. by comparing the actual energy use to the energy certificate or by monitoring the indoor temperature. Whether the rebound effect is likely to occur can be investigated, i.e. if the mean indoor temperature before the renovation is below 22 °C (Danish conditions) it is likely to increase after the renovation and expected savings could be adjusted.

2. Methods

As mentioned earlier, the original goal of the renovation was to meet the requirements given in the German Passivhaus standard [10]. The Passivhaus standard is normally proven through theoretical calculations using the Passive House Planning Package [17], however for the purpose of this paper the requirements of the standard are instead compared to the measured normalized energy consumption for the building. The methods used are described in the following subsections.

2.1. Passivhaus requirements

The renovation was carried out in 2014, which means that the Passivhaus requirements that were in effect at the time are used for the comparisons. However, since the renovation there have been relevant additions to the standard, i.e. the introduction of a specific certification related to renovation projects, which will also be included in the analysis.

In order to fulfil the 2014 Passivhaus standard, the building should achieve an energy use for space heating below 15 kWh/m^2 per year and a total primary energy use below 120 kWh/m^2 per year (both based on net heated area). In addition, the building should also have an air infiltration rate below 0.6 air changes per hour, however there has been no measurement of the building air tightness and therefore it is not possible to perform this comparison.

As mentioned, the Passivhaus Institut have since 2014 added another standard to their repertoire, i.e. the EnerPHit standard which is intended specifically for renovation projects. The requirements for this certification acknowledges the difficulties related to extensive reductions of energy use in existing buildings, e.g. in achieving an all-round high level of insulation in an existing building. In order to fulfil the EnerPHit certification, the building should simply have a space heating energy use below 25 kWh/m^2 per year and there is no specific requirement for the total primary energy use.

The regular Passivhaus standard (i.e. not the EnerPHit specifically) also include some recommendations on e.g. insulation levels etc. and comparing the actual U-values (heat loss coefficient) of the renovated block with these recommendations can give clues as to where the building performs adequately and where it does not. According to these recommendations, the U-values of the opaque façade should be below 0.15 W/m^2 K. Windows should have argon or krypton filling and a U-value below 0.80 W/m^2 K and a solar heat gain coefficient (SHGC) of at least 0.50. The building should be fitted with mechanical ventilation with heat recovery and the system should have a heat recovery rate above 75%. Finally, thermal bridges should be removed/reduced as much as possible, i.e. focus should be on developing joints with little or no thermal bridge effects. This final recommendation is also something that can be quite difficult to achieve in renovation projects.

2.2. Measurements

To assess the effect of the renovation and determine the actual energy savings, heating energy use measurements have been carried out in the renovated building and the corresponding non-renovated building. The measurements were conducted during the period from December 2014 to September 2016.

In order to further document and understand the achieved savings, measurements of the indoor climate and the ventilation rates were also carried out in both renovated and non-renovated building. Temperature and humidity meters were set up in 6 representative apartments on different floors in two different stairwells, one at each end of the buildings. The meters have logged data on an hourly basis during the period from December 2014 to April 2015.

2.3. Energy signature

The monthly measurements for heating use were degree-day adjusted by plotting the monthly heating use and corresponding monthly average outdoor temperature, i.e. known as the building's energy signature plot [18]. Using the energy signature, the heating energy use was degree-day corrected based on a monthly outdoor temperature corresponding to the Danish Reference Year (DRY) [19]. The energy signature also supplies two relevant characteristics of the building heating energy use, i.e. the specific heating energy use, i.e. the heating energy use in relation to outdoor temperature and the balance temperature, i.e. the outdoor temperature at which heating is needed in the building. A comparison of these figures before and after renovation is also carried out.

3. Materials

3.1. Description of the buildings

Gadehavegård is a social housing built-up area erected during 1977–1982 with 987 apartments and a total heated area of approx. 76 000 m^2 spread over 19 blocks of flats in four stories. It has approximately 2 500 tenants and is one of the largest public housing units in the municipality of Høje-Taastrup. The demonstration case building has facades facing north and south and consists of 54 apartments with a total heated gross area of 4 218 m^2. All apartments have windows in both facades. The building has four stories and an unheated basement with an area of 1 243 m^2 where the heating installation is located. The buildings in Gadehavegård are heated by district heating. Fig. 1 shows an aerial view of Gadehavegård.

3.2. Before renovation

Due to its age, Gadehavegård was facing a major renovation and modernization and block 9 (visible in the centre of Fig. 1 with the coloured shutters) was selected as a demonstration case for the remaining 18 blocks, i.e. for testing the overall renovation concept.

3.2.1. Building envelope

The walls in the original buildings were prefabricated concrete elements with 125 mm insulation (mean U-value including effects of thermal bridges of 0.57 W/m^2 K) and at balconies a light-weight construction with 125 mm insulation (mean U-value including effects of thermal bridges of 0.38 W/m^2 K). The roof was flat and had 100 mm insulation (U-value of 0.37 W/m^2 K). Windows were traditional 2-pane windows and they had 2–3 sashes each (U-value of 2.93 W/m^2 K and SHGC of 0.76). The horizontal division above the basement was 250 mm concrete with 100 mm insulation (U-value of 0.35 W/m^2 K) and the basement walls were 350 mm concrete (U-value of 3.70 W/m^2 K). The concrete constructions created several very large thermal bridges in the buildings, e.g., in assemblies between concrete elements and in roof/wall- and wall/floor assemblies, which is also evident in e.g., wall mean U-values. The thermal bridges created problems with the indoor climate in the form of mould and moisture in the apartments, and therefore one of the main purposes of the renovation was to remove/reduce the thermal bridges and improve indoor climate and avoid health risks. Fig. 2 shows the gable and the garden façade of one of the blocks before the renovation.

3.2.2. Installations

The building is supplied with district heating from a main plant, which distributes heat to the individual buildings. The pump in the heating system is quite inefficient and has a nominal power of 200 W. The building has a 2000-liter hot water tank with 100 mm insulation. There are circulation of the hot tap water via a pump with a nominal power of 50 W. There are two vertical heat pipes per apartment and a total of 384 m pipes for distribution of hot water with 40 mm insulation.

There was natural ventilation throughout the building in the form of open windows and mechanical exhaust ventilation in the bath and kitchen. The plant had an specific fan power (SFP-value) of 1.265 kJ/m^3.

3.3. After renovation

The renovation of the building has allowed for alteration of the building's existing floor plan. It was chosen to focus on the balconies, which after the renovation are closed balconies with windows that can be fully opened, so that the balcony can appear open during the warmer periods of the year. The new façade of the closed balcony is well insulated and has energy efficient glazing. Hereby, the heat from the sun is utilized during transition periods, while shutters can remedy overheating in the summer. The inclusion of balconies to the apartments adds 14-m^2 floor area per apartment, i.e. 754 m^2 for the entire building. Fig. 3 shows the façade facing the garden before and after renovation, demonstrating how the balconies have now been included in the apartments. The coloured shutters can be moved to protect against direct sunlight during warm periods.

The renovation of the building also covered new exterior mineral wool insulation on all other facades, new windows, mineral wool roof insulation, decentralized ventilation systems with heat recovery and a photovoltaic system as described in the following.

3.3.1. Building envelope

The concrete walls were fitted with 245 mm insulation and a new façade. This reduced the U-value of the wall to 0.14 W/m^2 K in general and 0.13 W/m^2 K at balcony walls. The windows were all replaced with new 3-layer energy windows with argon gas and a mean U-value of 0.92 W/m^2 K and a SHGC of 0.50.

The roof was insulated with 250 mm granulate insulation reducing the U-value to 0.11 W/m^2 K. The basement wall had 220 mm polystyrene added resulting in a U-value of 0.10 W/m^2 K, and the slab on ground (the floor of balconies at ground floor) was fitted with 400 mm polystyrene resulting in a U-value of 0.09 W/m^2 K. The new closed balconies were fitted with the same windows as the rest of the building. Fig. 4 shows a cross section of the building highlighting the parts related to the renovation of the building envelope.

The basement ceiling was originally planned to have 200 mm polystyrene added but this plan was abandoned, and the construction was left as it was. Due to the heating installations in the basement the temperature is relatively high and therefore heat loss from the ground floor to the basement is limited. It was suggested that the ceiling above the basement could be insulated in the future if the heating installation was renovated. Table 1 summarizes the U-values before and after renovation. From Table 1 it is clear that U-values have been improved substantially.

Fig. 5 shows a sketch of the apartment layout before and after renovation, demonstrating how the balconies are included as part of the heated area.

Fig. 1. Aerial view of Gadehavegård (Photo: Google Maps).

Fig. 2. Gable and garden façade before renovation (Photos: Technological Institute).

Fig. 3. Balconies of Gadehavegård before (left) and after (right) renovation (Photos: Bjerg Arkitektur).

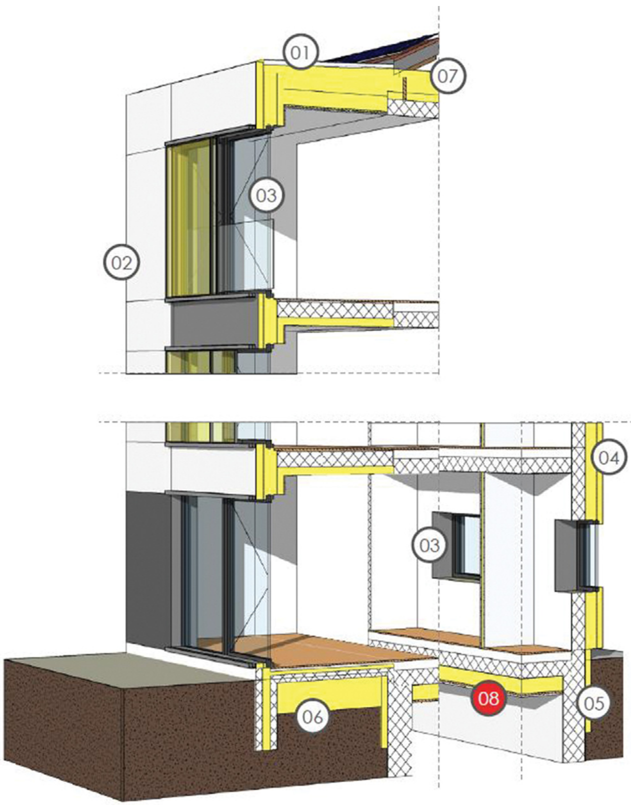

Fig. 4. 3D-view of the original plan for thermal insulation. 01 – roof over balcony, 02 – south-facing walls, 03 – new windows, 04 – north/east/west-facing facades, 05 – base, 06 – ground deck under balconies, 07 – roof construction, 08 – basement ceiling (not implemented) (Drawing: Bjerg Arkitektur).

3.3.2. Installations

The renovation focused on two parts of the building installations: the ventilation system and establishing a photovoltaic system for renewable energy production.

For the ventilation, a new decentralized balanced mechanical ventilation system with heat recovery was installed in each apartment. It utilizes the existing ducts from the extraction system and new supply ducts have been established above suspended ceilings. The heat recovery rate for the system is approx. 80% and it has an expected SFP value of 1.0 kJ/m^3. Each unit is regulated to supply an air flow of 0.3 l/s per m^2, which corresponds to an air change rate of approx. 0.5 h^{-1}. Unfortunately, no measurements were performed for the infiltration rate, but usually the infiltration rate will be reduced when windows are replaced and insulation is added to the walls. Natural ventilation is used during the summer period.

In order to reduce electricity needed from the grid a Winaico type WSP photovoltaic system was installed on the roof. The system covers the electricity use for the new ventilation systems and lighting in common areas, i.e. it cannot be used for covering private electricity use due to Danish legislation. Any remainder of electricity production is sold to the grid. The photovoltaic system is based on monocrystalline cells with an area of 204 m^2, a peak power of 155 W/m^2 and an efficiency of 87.6%. The photovoltaic plant has an expected total electricity production of approx. 33 000 kWh per year and will cover the common electricity use of the entire built-up area, i.e. not just the one building.

3.3.3. Summary of building renovation

Table 2 summarizes the changes to the building area and volume along with the changes to the building envelope and the installations.

Table 1
U-values before and after renovation of the building [W/m^2 K].

Element	U-value before	U-value after
Walls (north, east, west)	0.57	0.14
Walls, balconies (south)	0.38	0.13
Windows	2.93	0.92
Roof	0.37	0.11
Basement wall	3.70	0.10
Slab on ground	2.90	0.09
Basement ceiling	0.35	0.35

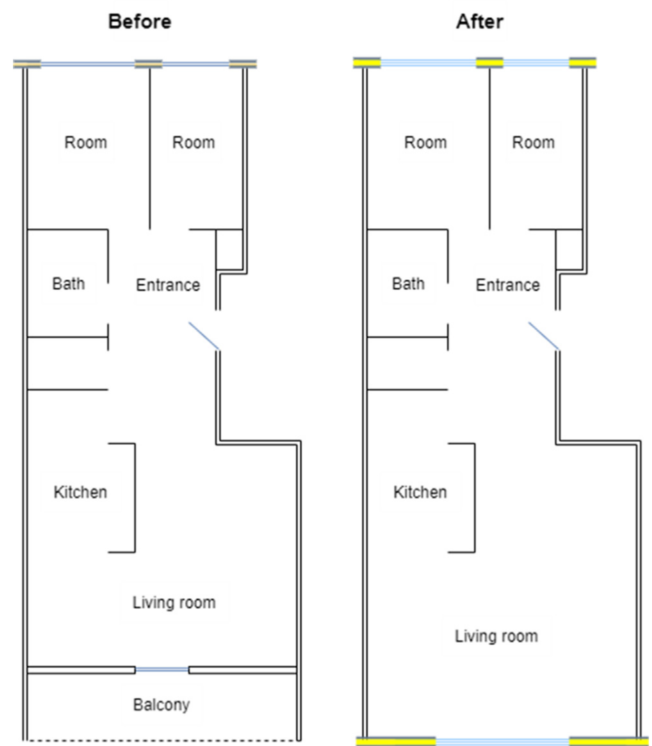

Fig. 5. Sketch of the apartment layout before and after renovation.

4. Results

Measurements were carried out before and after renovation and measurements covered indoor climate, i.e. indoor air temperature, relative humidity and ventilation rates and energy use, i.e. heat and electricity use. Measurement results are described in the following.

4.1. Before renovation

4.1.1. Indoor climate

Temperature and humidity measurements were carried out in six representative apartments spread over two entrances, one at each end of the building and on different floors and positions (two at ground floor, two at second floor and two at third floor). The measurements were carried out using Testo 174H with an accuracy of ±0.5 °C and ±3% RH. The meters have logged data on an hourly basis during a period from 9 December 2014 to 31 March 2015. Table 3 shows the results of the mean indoor temperature and humidity measurements.

The six measurements only cover approx. 10% of the building area (6 apartments out of 54) and therefore there is some uncertainty to this value. It is noted that the value is somewhat higher

Table 2
Summary of the renovation carried out for Gadehavegård.

	Before renovation	After renovation
Areas [m^2]		
Total gross heated area	4 218	4 972
Basement area	1 243	1 243
U-values [W/m^2 K]		
Walls (north, east, west)	0.57	0.14
Walls, balconies (south)	0.38	0.13
Windows	2.93	0.92
Roof	0.37	0.11
Basement wall	3.70	0.10
Slab on ground	2.90	0.09
Basement ceiling	0.35	0.35
HVAC systems		
Heating	District heating	District heating
Ventilation	Natural ventilation + mechanical exhaust in kitchen and bathroom SFP 1.265 kJ/m^3.	Decentral balanced mechanical ventilation with heat recovery. Efficiency 80%, SFP 1.0 kJ/m^3. Air flow of 0.3 l/s per m^2.
Renewable energy	–	Monocrystalline photovoltaic system. Area 204 m^2. Peak power 155 W/m^2. Efficiency 87.6%. Expected electricity production 33 000 kWh per year.

Table 3
Measured indoor temperature and relative humidity in six different apartments in the non-renovated block.

Logger	Mean indoor temperature [°C]	Dispersion [°C]	Relative humidity [%]
G10	22.1	0.6	31
G12	23.6	0.9	42
G13	22.3	0.8	45
G15	20.8	0.9	40
G20	20.6	0.6	34
G21	21.0	0.6	41
Mean	21.7	0.7	39

than the mean indoor temperature usually used for calculating heating energy use (20 °C).

The ventilation of the dwellings consisted prior to the renovation of pure mechanical extraction from the kitchen (extractor hood) and bath combined with natural ventilation through open windows. Two separate plants were used for the building and the extractors were located in the attic. Measurements were carried out by flow funnel kits corresponding to a 200 × 200 mm Kimo K35 funnel and a TSI Velocicalc 9665A velocity meter with an accuracy of ±3% of reading or ±0.015 m/s. Results showed that extracted air volumes corresponded more or less to the building regulations minimum requirement of 0.30 l/s per m^2. During the measurement power consumption for the ventilation system was measured as 710 W. Measurements are shown in Table 4.

A mean airflow of 0.33 l/s per m^2 is a little higher than the requirement according to the Danish Building Regulations (0.30 l/s per m^2) [20], i.e. what is typically used for calculations of heating energy use.

4.1.2. Electricity and heating energy use

The electricity use was obtained directly from the supplier. The measured electricity use is split into two parts; the private electricity use, i.e. tenants use for appliances, lighting etc. and the common electricity use, i.e. used for building operation, lighting in common areas etc. The electricity use was measured for 235 days (7 January 2015–31 August 2015) and showed electricity use of 64 204 kWh for private use and 9 514 kWh for common use. If these values are extrapolated to cover a whole year, i.e. assuming that the electricity use during the period is representative, they correspond to 99 721 and 14 775 kWh respectively. This results in a total electricity use of approx. 114 496 kWh or 27.1 kWh/m^2 per year.

The heating energy use was measured from 1. January 2016 to 30. September 2016 using Kamstrup MULTICAL 402 heat meters. In Fig. 6, the measured monthly heating energy use is plotted against the corresponding mean outdoor temperature to develop the so-called energy signature [18] for the building. In the graph, blue dots represent measurements during the heating season and orange dots represent measurements during summer months. The measurements do not include the energy used for the production of domestic hot water, and therefore heating energy use during summer months only represent the system losses related to the production of domestic hot water.

The energy signature shows that the balance temperature for the building before renovation is 14.6 °C, i.e. the intersection with the x-axis, and the specific energy use for space heating is approx. 0.7 kWh/m^2 K, i.e. the gradient of the line. The dispersion of the measurements shows a good correlation, and the calculated correlation coefficient for the energy signature is 0.99.

Based on the energy signature and utilising the monthly mean outdoor temperatures for Denmark, the total degree-day corrected heating energy use can be determined as 59 kWh/m^2, at an average indoor temperature of 21.7 °C (see Table 3).

4.2. After renovation

4.2.1. Indoor climate

Indoor climate measurements were also carried out in the renovated block. The indoor temperature was measured in the same manner as in the non-renovated building, i.e. during the same period, using the same type of dataloggers and in six different apartments at either end of the building. Table 5 sums up the measurement results.

Comparing Table 5 and Table 3 it is clear that the mean temperature is higher in the renovated block, whereas the dispersion is similar, i.e. temperature variations are at the same level. The relative humidity is approx. 10% lower in the renovated block, which would be expected with the combination of higher indoor temperature and mechanical ventilation with heat recovery. Relative humidity levels in dwellings should typically be in the range from 30 to 50% (depending on e.g. season etc.) and the renovated block is therefore at the lower limit in relation to having an acceptable indoor climate.

Table 4
Measured airflows in two plants.

Plant	Area covered [m^2]	Duct speed [m/s]	Duct area [m^2]	Air flow [l/s per m^2]	SFP [J/m^3]
1	1 769	1.80	0.312	0.32	1 265
2	1 607	1.78	0.312	0.35	1 277
Total/mean	3 376			0.33	1 271

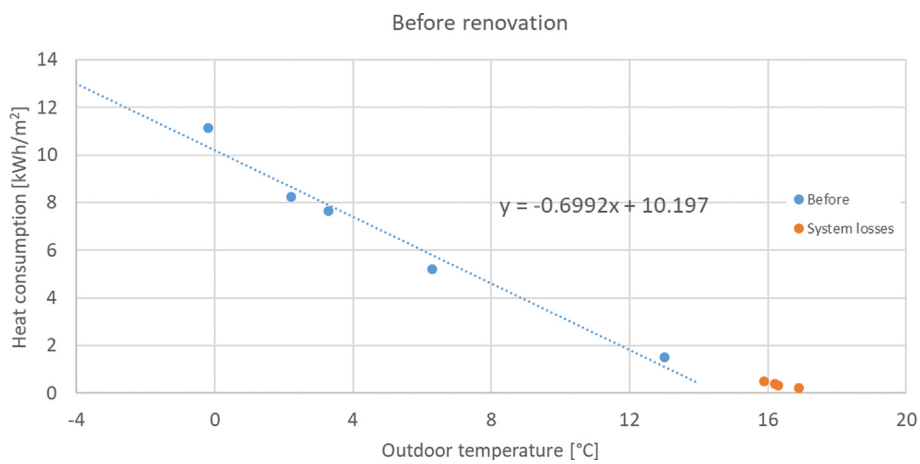

Fig. 6. Energy signature for building before renovation.

Table 5
Measured indoor temperature and relative humidity in six different apartments in the renovated block.

Logger	Mean temperature [°C]	Dispersion [°C]	Relative humidity [%]
G01	24.9	0.4	40
G03	23.6	0.4	28
G0X	21.9	0.5	29
G04	22.0	0.8	28
G06	24.2	1.2	30
G08	23.2	0.6	26
Mean	23.3	0.7	30

Ventilation rates were measured using the same flow funnel kit and velocity meter as described above. The new decentral ventilation systems have four different settings, where “2″ is the standard setting. Measurements were carried out for all four settings and the results are shown in Table 6.

There was no apparent difference between settings “2″ and “3”. Apart from this, the measurements show a fine balance between injection and extraction for all settings. The requirement according to the Danish Building Regulations is extraction of at least 0.30 l/s per m^2, which is clearly achieved on the recommended setting of “2”. The SFP of the ventilation system is a little lower than expected.

4.2.2. Electricity and heating energy use

No measurements have been carried out for the electricity use after renovation. It is assumed that the electricity use is the same in the after-situation since the new ventilation system uses more or less the same electricity as the old one. The PV system will produce an expected 33 000 kWh per year, but is supposed to supply the entire built-up area. This means that the plant produces approximately 0.4 kWh/m^2 heated floor area per year, which means that the electricity use after renovation is expected to be 26.7 kWh/m^2.

The heating energy use after renovation was measured from 1. January 2015 to 30. September 2016 using Kamstrup MULTICAL 402 heat meters. Fig. 7 shows the detailed measurement results of the heating energy consumption for both the renovated and the not-renovated block.

Table 6
Measured ventilation rates and SFP for the new decentral ventilation systems in an 85 m^2 apartment.

Extraction [m/s]	Setting “1”	Setting “2”	Setting “3”	Setting “4”
- Kitchen	2.10	2.90	2.90	4.00
- Bathroom	1.22	1.70	1.70	2.20
- Total	3.32	4.60	4.60	6.20
Extraction [l/s per m^2]	0.22	0.30	0.30	0.41
Injection [m/s]	Setting “1”	Setting “2”	Setting “3”	Setting “4”
- Living room	1.56	2.45	2.45	3.20
- Bedroom	0.88	1.32	1.32	1.75
- Spare room	0.82	1.16	1.16	1.64
- Total	3.26	4.93	4.93	6.59
Injection [l/s per m^2]	0.21	0.32	0.32	0.43
Electricity use [W]	14	25	25	48
Maximum airflow [m^3/s]	0.018	0.027	0.027	0.037
SFP [J/m^3]	759	913	913	1 311

From the figure it is clear that the heating energy use is significantly reduced, particularly during the winter months. During the period the renovated block has used 14.23 kWh/m^2 for heating whereas the not-renovated block has used 28.21 kWh/m^2, i.e. almost twice as much.

In Fig. 8, the measured monthly energy use for space heating is plotted against the corresponding mean outdoor temperature to develop the energy signature for the building.

The balance point temperature (intersection with the x-axis), i.e. the outdoor temperature at which heating is no longer needed, is approximately 15.1 °C and the specific heating energy use is approximately 0.30 kWh/m^2 K. Fig. 8 also shows the energy signature of the building before the renovation, and comparing the two graphs it is clear that the energy performance of the building envelope has been significantly improved, i.e. the gradient of the line is more than halved. The balance point is slightly increased (from 14.6 °C to 15.1 °C) which can be explained by the fact, that the indoor temperature is significantly higher (23.3 °C as opposed to 21.7 °C) in the renovated block. The dispersion of the measurements is slightly higher here, but there is still a good correlation. The correlation coefficient for the energy signature of the renovated block is 0.95.

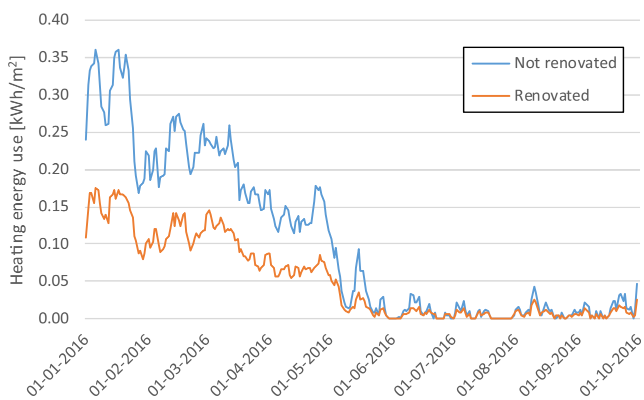

Fig. 7. Measured heating energy use in the two blocks of flats.

The degree-day corrected heating energy use can be determined as 26.5 kWh/m^2 per year, at an average indoor temperature of 23.3 °C (see Table 5). This means that the heating energy use has been reduced by more than 50%.

4.3. Energy savings analysis

Table 7 shows the measured degree-day corrected heating energy use before and after the renovation. The data are presented for the actual indoor temperatures and also converted to standard conditions, and for both the gross and net heated floor area. The gross heated floor area is 4.218 m^2 before renovation and 4.972 m^2 after renovation. The net heated floor area is 3.800 m^2 before renovation and 4.466 m^2 after renovation.

From the table it is clear that the Passivhaus criteria of a space heating use of 15 kWh/m^2 per year the project aim is not fully achieved (the building uses a normalized 24.1 kWh/m^2 net heated area per year). The actual heating energy use is reduced from 65.2 to 29.5 kWh/m^2 corresponding to a reduction of almost 55 % which is quite significant when also considering the rebound effect (increase in indoor temperature from 21.7 to 23.3 °C) that occurs.

The other requirement for energy in the Passivhaus Standard, i.e. < 120 kWh/m^2 per year primary energy demand, is usually not seen as a target, but more as an absolute minimum requirement. The calculation of the total primary energy demand is made using the Danish primary energy factors which were valid at the time of the renovation (2014). This means that district heating has a primary energy factor of 0.9 while electricity has a primary energy factor of 2.5. Table 8 shows the assumptions and calculations related to verifying the Passivhaus criteria.

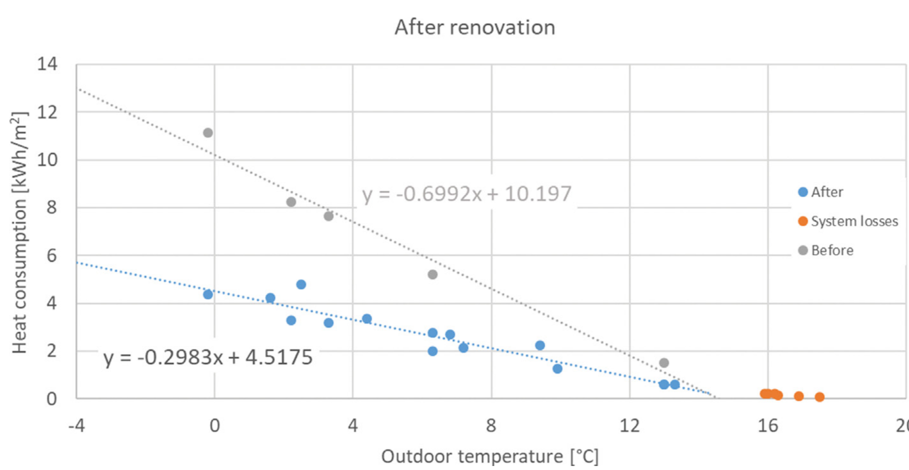

Fig. 8. Energy signature for the building after renovation.

Table 7
Measured heating energy use before and after renovation at actual measured indoor temperature and corrected to 20 °C.

Heat	Measured			Normalized degree-day corrected		
	Before 21.7 °C [kWh/m^2]	After 23.3 °C [kWh/m^2]	Actual savings [%]	Before 20 °C [kWh/m^2]	After 20 °C [kWh/m^2]	Savings 20 °C [%]
Gross/net heated area	58.7/65.2	26.5/29.5	54.8	52.6/58.5	21.7/24.1	58.8

Table 8
Assumptions and calculations verifying the Passivhaus criteria.

The primary energy consumption for heating can be determined by multiplying the value in Table 7 with the primary energy factor for district heating, i.e.:	24.1 kWh/m^2 • 0.9 = 21.7 kWh/m^2
The Passivhaus Standard assumes 1 person per 35 m^2 net area, which means that for the purpose of the compliancy check, there are:	4 218 m^2/35 m^2/person = 121 persons in the building
The standard further assumes, that each person uses 25 L of hot water per day, and that the water is heated from 10 °C to 60 °C. The total DHW use can therefore be determined as:	25 l/person/day • 121 persons • 365 days/year = 1 104 125 l/year or 262 l/m^2 per year
The primary energy use for domestic hot water can then be determined as:	262 l/m^2 • 4.18 kJ/kg K • (60–10) °C • 0.9 = 49 282 kJ/m^2 or 13.7 kWh/m^2
Similarly, the primary energy use for electricity can be determined by multiplying the total electricity use for the building by the corresponding primary energy factor:	26.7 kWh/m^2 • 2.5 = 66.8 kWh/m^2
Finally, the total primary energy use can be determined as:	21.7 + 13.7 + 66.8 = 102.2 kWh/m^2 per year

Comparing this to the requirement (120 kWh/m^2 per year), it is clear that the renovated building fulfills this part of the Passivhaus criteria.

5. Discussion

The assumptions behind the Passivhaus criteria of a maximum space heating use of 15 kWh/m^2 per year, will rarely correspond to the actual use of a building in all aspects, e.g. area per person or domestic hot water use per person. In the following, some of the assumptions of the Passivhaus certification and their influence will be reviewed for possible explanations of the performance gap.

The measurement of internal heat gain from private use of electrical appliances correspond to approximately 29.5 kWh/m^2 before the renovation. Measurement after the renovation has not been performed and hence the same use is assumed after the renovation as a conservative estimation. Comparing this to the Passivhaus assumption for electrical heat gain of 24 kWh/m^2 this should in practice decrease the actual measured space heating demand.

The actual occupancy level of the buildings in Gadehavegård can be calculated as approximately 30 m^2 per person (75 000 m^2/2 500 persons) which should be compared to the Passivhaus assumption of 35 m^2 per person. Again, the actual conditions should decrease the space heating demand.

If we compare the achieved U-values with the recommendations in the Passivhaus standard (see Table 1), it is clear that all parts of the building envelope perform according to the recommendations except for the basement ceiling where the U-value is higher than the recommendation (0.35 W/m^2 K compared to 0.15 W/m^2 K). However, this should only have a very limited influence on the space heating energy use and primary energy demand, since this building component has a limited area and the temperature in the basement is probably around 15 °C. The window U-values are 15% higher than recommended (0.92 W/m^2 K compared to 0.80 W/m^2 K), which increases the space heating by an estimated 5%, so this does not have a significant influence either. Finally, the mechanical ventilation system has a heat recovery rate which is slightly higher than recommended (80% compared to 75%), which would reduce the space heating demand by an estimated 8%.

All in all, there are no apparent explanations why the building does not achieve the traditional Passivhaus certification, but one of the major reasons could be the air tightness of the building envelope. No measurement was carried out for the building air tightness but a simple calculation shows that if the actual infiltration is 0.2 instead of 0.1 l/s per m^2 then this will increase the heating energy use by 10 kWh/m^2 and thereby this could be a very plausible explanation.

The Passive House Institute have recently developed a certification scheme for retrofits as well – EnerPHit. The requirements for this certification take into account, that in retrofits it can be quite difficult to achieve an all-round high level of insulation in an existing building, e.g. for basements etc. In order to fulfil the EnerPHit certification, the building should have a space heating energy use below 25 kWh/m^2 per year, which was achieved in Gadehavegård. So, while the building may not fulfil the prestigious Passivhaus standard, it fulfils the retrofit equivalent EnerPHit which acknowledges the difficulties related to extensive reductions in energy use in existing buildings.

6. Conclusion

The Gadehavegård renovation ambitiously aimed at fulfilling the traditional German Passivhaus standard. Detailed evaluation of the measured and calculated performance based on an energy signature analysis, however, shows that the renovation only fulfils one of the two requirements regarding the energy consumption. The measured and normalized total primary energy demand for the building is 102.2 kWh/m^2 per year and the Passivhaus requirement is 120 kWh/m^2 per year and therefore the renovation achieves this goal. The measured and normalized primary energy consumption for heating for the building is 21.7 kWh/m^2 per year and the Passivhaus requirement regarding space heating is 15 kWh/m^2 per year, which means that the requirement is not fulfilled.

After the renovation project of Gadehavegård was finalized the Passive House Institute introduced a new certification scheme, EnerPHit, which is aimed more directly at energy retrofits and takes into account the difficulties of achieving high levels of energy efficiency in existing buildings. The requirement for the space heating demand is more lenient, i.e. 25 kWh/m^2 per year and the requirement to the primary energy demand is the same, i.e. 120 kWh/m^2 per year. Comparing the achieved energy savings with this new standard shows that the renovation quite easily fulfils these requirements.

Results before and after renovation were also compared using the energy signature and the comparison shows that heating energy consumption has been reduced by more than 50% even though indoor temperature on average has increased from 21.7 °C to 23.3 °C (rebound effect).

Finally, it should be noted that the relative humidity levels in the renovated block are at the lower limit in relation to having an acceptable indoor climate. However, measurements were carried out during the winter months and therefore it is expected that these levels should not present a problem for occupant health.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was financed by Grundejernes Investeringsfond (GI).

References

[1] Danish Ministry of Climate and Energy, Energistrategi 2050 – fra kul, olie og gas til grøn energi.
[2] Klima- Energi og Forsyningsministeriet, Klimaaftale for energi og industri mv. 2020, July.
[3] European Commission, Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), Official Journal of the European Union.
[4] L. H. Mortensen, N. Nørregård, S. Aggerholm, Roadmap 2030 – Bygningers rolle i den grønne omstilling.
[5] F. Moran, T. Blight, S. Natarajan, A. Shea, The use of Passive House Planning Package to reduce energy use and CO2 emissions in historic dwellings, Energy Build. 75 (2014) 216–227.
[6] C. Liu, H. Mohammadpourkarbasi, S. Sharples, Evaluating the potential energy savings of retrofitting low-rise suburban dwellings towards the Passivhaus EnerPHit standard in a hot summer/cold winter region of China, Energy Build. 231 (2021) 110555, https://doi.org/10.1016/j.enbuild.2020.110555.
[7] A. Poletti, R. Iannetti, M. Berardi, Deep energy retrofitting of building: The decision-making and valuation process through passive house standard, International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM, vol. 17, no. 63, pp. 479–486.
[8] P. Leardini, M. Manfredini, M. Callau, Energy upgrade to Passive House standard for historic public housing in New Zealand, Energy Build. 95 (2015) 211–218.
[9] I. García Kerdan, R. Raslan, P. Ruyssevelt, S. Vaiciulyte, D. Morillón Gálvez, Thermodynamic and exergoeconomic analysis of a non-domestic Passivhaus retrofit, Build. Environ. 117 (2017) 100–117.
[10] Passive House Institute, Certified Passive House – Certification Criteria for Residential Passive House Buildings, Passive House Institute.
[11] X. Shi, B. Si, J. Zhao, Z. Tian, C. Wang, X. Jin, X. Zhou, Magnitude, causes, and solutions of the performance gap of buildings: A review, Sustainability (Switzerland), vol. 11, no. 3.
[12] D. Teli, T. Psomas, S. Langer, A. Trüschel, J.-O. Dalenbäck, Drivers of winter indoor temperatures in Swedish dwellings: Investigating the tails of the distribution, Build. Environ. 202 (2021) 108018, https://doi.org/10.1016/j.buildenv.2021.108018.
[13] L. Canale, B. Peulicke Slott, S. Finsdóttir, L.R. Kildemoes, R.K. Andersen, Do in-home displays affect end-user consumptions? A mixed method analysis of electricity, heating and water use in Danish apartments, Energy Build. 246 (2021) 111094, https://doi.org/10.1016/j.enbuild.2021.111094.
[14] J. Kragh, J. Rose, H.N. Knudsen, O.M. Jensen, Possible explanations for the gap between calculated and measured energy consumption of new houses, Energy Proc. 132 (2017) 69–74.
[15] M. Sunikka-Blank, R. Galvin, Introducing the prebound effect: The gap between performance and actual energy consumption, Build. Res. Inf.
[16] J. Daniel Khazzoom, Energy Saving Resulting from the Adoption of More Efficient Appliances, Energy J. 8 (4) (1987), https://doi.org/10.5547/ISSN0195-6574-EJ.
[17] Anonymous, Passive House Planning Package (PHPP), vol. 2021, no. 17-03-.
[18] L. Belussi, L. Danza, Method for the prediction of malfunctions of buildings through real energy consumption analysis: Holistic and multidisciplinary approach of Energy Signature, Energy Build. 55 (2012) 715–720.
[19] P.G. Wang, M. Scharling, K. Nielsen Pagh, B.K. Wittchen. C. Kern-Hansen, Technical Report 13-19 2001– 2010 Danish Design Reference Year – Reference Climate Dataset for Technical Dimensioning in Building, Construction and other Sectors.
[20] Trafik- og Byggestyrelsen, Bekendtgørelse om offentliggørelse af bygningsreglement 2015 (BR15).