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Case Report

Assessing the Impacts of Energetic Retrofitting on Economic, Ecological and Social Parameters–A Case Study in Germany

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Abstract: To pave the way towards climate neutrality in 2045, it is required for Germany to upgrade and retrofit its existing energetically low-performing building stock. This task is challenging because a major share of the existing building stock in Germany is being rented, leading to more complex landlord-tenant dynamics. Landlords mainly shoulder the initial costs of the energetic retrofitting measures but only indirectly benefit, through possible rent increases. Tenants, on the other hand, directly benefit from the improved thermal comfort and lower heating bills. To ensure the sustainability of the energetic retrofitting, a goal of harmony among the economic, ecological, and social factors must be attained, ideally benefiting tenants and landlords. This paper examined this balance in detail, focusing on the costs and subsidies for landlords to improve energy efficiency and how this affects rent and heating costs for tenants. A life cycle assessment of materials used in retrofits was conducted. The findings revealed that the retrofitting measures were environmentally and economically favorable from the landlord's perspective. However, the reduction in heating costs achieved by retrofitting the building was below the potential rent increase, making the measures economically unfavorable for the tenant.

***Keywords*:** energetic retrofit, energy efficiency, cost and benefit analysis, impact assessment, life cycle assessment

Nomenclature

ASHP	Air-sourced heat pump
BAFA	Bundesamt für Wirtschaft und Ausfuhrkontrolle (Federal Office for Economic Affairs and Export Control)
BDEW	Bundesverband der Energie- und Wasserwirtschaft (German Association of Energy and Water Industries)
BEHG	Brennstoffemissionshandelsgesetz (Fuel Emissions Trading Act)
BGB	Democratic Republic of Congo
BMWK	Bürgerliches Gesetzbuch (Civil Code)
CHP	Combined heat and power
CO_2-eqv.	Carbon dioxide equivalent
EEG	Erneuerbare-Energien-Gesetz (Renewable Energies Act)
GHG	Greenhouse gas

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GWP	Global warming potential
HP	Heating period
kWh	Kilowatt hour
kW_p	Kilowatt peak
MFH	Multi-family house
PV	Photovoltaic
TWh	Terawatt hours

1. Introduction

To achieve net greenhouse gas neutrality in the German building sector by 2045 [1], it is crucial to identify and quantify the major GHG emitters. Among all buildings in Germany, structures built between 1949 and 1978 accounted for roughly 42% of the entire housing stock, considering approximately 40 million living units in total [2]. As they were built before the first thermal insulation regulations in 1979, they have been the highest energy consumers in residential buildings, accounting for approximately 43% of the total energy consumption in the German building sector [2]. Considering that around 60% of the end energy was derived from fossil fuels and primarily used for heating purposes, these buildings represent a significant source of GHG emissions (see Figure 1). Therefore, to achieve the aforementioned target, it is important to focus on the energetic retrofitting of these structures by improving the building thermal envelope and/or upgrading the current heating system to a more energy-efficient one.

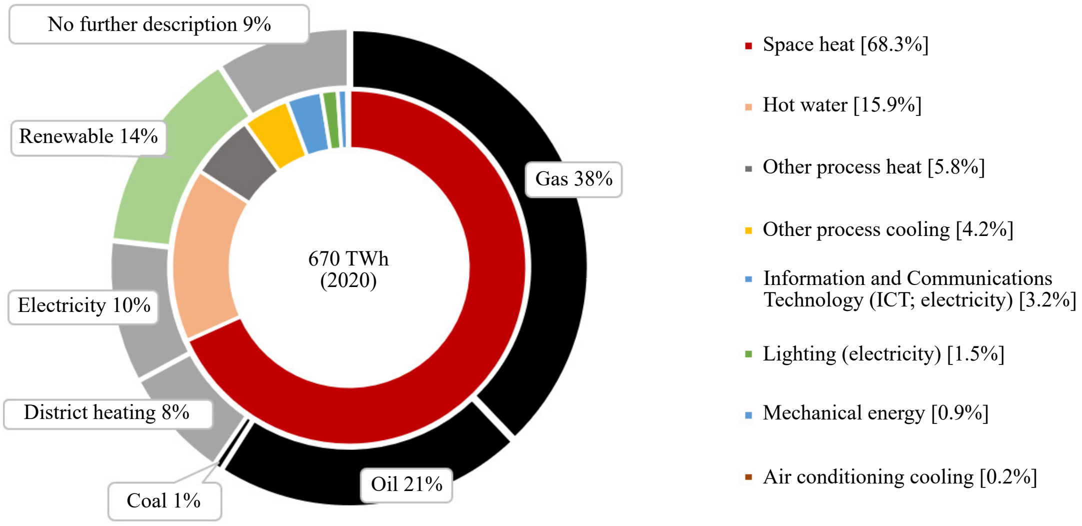


Figure 1. End energy consumption and primary energy carrier in private households in 2020 [3]

While energetic retrofitting offers substantial benefits in minimizing carbon footprints, a thorough analysis of this topic is required, especially in Germany, where only 42% of the approximately 39.3 million existing living units in Germany are privately owned (2022) [4]. The other 22.8 million living units are rented or in a comparable situation [4]. Therefore, the interaction between tenants and landlords is crucial to achieving the desired climate goal.

However, the available literature in the context of retrofitting while maintaining a connection to the landlord-tenant dilemma is generally limited, as indicated in a systematic review by Lang et al. on the willingness of landlords' to engage in energetic retrofit in a global context [5] and another study in Germany on the outcomes of energetic retrofit from the energetic and social aspects [6]. The majority of the examined papers in [5] focus on the aspects of why landlords do not retrofit their rented properties, primarily due to financial barriers [7-13]. Especially notable is the risk aversion displayed by the landlords by financing the measures from savings rather than taking a loan [14]. In Germany, evidence from a small-scale analysis also shows a low interest by landlords in investment in energy efficiency due to the absence of a sufficient price premium [15].

Based on this context, the study aimed to examine the costs and benefits for landlords and tenants regarding multiple retrofitting measures. To conduct this research, a MFH was adopted as a case study. The retrofitting measures were selected based on a literature review and expert interviews and analyzed towards the goal of achieving harmony between economic, environmental, and social parameters for landlords and tenants.

2. Materials and methods

To evaluate the impacts of the energetic retrofitting, a series of steps were carried out. The following sub-chapters provide detailed descriptions of these steps and their alignment with the mentioned research objectives.

2.1 *Case study*

A case study is a commonly used research method in studies about the impacts of energetic retrofits on multiple aspects of sustainability. For instance, in an investigation on the modernization of heating systems in older buildings, the BDEW adopted a 20-25-year-old single-family house and an MFH to study the impacts of various scenarios on the environment as well as financial aspects [16]. Accordingly, GHG emissions and the related costs and benefits of different heating systems were calculated.

A similar approach was utilized in this study, in which a typical MFH built before 1978 was examined for data collection and analysis. Based on on-site observation and measurement, a simple floor plan was sketched (see Figure 3). Data about the anticipated energy usage outlined in the energy certificate and the actual energy consumption reflected in the bills were analyzed for an insight into the energy demand of each living unit (see Chapter 3.1). Following this, an element-based energy balance was calculated, taking all components of the thermal envelope and the energy service system into account (see Chapter 3.2).

2.2 *Expert interview for energetic retrofit measures*

Based on the initial findings about the energy performance and characteristics of the studied building, consultancies with experts were conducted to gather recommendations for potential retrofit measures.

The consultation with experts was initiated as a type of preliminary request for proposals. Of the 25 companies contacted, 11 replied, allowing for an assessment of the economic, environmental, and social impact of the proposed energetic retrofit. (See Table 1).

Table 1. Number of contacted companies and their response rate

	Number of companies contacted	Number of companies replied	Response rate
Insulation	11	4	36%
Window exchange	7	4	57%
PV systems	6	0	0%
Heat system exchange	1	1	100%
Energy consultant	1	1	100%

As the opinions and suggestions from the contacted companies and experts in their respective fields were highly valued and cross-referenced among similar sectors, this approach served as the underlying framework for this empirical case study.

2.3 *Measure selection and calculation tools*

The suggested retrofit measures were first investigated for their technical details and performance and then evaluated for their sustainability and feasibility. They were categorized as passive or active measures and presented in detail in Chapters 3.3 and 3.4.

From the mentioned research methods, various options for retrofitting and underscoring the reasoning are discussed as follows: For exterior wall insulation, an external thermal insulation composite system (ETICS) was considered, as recommended by the energy consultant. This external and additive facade insulation can be anchored onto the brickwork and subsequently plastered. The insulation of the cellar ceiling was considered based on the suggestion of the energy consultant. No companies were contacted in this matter for cost estimation because this project might be undertaken by the landlord and the energetic benefit might be questionable (see Chapter 3). Additionally, the replacement of windows was considered due to tenant complaints about drafty windows. As the windows are the original ones from 1968, there is a need for modernization concerning the achievable U-values.

Table 2. Costs and potential savings when replacing the heating system in a 20-25-year-old or older apartment building with subsequent insulation measures and previous gas heating [16]

	System	Additional/ reduced costs in €/a	Savings GHG emissions in %	Avoidance costs GHG emissions in €/t GHG emission
1	Air-to-water heat pump + electric water heating	2.444	-23.4%	545
2	Mini CHP system	2.066	-93.1%	116
3	Air-to-water heat pump + PV system	1.904	-29.2%	339
4	Air-to-water heat pump	1.571	-29.2%	280
5	Local/district heating + freshwater station	1.325	-35.3%	195
6	Gas-BW unit + electric water heating	1.091	-8.8%	647
7	Brine-water heat pump	970	-43.7%	116
8	Air-water sorption gas heat pump	776	-34.4%	117
9	Pellet boiler	273	-90.2%	16
10	Gas condensing boiler appliance (10% biomethane)	27	-19.5%	7
11	Gas condensing boiler	-397	-16.1%	-129
12	Gas condensing boiler + solar warm water	-417	-24.4%	-89

From an economic perspective, literature suggests that replacing the heating system with a gas-condensing boiler for water heating is advisable (see Table 2, system 12). However, this replacement was not investigated, as the existing system relies on electric water heating, and centralizing the hot water supply seemed impractical due to the required piping. Upon recommendation from the contacted companies, the use of a CHP unit was also not considered (see CHP plant Table 2, system 2), as the required operating hours at full load would not be met. The company's suggestion involved a cascaded heating system with an ASHP alongside the existing gas heating. This partly reflects the appointed distribution of HP systems by the BMWK, in which they were suggested to cover approximately 40-59% of the future heat requirement [1]. Although this recommendation is not directly outlined in the BDEW's heating replacement (see Table 2), the cascading option could be compared with the measure proposed in system 1 (see Table 2), which suggested replacing the gas heating with an ASHP and an electric instant water heater. This would incur additional costs of 2.444 €/a and lead to a 23.4%/a reduction in GHG emissions. Since the company's recommendation included a base load-capable HP and the subsequently oversized gas heating would only be used during peak load periods, the additional costs and GHG reduction could be of a similar magnitude. Additionally, the installation of a PV system could reduce costs by 540 €/a and further decrease greenhouse gas emissions by 5.8%/a (see Table 2, systems 1 and 3).

Before considering the installation of a PV system, roof insulation could also be carried out. As the upper thermal barrier is already designed with EPS insulation material and, in the event of comprehensive roof refurbishment, the expansion of the attic could be included, the possibility of the PV system was initially only planned. Should the roof be modernized and insulated, the addition of an elevator could also be considered, which would exceed current budget expectations.

To support the data analysis, the thermal performance and ecological footprint of the thermal envelope components were illustrated and calculated using the Ubakus Ecobalance calculator and the database from the Ökobaudats Institute of the Federal Ministry of Housing, Urban Development, and Construction [17, 18]. PV*Sol software was adopted to calculate the energy balance with the introduction of the PY system. At last, nPro, a tool developed by BMWK, was used to investigate the interaction between the building service systems and the relevant key parameters [19]. In this study, the social aspect was interpreted as the acceptance of the measurements by the tenants, who were indirectly linked to the economic benefits accruing to them.

3. Results

3.1 *Billed heat demand of the case study object*

The examined MFH was built in 1968, is located in a village in the eastern part of Germany, approximately 100 km north of Cologne, and borders the Münsterland region. The main building, comprising a total of six apartments, along with attached garages and cellar spaces, occupies an 830 m² plot of land. In total, a surface area of 443 m² has been rented and unevenly distributed in flat sizes ranging from 57 m² and 66 m² on the ground floor and two times 80 m² on the 1st and 2nd floors, respectively (see Figure 3). Currently, those flats have been equipped with electric water heaters, and the room heat has been provided by a gas-condensing boiler since 2019. In Table 3, the billed gas prices can be observed.

Table 3. Billed heating demand for the case study object based on the time interval from 01.06.-31.05

	2017	2018	2019*	2020	2021	2022
Consumption in kWh						
	59.611	51.198		51.084	52.574	40.693
Gas costs in €	4.144	3.577		3.669	4.044	3.722
in $€_{cent}$/kWh	6.95	6.99		7.18	7.69	9.15
Total price in €	4.886	4.267	4.337	4.440	4.830	4.535
in $€_{cent}$/kWh	8.20	8.33		8.69	9.19	11.14

Note:
- The total price included the gas cost and the additional cost (or the basic cost).
- (*): No data available.

Notably, the total price of gas in $€_{cent}$/kWh was steadily increasing while the gas demand was overall decreasing in 2017-2022. This lower demand could be caused by changing user behavior, different climatic conditions, or the heating system modernization in 2019. According to the apartments' specific and billed energy costs, the costs were unevenly distributed (see Figure 2). This disparity could be attributed to variations in user behavior as well as apartment sizes and locations within the building's geometry.

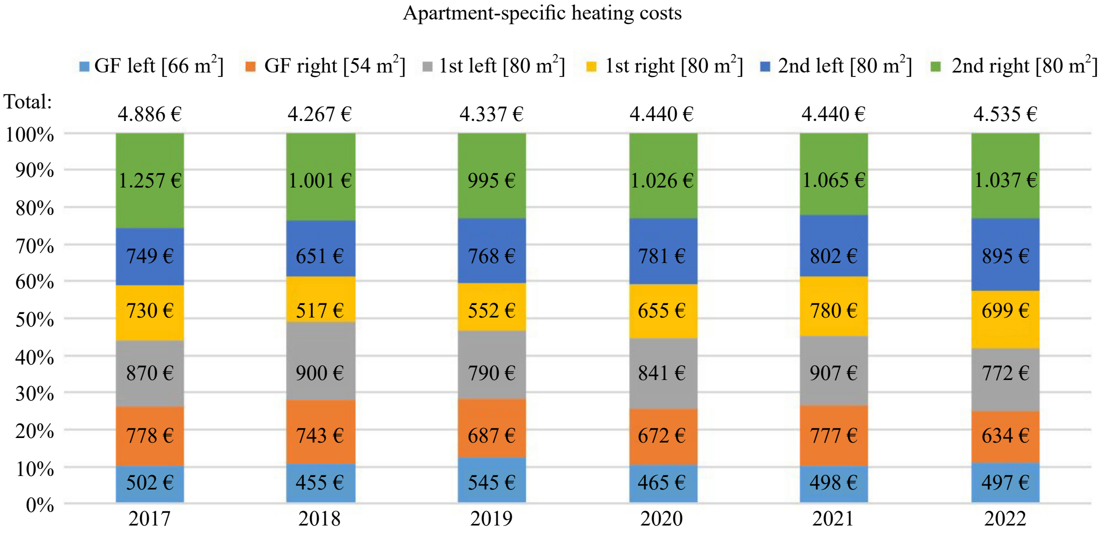
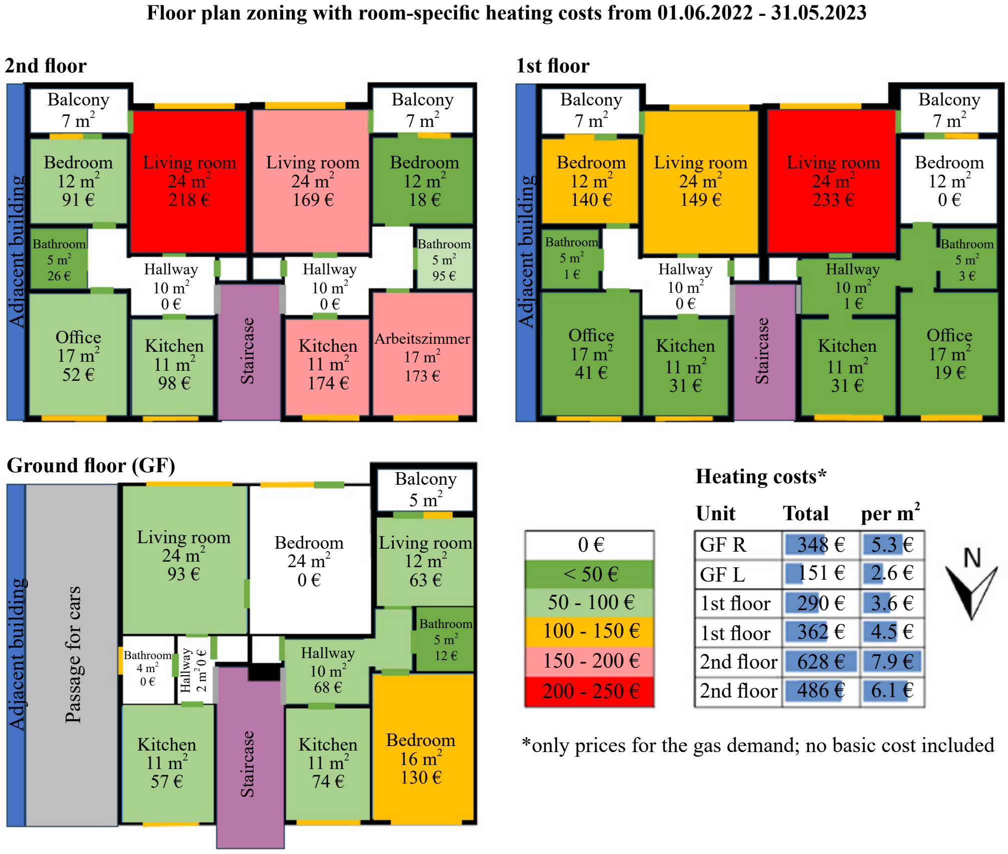


Figure 2. Apartment-specific and total billed heating costs in 2017-2022

Due to the individual sensors mounted to each radiator, a room-specific heat cost distribution is possible (see Figure 3). In this context, the apartment on the 2nd floor on the right stands out because it consistently accounted for more than 20% of the total heating costs (see Figure 2). This could indicate insufficient insulation, possibly due to an unheated exterior wall in the west and the adjacent roof.


Floor plan zoning with room-specific heating costs from 01.06.2022 - 31.05.2023

0 €
< 50 €
50 - 100 €
100 - 150 €
150 - 200 €
200 - 250 €

Heating costs*

Unit	Total	per m²
GF R	348 €	5.3 €
GF L	151 €	2.6 €
1st floor	290 €	3.6 €
1st floor	362 €	4.5 €
2nd floor	628 €	7.9 €
2nd floor	486 €	6.1 €

*only prices for the gas demand; no basic cost included

Figure 3. Room-specific heat requirements for the case study object (01.06.2022-31.05.2023); green = doors, yellow = windows

Furthermore, the following insights can be gained from Figures 2 and 3:

1. The 2nd floor apartment: Compared to the 2nd floor right apartment, the 2nd floor left apartment had a lower share of the total heating costs, despite both apartments being on the same floor and having mirrored floor plans. This could be attributed to the adjacent building (to the east).
2. The 1st floor apartment: Although one might expect the 1st floor left apartment to have the lowest heating costs due to its location, it appears that the heating costs were higher than in the 1st floor right apartment in a yearly comparison (see Figure 2). This could be due to an adjacent partially covered courtyard passage below or different user behavior.
3. The GF apartments: These apartments had the lowest specific consumption values (GF left), despite being adjacent to the unheated cellar space.
4. Room-specific distribution: It is noticeable that corridors and bathrooms were hardly heated, while rooms on the outer side were primarily heated (see Figure 3). The 2nd floor apartments showed the highest consumption, indicating potentially insufficient roof insulation.
5. Living rooms: When considering only the living rooms, they represented a significant portion of the heating costs but occupied a small fraction of the total floor area. This insinuates that residents mainly heated the living rooms while keeping the rest of the apartment less heated.

Based on those insights, the energetic retrofitting should be adjusted to attain not only theoretical energy savings but also practical energy savings measurements.

3.2 *Calculated energy consumption*

Based on the energy certificate, which was created by the energy consultant based on the estimated demand rather than the billed energy consumption, the building has a final energy demand of 179.1 kWh/m²a (category F) and covers a usable area of 551.3 m² (2022). Based on this assumption, the final energy demand should be 98.737 kWh/a. This energy is primarily used for room heating (163 kWh/m²) and water heating (14 kWh/m²). Consequently, the energy certification predicts a room heat demand of 89.861 kWh/a. Comparing those figures to the insights from Chapter 3.1, the predicted numbers differ significantly.

Nevertheless, to recalculate the numbers provided by the energy consultant, the Ubakus tool was used [20]. Utilizing the information gained from the energy consultant regarding the U-values of the given structures and calculating the areas according to those structures based on the building plans, the related room heat demand can be calculated (see Table 4).

Table 4. Calculated room heat demand using Ubakus, the information provided by the energy consultant and the building plans

	U-value in W/m²K	Surface area	Heat loss in kWh/Hp (*)	Proportional heat loss	Heat gains in kWh/Hp
Exterior wall	1.3	285 m²	40.019	32.6%	
South window	2.8	47 m²	13.739	11.2%	14.221
North window	2.8	38 m²	11.255	9.2%	5.978
2nd floor ceiling	0.3	213 m²	7.551	6.2%	
1st floor ground	2.3	123 m²	18.357	15.0%	
Ventilation*			31.854	25.9%	
		Total	**122.776**	**100%**	**20.199**

Note:

- Data from the calculator: Location: Essen; building volume 1,151 m³; room temperature 22 °C; thermal bridge allowance 0.1 W/m²K; air exchange rate of 1.
- (*) Hp.

Taking into account transmission heat losses (90.921 kWh/Hp), ventilation losses (31.854 kWh/Hp), heat gains (solar radiation yields; 20.199 kWh/Hp), and internal gains (12.075 kWh/Hp), the calculated heating demand amounts to 90.502 kWh/Hp [20]. Thus, the calculated heat demand for a total usable area of 551.3 m² is 164.3 kWh/m²a. In comparison to the values obtained from the energy consultant, a minor difference can be observed (163.0 kWh/m²a). Consequently, the Ubakus' calculation could approximate the theoretical heating demand.

Table 3 indicates that the energy loss through the external facade accounts for 33% of the total heat loss, making it the largest share. Window ventilation is responsible for about 26% of the heat losses, and heat losses through the transmission of windows constitute about 20%. It's observed that south-facing windows generate more solar gains than heat losses, but due to seasonal shifts, these gains result in cooling demand in summer, and during winter, the gains are insufficient to offset the losses.

3.3 *Evaluation of passive measures*

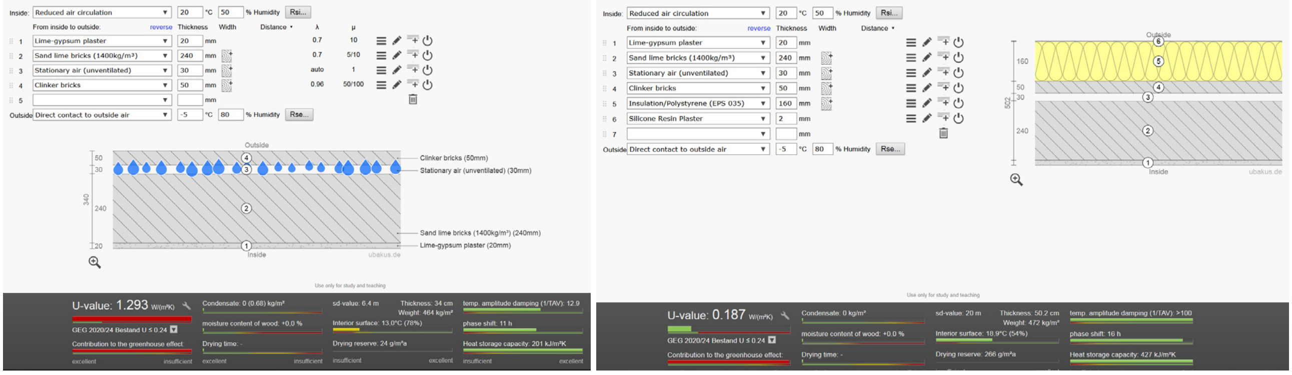
In the following sections, individual passive measures, i.e., the measures for the components in the thermal envelope, will be evaluated and initially presented from ecological and economic standpoints. The social aspect will focus on the economic impact on the tenant, which will be addressed in Chapter 4.2.

3.3.1 *Exterior wall*

The exterior wall, covering an area of 285 m², represents the largest potential surface. According to the information provided by the energy consultant, the exterior wall is constructed as depicted in Figure 4A.

Considering the wall insulation structure proposed by one of the contacted companies, the exterior wall could be insulated with an ETICS system (see Figure 4B). This would involve fixing or bonding a 16 cm thick rigid foam EPS panel onto the existing brickwork, followed by coating the new exterior facade with a silicone resin render. This process could reduce the U-value from 1.3 W/m²K to 0.3 W/m²K.

By adjusting only the U-value of the exterior wall in the Ubakus calculator (see Chapter 3.2), the total heat demand is calculated to be 60.281 kWh/a. This would result in a nearly one-third reduction (30.221 kWh/a) from the previous theoretical consumption of 90.502 kWh/a. The company offered a price of 62.261 € for this measure.



Inside: Reduced air circulation 20 °C 50 % Humidity

From inside to outside:	Thickness	λ	μ
1 Lime-gypsum plaster	20 mm	0.7	10
2 Sand lime bricks (1400kg/m³)	240 mm	0.7	5/10
3 Stationary air (unventilated)	30 mm	auto	1
4 Clinker bricks	50 mm	0.96	50/100
5	mm		

Outside Direct contact to outside air -5 °C 80 % Humidity

U-value: 1.293 W/(m²K)
GEG 2020/24 Bestand U ≤ 0.24
Contribution to the greenhouse effect:
Condensate: 0 (0.68) kg/m²
moisture content of wood: +0,0 %
Drying time: -
sd-value: 6.4 m
Thickness: 34 cm
Weight: 464 kg/m²
Interior surface: 13.0°C (78%)
Drying reserve: 24 g/m²a
temp. amplitude damping (1/TAV): 12.9
phase shift: 11 h
Heat storage capacity: 201 kJ/m²K

Use only for study and teaching

Inside: Reduced air circulation 20 °C 50 % Humidity

From inside to outside:	Thickness
1 Lime-gypsum plaster	20 mm
2 Sand lime bricks (1400kg/m³)	240 mm
3 Stationary air (unventilated)	30 mm
4 Clinker bricks	50 mm
5 Insulation/Polystyrene (EPS 035)	160 mm
6 Silicone Resin Plaster	2 mm
7	mm

Outside Direct contact to outside air -5 °C 80 % Humidity

U-value: 0.187 W/(m²K)
GEG 2020/24 Bestand U ≤ 0.24
Contribution to the greenhouse effect:
Condensate: 0 kg/m²
moisture content of wood: +0,0 %
Drying time: -
sd-value: 20 m
Thickness: 50.2 cm
Weight: 472 kg/m²
Interior surface: 18.9°C (54%)
Drying reserve: 266 g/m²a
temp. amplitude damping (1/TAV): >100
phase shift: 16 h
Heat storage capacity: 427 kJ/m²K

Use only for study and teaching

(A) (B)

Figure 4. (A) Prior structure of the exterior wall. (B) Structure with recommended insulation

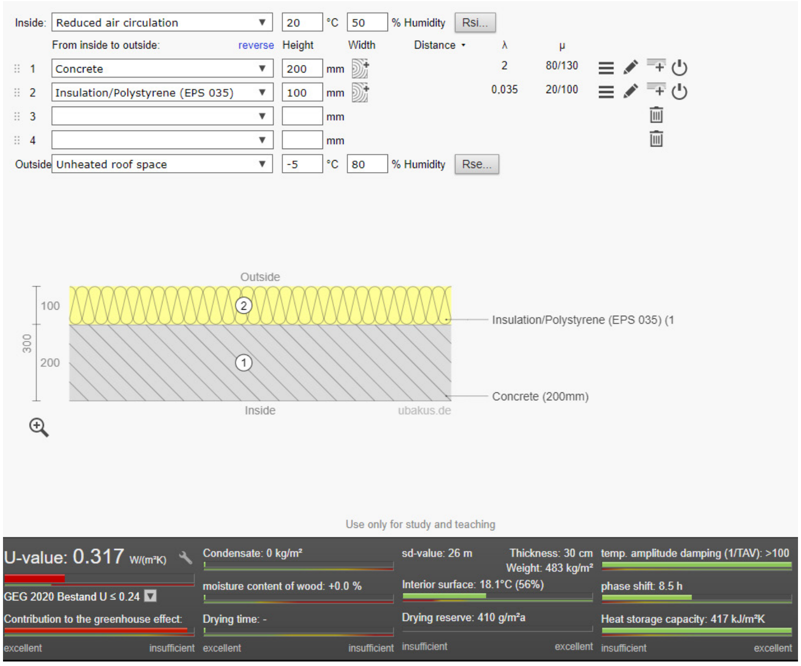
3.3.2 *Windows*

The window area covers 85 m² and represents the building section with the highest U-value of 2.8 W/m²K within the MFH. The relatively small area could be compensated by significantly improving the U-value by over 2 W/m²K. The final U-value would amount to 0.76 W/m²K with a triple-glazed unit. Additionally, replacing the windows could enhance the air tightness. As described in Chapter 2.1, there have been tenant reports regarding draft windows. The potential savings concerning air tightness are challenging to estimate without additional testing.

Similar to the exterior wall, only the U-value of the windows was altered for calculation purposes, observing its impact on heat demand. In this scenario, the heat demand has decreased from 90.502 kWh/a to 79.101 kWh/a. Therefore, the window replacement theoretically saves 11.401 kWh/a and is estimated to cost 48.788 €, according to the offer made by the contacted companies.

3.3.3 *Attic floor*

The attic floor has already been retrofitted with 100 mm thick EPS foam panels. Consequently, the higher specific heating costs per square meter on the 2nd floor can primarily be explained by individual tenant behavior rather than the presumed uninsulated roof/attic floor (see Chapter 3.1). The structure of the attic floor is illustrated in Figure 5.



Inside: Reduced air circulation 20 °C 50 % Humidity

	From inside to outside:	Height		λ	μ
1	Concrete	200	mm	2	80/130
2	Insulation/Polystyrene (EPS 035)	100	mm	0,035	20/100
3			mm		
4			mm		

Outside Unheated roof space -5 °C 80 % Humidity

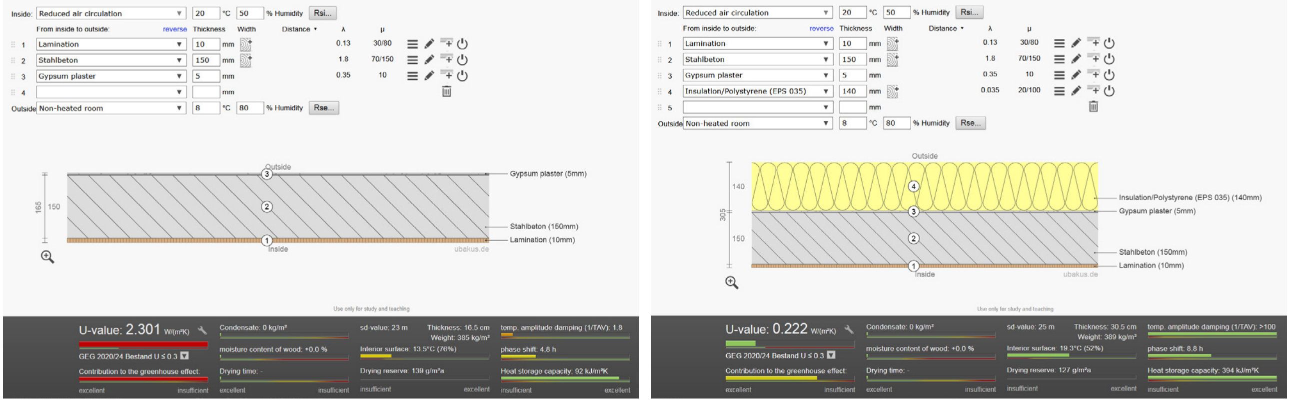
U-value: 0.317 W/(m²K)
GEG 2020 Bestand U ≤ 0.24
Contribution to the greenhouse effect:
Condensate: 0 kg/m²
moisture content of wood: +0.0 %
Drying time: -
sd-value: 26 m
Thickness: 30 cm
Weight: 483 kg/m²
Interior surface: 18.1°C (56%)
Drying reserve: 410 g/m²a
temp. amplitude damping (1/TAV): >100
phase shift: 8.5 h
Heat storage capacity: 417 kJ/m²K

Figure 5. Structure of the attic floor

3.3.4 *Cellar ceiling*

The insulation of the cellar ceiling might be questionable due to the low heating costs per square meter in the GF apartments (see Figure 3). However, this could be attributed to individual user behavior and may change in the future. The structure of the uninsulated cellar ceiling is depicted in Figure 6A, while a theoretically insulated structure, analogous to the attic floor, is shown in Figure 6B.

The insulation of the cellar ceiling, following a similar approach to the steps taken for window replacement and exterior wall insulation, would decrease the theoretical heating demand from 90.502 kWh/a to 75.321 kWh/a.



(A)

Inside: Reduced air circulation 20 °C 50 % Humidity

From inside to outside:	Thickness		λ	μ
1 Lamination	10	mm	0.13	30/80
2 Stahlbeton	150	mm	1.8	70/150
3 Gypsum plaster	5	mm	0.35	10
4		mm		

Outside Non-heated room 8 °C 80 % Humidity

U-value: 2.301 W/(m²K)
GEG 2020/24 Bestand U ≤ 0.3
Contribution to the greenhouse effect:
Condensate: 0 kg/m²
moisture content of wood: +0.0 %
Drying time: -
sd-value: 23 m
Thickness: 16.5 cm
Weight: 385 kg/m²
Interior surface: 13.5°C (76%)
Drying reserve: 139 g/m²a
temp. amplitude damping (1/TAV): 1.8
phase shift: 4.8 h
Heat storage capacity: 92 kJ/m²K

(B)

Inside: Reduced air circulation 20 °C 50 % Humidity

From inside to outside:	Thickness		λ	μ
1 Lamination	10	mm	0.13	30/80
2 Stahlbeton	150	mm	1.8	70/150
3 Gypsum plaster	5	mm	0.35	10
4 Insulation/Polystyrene (EPS 035)	140	mm	0.035	20/100
5		mm		

Outside Non-heated room 8 °C 80 % Humidity

U-value: 0.222 W/(m²K)
GEG 2020/24 Bestand U ≤ 0.3
Contribution to the greenhouse effect:
Condensate: 0 kg/m²
moisture content of wood: +0.0 %
Drying time: -
sd-value: 25 m
Thickness: 30.5 cm
Weight: 389 kg/m²
Interior surface: 19.3°C (52%)
Drying reserve: 127 g/m²a
temp. amplitude damping (1/TAV): >100
phase shift: 8.8 h
Heat storage capacity: 394 kJ/m²K

Figure 6. (A) Prior structure of the cellar ceiling. (B) Structure with insulation

3.3.5 *Theoretical added value of insulation*

The theoretical economic value of the insulation measures while maintaining the existing heating system is derived from the previously calculated total prices for the gas heating system (see Table 2). The average value of the last three years can serve as a reference. Although this period might encompass the effects of the COVID-19 pandemic and the Ukraine war, the average value provides a certain balance. Based on this, every saved kWh of gas would lead to a cost reduction of 9.67 $€_{cents}$/kWh_{th}.

Moreover, assuming no annual adjustment of the gas price with respect to inflation and no further changes in gas and CO_2 prices, static payback periods can be calculated. The energy retrofitting measures are eligible for funding under the individual measures funding of the BAFA [21]. This funding allows support of 15% of the cost for each measure (up to 60.000 € per apartment and 600.000 € per building) [22]. Additionally, an extra 5% of funding is granted if an individual renovation plan has been created in advance by an energy consultant [22]. Thus, there is a total funding of 20% per measure. Table 5 reveals that the exterior wall insulation would yield the quickest return on investment and hold the greatest potential for economic savings.

Table 5. Economic perspective on the insulation measurements

Measure	Energy demand after the retrofit in kWh/a	Savings in kWh	Savings in €	Investment in €	Subsidy in €	Amortization period in years (with subsidy)
Exterior wall	60.281	30.221	2.924	62.261	12.452	17.04
Window replacement	79.101	11.401	1.103	48.788	9.758	35.38
Cellar ceiling	75.321	15.181	1.468	No offer available		

Table 5 reveals that insulating the cellar ceiling might offer a more favorable energy-saving effect than window replacement. At the same time, insulating the cellar ceiling could be more cost-effective compared to the window replacement, as it might only require materials to be added to the cellar ceiling, and the required labor might potentially be lower. Nevertheless, the apartments on the 1st floor, as introduced in Chapter 3.1, are already among those with the lowest specific heating costs, raising questions about the actual benefit given the current user behavior.

However, it is important to consider that, due to the BEHG, rising CO_2 prices can be anticipated as annual CO_2emissions are limited and priced [23]. This could positively impact payback periods since saved fuel would become more expensive. Using the Ubakus Ecobalance calculator and the database from the Ökobaudats Institute for this purpose, the ecological impacts are presented in Table 6.

Table 6. Environmental impact of discussed measurements

Measure	Greenhouse gas potential in kg CO_2-eqv./m²	CO_2 emissions caused by the raw materials in kg CO_2 (*)	CO_2 saved as the amount of natural gas saved in kg CO_2	CO_2 amortization in years
Exterior wall [18]	18	5.130	6.346	0.8
Window replacement [24]	204	17.340	2.394	7.2
Cellar ceiling [25]	11	1.353	2.963	0.5

Note:
- (*) GWP-total with phases A1-A5, B2-B7, C1-C4, and D

3.4 *Evaluation of active measures*

As mentioned in Chapter 2, the active measures, i.e., those connecting to building services, were also considered to improve the overall energy balance of the MFH. A PV system and a heat pump were investigated as follows.

3.4.1 *PV system*

The PV system could be installed on the 138 m² large, 30° inclined, and south-facing gable roof. Unfortunately, the area cannot be fully utilized currently due to small window openings, three chimneys, and a satellite dish preventing the complete occupancy of the roof. Therefore, some areas have been kept clear, and the remaining space has been covered with "IBC solar AG-18C MonoSol 420 MS10-HC-N" PV modules. A total of 46 modules with an installed capacity of 19.32 kW_p were used, as shown in Figure 7, using the software PV*SOL (PV Sol; [26]). Subsequently, 23 modules each were connected in series and wired to one of the two MPP trackers of the "FRONIUS Symo 17.5-3-M" inverter. The configuration of the modules and the positions of the obstructing objects are depicted in Figure 7.

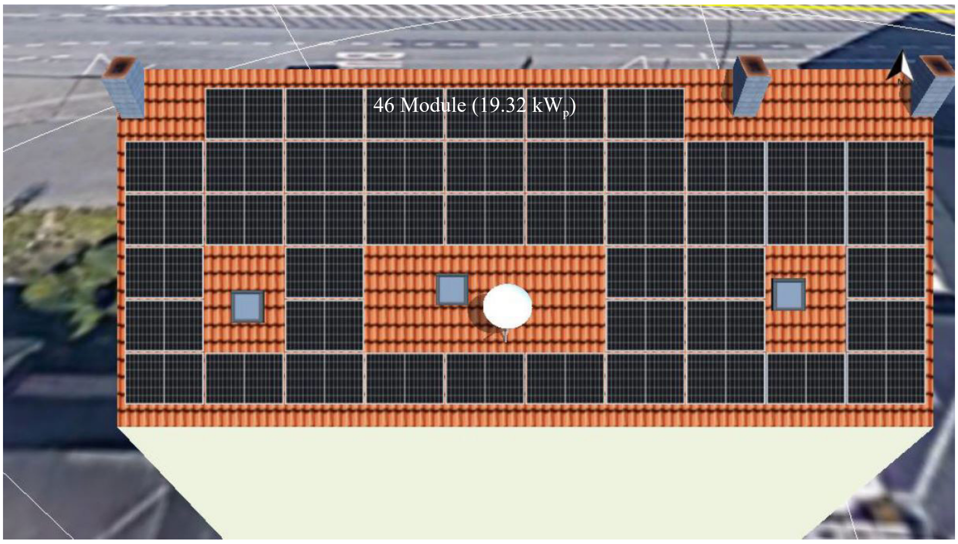


Figure 7. Potential PV system installed on the roof surface

With the provided information, PV*Sol calculates an annual electricity generation of 19.136 kWh/a [26]. Assuming an electricity consumption of 22.139 kWh/a, based on the number of tenants living in each flat including household electricity, electric hot water generation, and the distribution of the energy quantity using a standard load profile from PV*Sol, self-consumption and autonomy can be calculated [27]. The "household, seasonal course comparable with a standard load profile" load profile was selected for the dynamization of the energy quantity. With this profile, a theoretical self-consumption of 6.208 kWh/a (32.4%) and an autonomy rate of 28.0% are calculated.

From an economic perspective, the installation of the PV system can lead to cost savings in terms of electricity savings. The cheapest electricity tariff for a residential unit in the apartment building was assumed to be 33.2 $€_{cent}$/kWh with a monthly basic price of 12.11 €. For the designed PV system, an online offer calculator was used and suggested a price of 30.825 € for 46 modules. This corresponds to an installed capacity of 19.32 kW_p and a specific investment of 1.595 €/kW_p.

Comparing the electricity price of 33.2 $€_{cent}$/kWh with the specific electricity generation cost of 11.89 $€_{cent}$kWh from PV*Sol, the economic value of self-consumed electricity becomes evident. Through self-consumption, savings of 21.31 $€_{cent}$/kWh (nearly two-thirds of the electricity price) can be achieved. However, for feed-in, the PV system receives a fixed feed-in tariff of 7.67 $€_{cent}$/kWh, resulting in losses of 4.22 $€_{cent}$/kWh for every kWh fed into the grid. Nevertheless, the forecasted ratio of self-consumption and feed-in indicates that the system would financially amortize after 12.5 years.

From an ecological standpoint, the generated electricity can be compared to the grid's electricity mix. In 2022, the grid's electricity mix had a carbon footprint of 434 gCO_2/kWh [28]. With a total production of 19.136 kWh/a, approximately 8.3 tCO_2/a could be saved. However, the production-related CO_2 emissions for a PV system with a 30-year lifespan are estimated at 43-63 gCO_2e/kWh [29]. Considering these aspects, the CO_2 savings would range between 7.1 and 7.5 tCO_2/a. With a 30-year lifespan and constant production quantity, the total emissions "caused" by the PV system would range between 24.7 and 36.2 tCO_2. With a saving of 7.1-7.5 tCO_2/a, the system would environmentally amortize within two to three years.

Overall, it is evident that the installation of a PV system would be financially and ecologically profitable. However, the PV systems are linked in Germany by the EEG and encounter bureaucratic hurdles if the landlord-tenant situation is established [30]. In order to supply and invoice electricity to their tenants, landlords must have the corresponding legal capability, either through a self-registered service or through a commission (§ 21 Para. 3 EEG). The associated process requires time and effort, which may discourage landlords from this option. Moreover, as tenants have the freedom to select their energy supplier, the landlords are likely to provide electricity generated by their PV systems to the tenants only if the offered price is more cost-effective than their other options. Because of these reasons, a PV system was not suggested, even though it was in general economically and environmentally beneficial.

3.4.2 *Heat pump*

The ASHP system was further examined based on recommendations from the literature [1]. Consideration must be given to the interactions between the insulation measures, the new heating system, and the existing gas condensing unit. An offer was made by one of the contacted companies for the integration of the ASHP, demanding a total of 52.549 €, with 35% of the installation eligible for funding [21]. The offer includes the integration of a 16 kW ASHP with a 500-liter buffer tank. After deducting the subsidy, this measure would cost 34.157 €. However, the question arises whether the installation of the ASHP should be carried out simultaneously with the insulation measures.

On one hand, the ASHP could act as a base load heater during transition periods (autumn and spring), assisting in relieving the existing natural gas heating. During peak demand periods, the potentially oversized natural gas heating system could support the HP. This way, the existing heating system from 2019 could be used while enhancing independence from natural gas and CO_2 prices.

On the other hand, studies in the literature suggest that for MFHs transitioning from a previous gas heating system to an ASHP, additional costs of 2.444 € and a reduction in greenhouse gas emissions of 23.4% are to be expected. Hence, the economical operation of the HP can only be feasible if either the CO_2 prices increase significantly and the CO_2 footprint of the electricity grid decreases, the HP is considerably more efficient than the existing gas condensing unit, or the electricity purchase price decreases significantly.

Since none of the measures described in Chapter 3.3 have been implemented yet, estimating the actual benefits is challenging. As mentioned in Chapter 3.1, the projected heat demand (90.502 kW/a) significantly deviates from the billed heat demand (40.693 kWh in 2022). Accordingly, if the actual heat demand is lower, the ecological and economic amortization periods of the insulation measures would further extend. If the installation of the HP proves to be economically and ecologically viable, the amortization periods for the insulation measures would be further prolonged. The HP would produce heat at more favorable prices and with lower CO_2 emissions, therefore reducing the theoretical savings compared to the gas condensing unit. Hence, only the consideration of the insulation and replacement measures is currently being contemplated. Therefore, based on the subsequently measured consumption, a heating system modernization should not be carried out.

However, the interaction between the gas heating system and the HP should be examined, and key parameters such as the CO_2 price at which the HP becomes economically viable need to be determined. For this purpose, the nPro tool was used. In the web application, the MFH was modeled using the data from the energy certificate, and energetic retrofits were simulated. Scenarios, including the PV system, were also simulated. The PV system could offer a way to obtain electricity at a lower cost, thereby increasing the profitability of HP. Nonetheless, the electricity is seasonally shifted, as it's produced in the summer and needed for heating in the winter.

The simulation was mainly conducted using the recommended standard values from nPro. The following parameters were used for the simulation:

Table 7. Assumptions for the nPro simulation

Category	Price
Electricity price	33.20 $€_{cent}$/kWh
Feed-in tariff	7.67 $€_{cent}$/kWh
Gas price	9.67 $€_{cent}$/kWh
Investment cost for the heat pump (16 kW heat pump; offer price minus subsidy 34.157 €)	2.135 €/kW_{th}
Size of the PV system	19.32 kW_p
Investment cost for the PV system	1.595 €/kW_p
Increase in natural gas and electricity prices	2%
CO_2 factor for electricity purchase	434 g/kWh
CO_2 factor for natural gas purchase	250 g/kWh

The tool then determines, based on the given data, the ecological and economic way to operate this energy system. CO_2 prices of 0 €/t, 50 €/t, 200 €/t, and 500 €/t are assumed in four scenarios. When evaluating these default settings for the fully insulated variant (window replacement, exterior wall insulation, and cellar ceiling insulation) and the uninsulated base variant, each with the option of a 19.32 kW_p PV system, the following insights could be gained (see Appendix Tables 11 and 12):

1. With an increasing CO_2 price, the share of installed capacity of the ASHP also increases. If there's an expected decarbonization of the electricity mix, its economic viability will further improve in the future.
2. In all scenarios, a PV system is implemented, demonstrating economically viable operations even if the operation of the system is legally complicated (see Chapter 3.4).
3. In the fully insulated variant, the ASHP is not used even at CO_2 prices of 200 €/t. This confirms the higher anticipated additional costs mentioned in Chapter 2.1. Only at CO_2 prices of 500 €/t, nPro would suggest using a 4 kW_{th} HP.
4. If the insulation measures are carried out as planned, the installed capacity of the natural gas heating could be reduced by nearly 50%.
5. In the uninsulated variant, the HP is applied in all systems. However, installing a 4 kW_{th} (50-100 €/t), 8 kW_{th} (200 €/t) or 24 kW_{th} (500 €/t) is highly dependent on the CO_2 price. This also sets in certain "lock-in" mechanisms, because if the building is renovated, the operation of the existing gas system would be cheaper due to the high investment costs of the ASHP.

It's also crucial to note the discrepancy between the billed heating demand and the predicted heating demand. In 2022, a heating demand of 40.693 kWh was billed, whereas the energy consultant had made a forecast of 90.502 kWh/a. Therefore, the implementation of the ASHP is difficult to estimate given the significant deviation between actual consumption and the forecast, making it challenging to predict actual consumption post-insulation measures.

Consequently, the installation of the ASHP is only considered after the insulation measures have been implemented and the energy savings have been observed and monitored.

4. Discussion

4.1 *Investor perspective*

From the perspective of investors, the primary consideration lies in the feasibility and profitability of the measures. In this context, the saved gas quantity is not relevant; instead, their attention might be directed toward the possibilities for rent increases and the improvement of the energy certificate. The planned insulation measures can be categorized as modernization measures according to § 555b Para. 1 of the BGB [31]. This allows the landlord, in accordance with § 559 Para. 1 BGB, to increase the rent after carrying out the modernization measures [31]. The rent increase is limited to 8% of the costs incurred for the apartment in accordance with § 559 Para. 1 BGB and, as per Para. 3a, must not exceed 3 €/m² within six years [31]. Since in this case the rents are below 7 €/m², the rent can only be increased by 2 €/m² (over six years) (see § 559 Para. 3a Sentence 2 BGB [31]). It is important to note that these are the actual costs incurred by the landlord. Therefore, the 8% can be applied to the costs minus any subsidies. The cost components concerning rent increases, costs, and incentives are listed in Table 8.

Table 8. Components of investment and rent increase rent based on the retrofitting measures

Measure	Energy requirement after modernization	Costs	Subsidies	Total investment after subsidies	Monthly rent increase according to § 559 BGB
External facade insulation	60.281 kWh/a	62.261 €	12.452 €	49.809 €	0.75 €/m²
Window replacement	79.101 kWh/a	48.787 €	9.758 €	39.029 €	0.58 €/m²
Basement ceiling	75.321 kWh/a				
Total		**111.049 €**	**22.210 €**	**88.839 €**	**1.37 €/m²**

For the cost of 88.839 € over a gross rented area of 443 m^2, the investment per area unit is 200.54 €/m^2. It will have paid for itself under full occupancy in the 12th year. Since then, the yearly rent increase will also be an added value for the landlords (Table 9).

Table 9. Economic potential from the landlord perspective

Investment per area unit	Monthly rent increase per area unit	Yearly rent increase per area unit (also, the yearly added value after the amortization period)	Amortization period
200.54 €/m^2	1.37 €/m²	16.44 €/m^2	12.19 years

4.2 *Tenant perspective*

From the perspective of the tenants, the rent increases and the theoretical savings in heating costs need to be calculated. The landlord would most likely implement rent increases according to § 559 of the BGB. Table 10 expresses the rent increases with the heating savings.

Table 10. Impact of energetic retrofitting measurements on the tenant

Measure	Theoretical rent increase according to § 559 BGB	Theoretical heating cost savings	Added value	Theoretical total costs for kWh of natural gas in $€_{cent}$/kWh
Exterior wall insulation	0.75 €/m²	0.55 €/m²	-0.20 €/m²	13.19
Window replacement	0.58 €/m²	0.21 €/m²	-0.38 €/m²	27.39
Total	**1.37 €/m²**	0.76 €/m²	-0.58 €/m²	

According to Table 8, the refurbishment measures would not be cost-effective for the tenants at the current overall price of natural gas at 9.67 $€_{cents}$/kWh. The tenant would pay an additional 0.58 €/m² compared to what they would theoretically save through the gas consumption reduction. Only at gas prices of 13.19 $€_{cents}$/kWh and 27.39 $€_{cents}$/kWh would the measures break even for the tenants.

Given that the actual billed heating demand is significantly lower than the predicted demand, the real cost savings on heating are likely to be lower than the calculated theoretical savings (0.76 €/m²). Consequently, the theoretical total costs for natural gas would increase, making it currently less economically attractive for the tenant.

5. Conclusions

This paper investigated the energy modernization of an apartment building constructed in 1968. The six apartments exhibit diverse sizes and heating demands. A data-point-specific evaluation of heating costs revealed that primarily the rooms positioned on the exterior were heated, with the living room being heated most significantly. To align with the German government's objectives and achieve a climate-neutral building stock by 2045, a comprehensive retrofitting of the apartment building is necessary. Consequently, an appropriate energy modernization roadmap was devised for the apartment building based on approaches from the literature and recommendations from an energy consultant. The planning considered ecological, economic, and social factors. Within the social context, the focus was on the economic impact on tenants and the acceptance of these measures. Following this approach, a conceptual framework was developed, and energy flows were quantified using various tools such as nPro, Ubakus, and PV*Sol (see Figure 8).

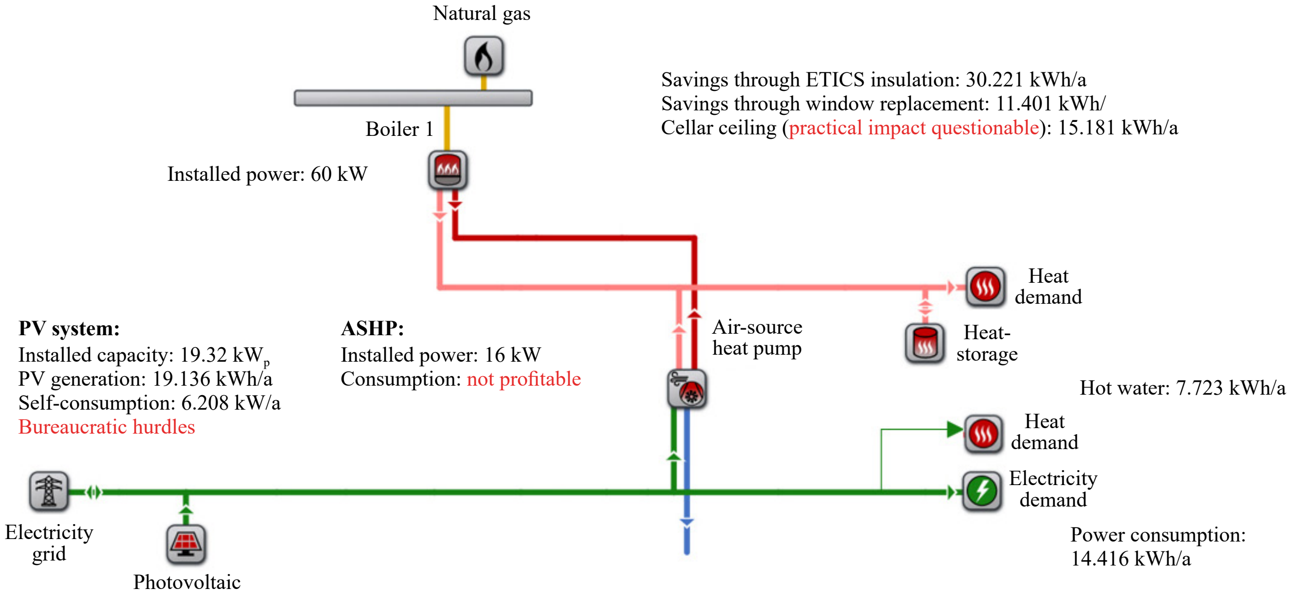


Figure 8. Final energy concept (in red, reasons for not implementing the measure)

During the examination of this case study, new insights emerged regarding the planned PV system, ASHP, and cellar ceiling insulation. Despite the ecological and economic viability of a partially-fed PV system, it was discovered to be challenging to implement due to bureaucratic complexities related to the landlord-tenant situation. The ASHP aimed to alleviate the gas heating system and be used during peak demand periods. However, it was discovered that the ASHP, in its current uninsulated state, would initially be undersized and would only be economically viable in the insulated version once CO_2 prices exceeded 200 €/t. Furthermore, the actual savings resulting from insulation measures are currently only theoretically estimable, as they are significantly influenced by individual user behavior, thereby significantly affecting the utilization of the ASHP. The cellar ceiling insulation was initially not further considered as the data point analysis of billed heating costs indicated that the GF apartments already had low specific heating costs. Consequently, the actual benefit of cellar ceiling insulation with this current user behavior would be questionable.

From an economic perspective, it was evident that insulating the exterior wall would offer the most significant savings at relatively low costs. Window replacement, although significant in potentially improving U-values, was the slowest in terms of economic and ecological return due to its small surface area and high costs. Nonetheless, window replacement could enhance thermal comfort by increasing airtightness and preventing uncomfortable drafts. Ecologically, both external facade and cellar ceiling insulation would amortize in less than a year, whereas window replacement would take longer, with an amortization period of 7.2 years based on the current heating system. Ultimately, it is crucial to note that the theoretical heating cost savings for the tenant are lower than the proposed rent increases. This implies that the planned measures (external facade and window replacement) would only financially benefit the landlord after approximately 12 years with full occupancy, following § 559 BGB, which would increase rent by 1.37 €/m². However, the exact real savings are unknown and could significantly influence the calculations. As the actual consumption might be below the theoretical saving, this would negatively impact the feasibility of the tenants. Consequently, it depends on the investors' perspective to weigh whether the economic and ecological factors of the measures are decisive and whether the additional costs for the tenants are reasonable. From the tenants' side, the retrofit can be more viable if gas and CO_2 prices increase in the future.

The insights gained on the landlord-tenant dilemma show the necessity of changing the current policy framework in such a way that tenants would also profit from the retrofitting measures. This paper shows that, in theory, the landlord would indirectly and not proportionally economically profit from applying the retrofitting measures. Although the landlord shoulders the risk and must raise the initial capital for the measure, the financial gap between tenant and landlord should be reduced. Potentially, a policy could be created that somehow links the heat cost reduction to the investments of the landlord, which could increase social acceptance by the tenants.

The methods developed in this paper can be applied to different building typologies in various countries. Using Ubakus and PV*Sol, the heat demand and PV generation can be accurately calculated. However, this theoretical calculation might be influenced by changing geographical-dependent user behavior, which has a significant impact on the economic and environmental rentability of the applied measures.

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Conflict of interest

There is no conflict of interest in this study.

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Appendix

Table 11. nPro simulation results in the uninsulated case

	System 1	System 2	System 3	System 4
CO_2 price	0 €/t	50 €/t	200 €/t	500 €/t
Total annual costs in €/a	ca. 20.000	ca. 20.000	ca. 20.000	ca. 23.000
Comparison to system 1		+ 0%	+ 0%	+ 15%
CO_2 emissions in t/a	ca. 32	ca. 32	ca. 30	ca. 21
Comparison with system 1		+ 0%	– 6%	– 34%
Photovoltaics	13 kW_p	13 kW_p	18 kW_p	20 kW_p
Natural gas boiler 1	56 kW_{th}	56 kW_{th}	53 kW_{th}	40 kW_{th}
Air heat pump	4 kW_{th}	4 kW_{th}	8 kW_{th}	24 kW_{th}
Heat storage tank	0 kWh/0 m^3	0 kWh/0 m^3	16 kWh/0.69 m^3	40 kWh/1.7 m^3
Electricity consumption in MWh/a	ca. 17	ca. 17	ca. 18.9	ca. 36.3
Electricity feed-in in MWh/a	ca. 3.9	ca. 4.1	ca. 6.5	ca. 6.5
Natural gas consumption in MWh/a	ca. 100	ca. 100	ca. 86	ca. 22.8

Table 12. nPro simulation results in the insulated case

	System 1	System 2	System 3	System 4
CO_2 price	0 €/t	50 €/t	200 €/t	500 €/t
Total annual costs in €/a	ca. 14.515	ca. 14.517	ca. 14.545	ca. 14.976
Comparison to system 1		+ 0%	+ 0%	+ 3%
CO_2 emissions in t/a	ca. 20	ca. 20	ca. 20	ca. 19
Comparison with system 1		+ 0%	+ 0%	– 5%
Photovoltaics	12 kW_p	12 kW_p	14 kW_p	19 kW_p
Natural gas boiler 1	31 kW_{th}	31 kW_{th}	31 kW_{th}	30 kW_{th}
Air heat pump	0 kW_{th}	0 kW_{th}	0 kW_{th}	4 kW_{th}
Heat storage tank	0 kWh/0 m^3	0 kWh/0 m^3	0 kWh/0 m^3	7 kWh/0.3 m^3
Electricity consumption in MWh/a	ca. 15.9	ca. 15.8	ca. 15.2	ca. 15.7
Electricity feed-in in MWh/a	ca. 0.92	ca. 1.1	ca. 1.7	ca. 3.1
Natural gas consumption in MWh/a	ca. 53	ca. 53	ca. 53	ca. 47.7