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The Economic Challenges of Deep Energy Renovation—Differences, Similarities, and Possible Solutions in Central Europe: Austria and Germany

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ABSTRACT

Within EBC Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings *(IEA 2015) strategies are developed to increase pace and quality of deep energy retrofit (DER) projects in the public sector. Annex 61, Subtask A's target is to assess accomplished DER projects to define and find optimized measure bundles from both energy-efficiency and economical perspectives in each of the participating countries. Based on general assumptions defined by the Annex 61 team, modeling studies for different types of buildings and different climate zones have been done. The following scenarios and assumptions for all national case studies have been defined.*

Scenario 1 (baseline) represents the pre-1980 standard to describe the building envelope and systems before any renovation addressing the consumption of site energy, heating, and electricity. Scenario 2 (base case) is the country-specific "business as usual" retrofit; in this case, the retrofit is initiated by a general repurposing and only considers minimum requirements by the national building code. Scenario 3 has to achieve approximately 50% energy reduction relative to the baseline (Scenario 1), and Scenario 4 aims to achieve the current national "dream energy standard" (which can be the national definition for net zero energy buildings [WDBG 2014], Plusenergy Standard, Passive House [PHI 2015a], etc.). Targets to be reached in all scenarios are based on the site energy demand, including all kinds of energy use, such as domestic hot water (DHW), heating, cooling, lighting, household electricity, plug loads, and others.

The results of the modeling will be different U-factors for the thermal envelope and specific HVAC and supply systems. For each component, the investment costs are calculated and a 40-year life-cycle cost analysis is prepared, considering the global costs and benefits for energy- and non-energy-related measures. To decide between different scenarios, the incremental energy-related costs and benefits of each scenario are compared to each other. In this paper, the modeling results of Austrian and German case studies are presented.

The Austrian modeling project is a multistory housing block with four floors and 24 flats in the city of Kapfenberg, constructed in 1960–1961. The total site energy demand (DHW, heating, and supply and household electricity) of Scenario 1 is 155 kWh/m^{2}yr (49 kBtu/ft^{2}yr) and has been reduced in Scenario 4 to 71 kWh/m^{2}yr (23 kBtu/ft^{2}yr), achieving the Passive House standard (heating energy demand of 15 kWh/m^{2}yr [5 kBtu/ft^{2}yr]). Measures from Scenario 2 and 3 focused only on the reduction of transmission losses (e.g., improvement of insulation, change of windows) and the reduction of infiltration losses, as these measures enable the achievement of the required energy use intensities (EUIs) in a cost-efficient way. To achieve the Austrian dream target (Passive House standard [IPHA n.d.]) in Scenario 4, the implementation of mechanical ventilation with heat recovery is necessary, which means higher investment costs (higher costs for energy saved) from the cost point of view.

The German modeling project is a compact (Building envelope area in m^2/building volume in m^3 [A/V]: 0.38) multistory office block with three floors and 1680 m^2 (18.083 ft^2) net floor area in the city of Darmstadt, Hesse, constructed in1962 and situated in ASHRAE Climate Zone 5. The building was refurbished in 2012 and allowed the calibration of the modeling using the performance data (Scenario 4). The total site energy demand (DHW, heating, supply and household electricity) taken as the baseline was the consumption collected

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from the utility bills: 236 kWh/m^{2}yr (75 kBtu/ft^{2}yr) heating and 20 kWh/m^{2}yr (6 kBtu/ft^{2}yr) electricity. Compared to average EUIs for German office buildings <10,000 m^2 (<107.639 ft^2), the heating consumption is 12% over average, and the electricity consumption is 18% below average. Typical for office buildings of that size and age is that air conditioning was only in use for the IT server and the restrooms, but not for the office spaces. Following the requirements of the German national building code for refurbishment of the building stock in Scenario 1 leads to a reduction of 39% of primary energy including plug loads, or 41% final energy for heating. In Scenario 2, the standards for new buildings were adopted with significant reduction of thermal bridges and air leakage and a 67% decrease in primary energy and 72% decrease in final energy for heating. Scenario 4 considered the Passive House standard for building stock and depicts exactly the situation after the refurbishment was accomplished, with 76% primary energy savings and 81% final energy for heating savings. Scenario 4 actually achieved 48 kWh/m^{2}yr (14kBtu/ft^2 yr) heating site energy after refurbishment. Because of the improved airtightness of the thermal envelope, the minimum requirements for indoor air quality required the implementation of a mechanical ventilation system with high-efficiency heat recovery but without cooling. The assessment of the life-cycle cost analysis showed the best net present value (NPV) is for Scenario 2 (adoption of building code for new buildings) while the second best is Scenario 4 (cost-optimized Passive House scenario). The main difference between the two scenarios is that Scenario 2 has only a cheap exhaust air system and Scenario 4 has a costly ventilation system with heat recovery. The added insulation for Scenario 4 has almost no impact on the NPV because the delta costs are refinanced by the energy savings.

This paper describes the baselining and modeling process; describes the economic assumptions made for energy prices, maintenance, and other operating costs; and considers the investment costs and the cost optimization process.

INTRODUCTION

Many governments worldwide are setting more stringent targets for reductions in energy use in government/public buildings. Buildings constructed more than 10 years ago account for a major share of energy used by the building stock. However, the funding and know-how (applied knowledge) available for owner-directed energy retrofit projects has not kept pace with the new requirements. With typical retrofit projects, reduction of energy use varies between 10% and 20%, while experience from executed projects around the globe shows that energy use reduction can exceed 50% and that renovated buildings can cost-effectively achieve the Passive House standard or even approach net zero energy status. Previous research conducted under IEA EBC Annex 46 (IEA 2011) identified and analyzed more than 400 energy efficiency measures that can be used when buildings are retrofitted. Measures include those related to the building envelope, mechanical and lighting systems, energy generation and distribution, internal processes, and others. Implementation of some individual measures (such as building envelope insulation, improved airtightness, and cogeneration) can significantly reduce building heating and cooling loads or minimization of energy waste but require significant investments with long paybacks. However, when a limited number of core technologies are implemented together ("bundled"), they can significantly reduce energy use for a smaller investment, thereby providing a faster payback. Also, reliable data from accomplished deep energy retrofit (DER) is scarcely available, which does not allow for evaluating the exactness of modeling approaches for DER—especially when a bundle of energy efficiency measures is applied. In IEA Annex 61 EBC Subtask A (IEA 2015), modeling efforts in different countries were made to set up a methodology for the determination of such cost-optimized DER bundles. For the modeling, each participant selected one typical building and modeled four scenarios: baseline with national building codes from 1970–80 the base case with the least requirements according to the national building code for renovation of the building stock, 50% of baseline consumption, and a "dream scenario," i.e,. the Passive House standard.

AUSTRIAN MODELING BUILDING

Building Model

The basis of the Austrian modeling project is a multistory housing block with 4 floors and 32 flats in the city of Kapfenberg (DOE Climate Zone 5A, city of Graz) constructed in 1960–1961. The floor plans, construction system, design, and energetic performance are representative for most of the buildings constructed in this period (Figure 1 and Table 1). The building consists of walls constructed with sandwiched concrete elements without additional insulation, a pitched concrete roof, and concrete ceilings. Source energy for heating and domestic hot water (DHW) is the district heating system of the city of Kapfenberg. For modeling, a two-pipe radiator heating system is assumed. Radiators are equipped with thermostats. Room temperature for the whole building is regulated in heat substations depending on outdoor temperatures.

Simulation Methods

Energy performance of the building was simulated by using the energy and indoor climate simulation program Passive House Planning Tool (PHPT) (PHI 2015b). This software is meticulously validated and allows the modeling of internal and solar loads of outdoor climate and HVAC systems. The Austrian Test Reference Year (ASHRAE Climate Zone 5, Graz) is used for outdoor climate conditions. The following parameters/assumptions were chosen for all scenarios:

- Indoor temperature in winter: 21°C (69.8°F)
- Indoor temperature in summer: 25°C (77°F)
- Internal heat gains in winter: 2.1 W/m^2 (0.666 Btu/ft^2)


(a)


(b)

Figure 1 *Views of the Austrian case-study building from (a) east and (b) west.*

Table 1. Characterization of the Austrian Modeling Building

Number of floors	4
Net area, m^2 (ft^2)	2091 (22,507)
Heated area, m^2 (ft^2)	2091 (22,507)
Number of apartments	32
Compactness: Building envelope area in m^2/building volume in m^3, (A/V)	0.38
Usage of building	Residential

- Internal heat gains in summer: 8.7 W/m^2 (2.71 Btu/ft^2)
- Internal heat gains from people: 11.0 kWh/m^{2}yr (34.6 kBtu/ft^{2}yr) based on 1.26 W/m^2 (0.4 Btu/ft^2)
- Lighting: 5.0 kWh/m^{2}yr (17 kBtu/ft^{2}yr); heat from lighting is counted using 0.57 W/m^2 (0.182 Btu/ft^2)
- Appliances and equipment: 12.9 kWh/m^{2}yr (40.6 kBtu/ft^{2}yr); heat from appliances and equipment is counted using 1.38 W/m^2 (0.42 Btu/ft^2)
- DHW consumption: 25 L/person and day
- Ventilation airflow: 0.30 L/h based on a fresh air requirement of 30m^3/person and hour (1.059 ft^2/person and hour)

Economic Calculations

The economic calculations are based on calculated investment costs and the annuities from investment costs and annual energy costs. Costs for maintenance, refurbishment, operation, replacement, and synergies in downsizing of components were not accounted for. The annual costs are collected in a net present value (NPV) method for a lifetime of 40 years. The following parameters/assumptions were chosen for all scenarios:

- Energy price for electricity: € 0.094 kWh
- Energy price district heating: € 0.079 kWh
- Inflation rate: 2.20%
- Interest rate: 3.75%
- Escalation rate price electricity: 3.90%
- Escalation rate price district heating: 4.80%

Simulation Scenarios

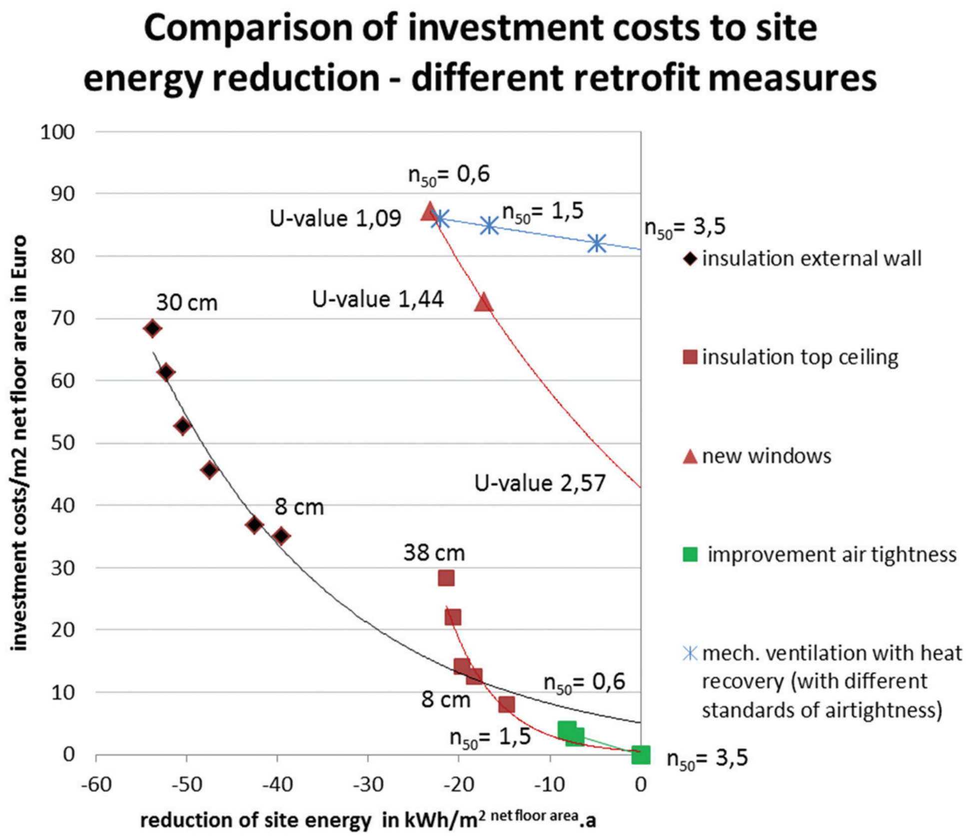
Single Measures: In a first step, investment costs and the energy performance influence of single retrofit measures (e.g., insulation of walls and ceilings, exchange of windows, improvement of airtightness, and the implementation of a mechanical ventilation plant with heat recovery) were investigated. Figure 2 shows the results of this study.

Insulating the exterior of the external wall showed the highest effect on energy and money savings. Investment costs of energy saved per 1 kWh/m$^{2\ \textit{net floor area}}$ (equating to 3.15 kBtu/ft$^{2\ \textit{net floor area}}$yr) range between 0.9 €/m$^{2\ \textit{net floor area}}$ (0.088 €/ft$^{2\ \textit{net floor area}}$) to 1.3 € for an increase of 8 to 30 cm (3.14 to 11 in.) insulation. The trend of the curve shows typical results for the relation of investment costs and energy reduction through increase of insulation: costs for energy saved increase with the improvement of the wall insulation. For the insulation of the top ceiling, the results are similar.

Investment costs of energy saved per kWh/m$^{2\ \textit{net floor area}}$yr (equating to 3.15 kBtu/ft$^{2\ \textit{net floor area}}$yr) for the exchange of windows range between 4.3 €/m$^{2\ \textit{net floor area}}$ (0.46 €/ft$^{2\ \textit{net floor area}}$) for double glazing to 3.78 €/m^2 (0.36 €/ft^2) for triple glazing.

Investment costs of energy saved per kWh/m$^{2\ \textit{net floor area}}$yr (equating to 3.15 kBtu/ft$^{2\ \textit{net floor area}}$yr) for the improvement of the airtightness range between 0.4 to 0.5 €/m$^{2\ \textit{net floor area}}$ (n_{50} = 1.5 to n_{50} = 0.6) (0.036 to 0.046 €/ft$^{2\ \textit{net floor area}}$).

Investment costs of energy saved per kWh/m$^{2\ \textit{net floor area}}$yr for the implementation of a balanced ventilation with



kWh/m²yr	10	20	30	40	50
kBtu/ft²yr	31.46	62.93	94.4	125.86	157.33

Figure 2 *Investment costs of single retrofit measures and energy reduction of the Austrian modeling project.*

heat recovery range between 16.4 to 3.9 €/m$^{2\ net\ floor\ area}$ (n_{50} = 3.5 to n_{50} = 0.6). This equates to 0.15 and 0.36 €/ft$^{2\ net\ floor\ area}$. The huge range emphasizes the importance of good airtightness for buildings with heat recovery.

Scenario 1—Baseline: Scenario 1 represents the Austrian pre-1980 standard for the building envelope and the HVAC system. As there were not legal requirements for the energy performance of buildings before 1980, U-factors of the building envelope were adapted to achieve a heating energy demand of 151 kWh/m$^{2\ net\ floor\ area}$yr (475.15 kBtu/ft$^{2\ net\ floor\ area}$yr), which is the typical energy demand of residential buildings constructed in the period between 1970 and 1980.

Scenario 2—OIB New Building Standard (Base Case): Scenario 2 represents the minimum standard for newly built residential buildings required by Austrian building directive OIB No. 6 (OIB 2011). For the Austrian modeling building, the following requirements are given:

- Minimum heating energy demand: 67 kWh/m$^{2\ net\ floor\ area}$yr (210 kBtu/ft$^{2\ net\ floor\ area}$yr)
- Minimum site energy demand: 135 kWh/m$^{2\ net\ floor\ area}$yr (424.8 kBtu/ft$^{2\ net\ floor\ area}$yr)

Retrofit measures are the improvement of the U-factors of walls, top ceiling, exchange of windows (double glazing) and the improvement of the airtightness of the building envelope (from n_{50} = 3.5 to n_{50} = 1.5).

Scenario 3—50% Energy Reduction Against Scenario 1 (Baseline): This scenario represents the reduction of exactly 50% of the site energy demand of Scenario 1 (baseline). As energy retrofit measures only contribute to the reduction of the heating energy demand, Scenario 3 is split into two scenarios:

- Scenario 3a: 50% reduction of the heating energy demand
- Scenario 3b: 50% reduction of the total site energy demand

Retrofit measures are further improvement of the U-factors of walls, top ceiling, basement ceiling, exchange of windows (double glazing in Scenario 3a, triple glazing in Scenario 3b), and the improvement of the airtightness of the building envelope (from n_{50} = 3.5 to n_{50} = 1.5).

Scenario 4—Best Solution: Scenario 4 represents the best solution (dream scenario of energy savings). Additional measures to Scenario 3b are the improvement of the airtightness (from n_{50} = 1.5 to n_{50} = 0.6) and the implementation of a balanced ventilation with heat recovery (semicentral ventilation plant).

Resume of Modeling Results

An overview of all scenarios and their retrofit measures as well as information on the investment costs per $m^{2\ net\ floor\ area}$ ($ft^{2\ net\ floor\ area}$) is shown in Table 2. Results concerning the energy performance of all scenarios expressed in site (Figure 3) and source energy (Figure 4) given in the following paragraphs.

Scenario 2—OIB new building standard (base case) (OIB 2011)—leads to a reduction of 38% of site energy demand, Scenario 3b—50% reduction of the total site energy demand—achieves a reduction of 50%, and Scenario 4—best solution—achieves a reduction of 55%. As all measures only contribute to the reduction of the heating energy demand (energy demand for supply and household electricity and DHW are the same in all scenarios), energy and cost reduction is only dedicated to district heating. Additional energy demand only emerges in Scenario 4 through supply electricity for the ventilation plant.

Concerning the results on the level of source energy, which are showing lower values than site energy, it has to be mentioned that the district heating of the city of Kapfenberg is a combined heat and power (CHP) station. Energy for DHW and heating is 30% provided with waste heat. Conversion from site to source energy was done with the following factors:

- Source energy factor for heat: 0.70
- Source energy factor for electricity: 2.60

Economic calculations using parameters mentioned in the section "Economic Calculations" show the following dynamic payback periods:

- Scenario 2: 17 years
- Scenario 3a: 17 years
- Scenario 3b: 18 years
- Scenario 4: 25 years

Table 2. Overview of Retrofit Measures, Site Energy Demand in $kWh/m^{2\ net\ floor\ area}yr$ ($Btu/h{\cdot}ft^{2\ net\ floor\ area}{\cdot}°F$) and Investment Costs (in Euro) per $m^{2\ net\ floor\ area}$ ($ft^{2\ net\ floor\ area}$) of the Austrian Modeling Project

Scenarios	1 Baseline—Austrian Pre-1980 Standard	2 OIB No. 6 Minimum Standard	3a 50% Reduction of Heating Energy of Scenario 1	3b 50% Reduction of Total Energy of Scenario 1	4 Best Solution
External wall U-factor, $W/m^2{\cdot}K$ ($Btu/h{\cdot}ft^2{\cdot}°F$)	0.867 (0.167)	0.272 (0.053)	0.315 (0.06)	0.135 (0.026)	0.115 (0.22)
Thickness of insulation, cm (in.)	—	10 (3.9)	8 (3.14)	25 (9.84)	30 (11.81)
Insulation top ceiling U-factor, $W/m^2{\cdot}K$ ($Btu/h{\cdot}ft^2{\cdot}°F$)	0.769 (0.148)	0.208 (0.04)	—	0.159 (0,03)	0.093 (0.018)
Windows U-factor, $W/m^2{\cdot}K$ ($Btu/h{\cdot}ft^2{\cdot}°F$)	2.57 (0.497)	1.44 (0.278)	1.44 (0.278)	1.09 (0.3675)	1.09 (0.3675)
Glazing	Double	Double	Double	Triple	Triple
Basement ceiling U-factor, $W/m^2{\cdot}K$ ($Btu/h{\cdot}ft^2{\cdot}°F$)	0.415 (0.08)	0.415 (0.08)	0.307 (0.059)	0.307 (0.059)	0.307 (0.059)
Airtightness, n_{50}	3.5/h	1.5/h	1.5/h	1.5/h	0.6/h
Ventilation with heat recovery	No	No	No	no	No
Site energy demand, kWh/m^2yr ($kBtu/ft^2yr$)	218 (684)	135 (432)	143 (449)	109 (342)	98 (305)
Investment costs, €/m^2	—	125	111	176	284
Investment costs, €/ft^2	—	11.5	10.6	16.8	26.3

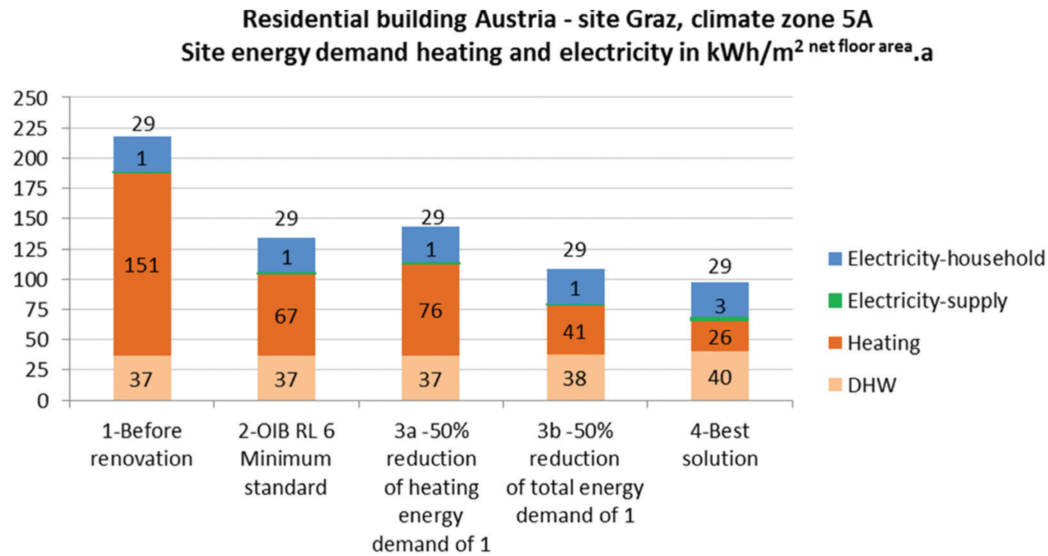
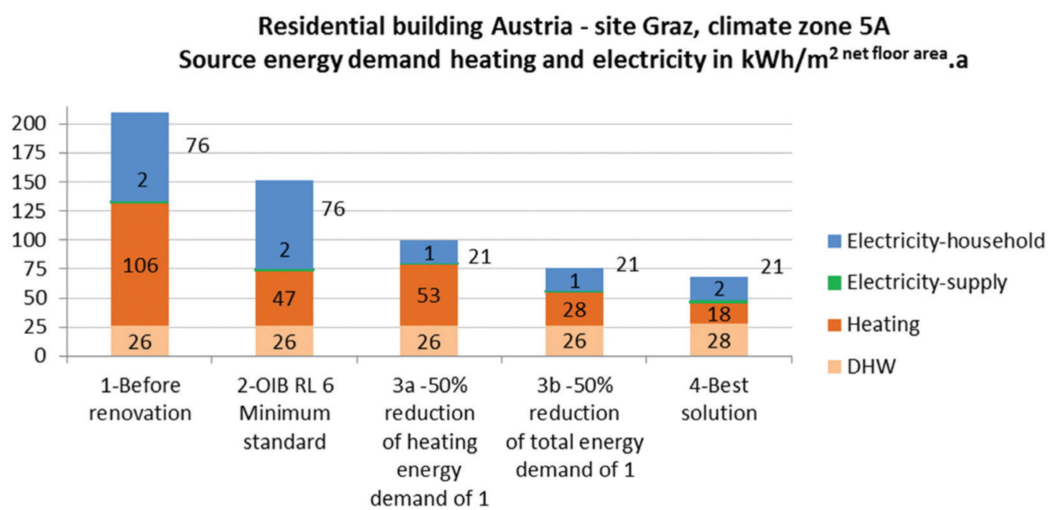


Figure 3 *Site energy demand of the Austrian modeling project.*



kWh/m^{2}yr	10	50	75	125	150	175	200
kBtu/ft^{2}yr	31.5	157.3	186	394	472	552	630

Figure 4 *Source energy demand of the Austrian modeling project.*

Scenarios 2, 3a and 3b have payback periods close to common payback periods in Austria (10–15 years); however, Scenario 4 is far away from this range. NPVs[1] for all scenarios are shown in Figure 5.

[1] The NPV is defined as the sum R_t of the present values of incoming and outgoing cash flows over a period of time t and by considering a discount rate i:

$$\text{NPV} = \frac{R_t}{(1+i)^t}.$$

GERMAN MODELING BUILDING

Description of the Building, Installations, and Usage

The German building modeled is an existing office building in Darmstadt, Germany (Figure 6). The building is composed of prefabricated large concrete panel elements, a typical building and construction in Germany during the period 1960–80. Before the refurbishment, all necessary data of the existing building were collected in an on-site assessment (Table 3).

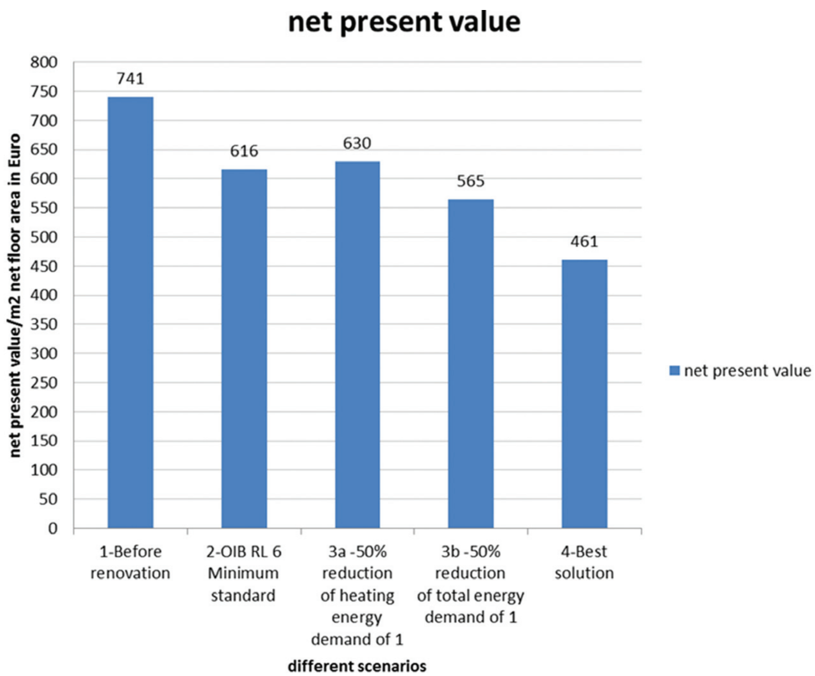


Figure 6 *NPVs of Austrian scenarios.*

Figure 5 *German case study: front view from the street on the southern part of the building before refurbishment.*

Ventilation System: The restrooms of the buildings were equipped with three exhaust air systems (3000, 3900, and 5000 m^3/h [10596, 13772, and 17657 ft^3/h]), constant airflow, an electrical load for the fans in total 8 kW (27.4 kBtu/h), and an annual usage of 8.000 h/a. The three restroom areas and the street-side office rooms on each floor were connected by a vertical concrete exhaust air duct from basement to rooftop. In the office areas, windows could be opened for airing purposes. The indoor air quality of the building was achieved by a high leakage rate and exhaust air ventilation units. The indoor climate conditions required by German building codes did not require additional air-conditioning and cooling systems. Cooling was only in established in the IT server room.

Table 3. Characterization of the German Modeling Case Study

Number of floors	3
Net area, m^2 (ft^2)	1680 (18,083)
Heated area, m^2 (ft^2)	1680 (18,083)
Number of zones	10
Compactness, building envelope/volume	0.38
Usage of building	Office, 8 a.m.–7 p.m., 5 days per week

Heating and Heating Distribution: The building was heated by two gas boilers with a capacity of 500 kW (1706 kBtu/h) each, built in 1992. The bolers were used for heating and DHW purposes. The heating water temperature was controlled by an outdoor-temperature-based control system with a maximum heating temperature of 90°C (194 °F) at the assumed minimum outdoor temperature of –12°C (10.4°F) in that climate zone. The heating pumps were at constant speed.

The heating distribution was by steel pipes distributed in a duct system in four building zones with steel radiators equipped with thermostats allowing for individual control of each zone. The insulation was mineral wool dimensioned at one-fourth of the pipe diameter.

DHW: The existing DHW was a centralized system with the boiler as a heating source at constant temperature of 70°C (158°F). German building codes require at least once a week a temperature of >70°C (>158°F) to provide hygienic minimum requirements; however, in most of the buildings, this temperature is permanent. The DHW was distributed in two distribution steel pipe systems: one is responsible for the transport of the DHW and the second (the circulation) provides the minimum circulation of DHW for hygienic purposes and the first response on DHW demand. DHW required 18% of the heating site energy.

Lighting System: The building was mainly equipped with white-reflector T8 fluorescent lamps with 15 W/m^2 (4.9 Btu/ft^2) average in office spaces and 10 W el/m^2(2.9 Btu/ft^2) average in the floor space.

Construction: The thermal transmittances of the building envelope were as follows:

- External walls—1310 m^2 (14,100 ft^2): $U_{wall} \approx$ 1.36 W/m^2·K (0.24 Btu/h·ft^2·°F)
- Roof-ceilings—692 m^2 (7449 ft^2): $U_{roof} \approx$ 0.7 W/m^2·K (0.12 Btu/h·ft^2·°F)
- Windows—352 m^2 (3789 ft^2): $U_{window} \approx$ 3.3 W/ m^2·K (0.58 Btu/h·ft^2·°F)
- Basement—620 m^2 (6674 ft^2): $U_{basement} \approx$ 0.52 W/m^2·K (0.09 Btu/h·ft^2·°F)

The building envelope contained multiple structural thermal bridges (e.g., jalousie niches).

Simulation Process

The energy performance of reference buildings was simulated by using the energy and indoor climate simulation program PHPT (PHI 2015b). This software is meticulously validated and allows the modeling of internal and solar loads of outdoor climates and HVAC systems.

The German Test Reference Year (ASHRAE Climate Zone 5, Würzburg) is used for outdoor climate conditions (with the design temperature for heating measuring –15°C [5°]).

The project was carried out as described in Scenario 4 (Passive House). In preparation for the refurbishment project, the building was assessed in a detailed building audit, which is documented in the "baseline scenario", Scenario 1. For this modeling approach, the following different scenarios were assessed:

- Scenario 1, with the basic requirements of German building code for existing buildings
- Scenario 6 targets 50% savings of the baseline
- Scenario 2/3/4/5 describe different technical approaches to acheive at least 79% of energy savings

The modeling was carried out with PHPT (PHI 2015b), which provides monthly site and source energy balance calculation in Microsoft® Excel format and is mostly in use for the certification of low-energy and net zero energy buildings in Germany.

One of the research targets in this modeling effort was to improve the accuracy of the modeling process. Findings from the assessment of eight accomplished DER projects (EDLIG 2014) shows that, in more of 50% of the cases, the predicted performance of the modeling process is actually not met; in more than 40% of the cases, the energy performance exceeds more than 10% of the predictions.

In most of the modeling processes, the information loop between the modeling and the actual performance is not closed. This is even the case in existing buildings where a back calibration using the actual performance data of the pre-refurbishment status is not carried out. The effect has been described by IWU (IWU 2013) as the modeling rebound and prebound effect. The rebound effect has been considered in this modeling process. As the building has been already refurbished, a second back calibration of the modeling was carried out using actual performance of the building from the accomplished Scenario 4.

The back calibration was carried out in an iterative process using the following parameters until the measured and climate-adjusted consumption before and after the refurbishment was exactly depicted in the modeling tool:

- The usage parameters have been adjusted.
- *Indoor temperature profiles:* the assumed indoor temperature for the usage time of office spaces had to be reduced in accordance with the reduced hours of usage. In the modeling calculation, two temperature profiles are assumed: the "in use" temperature profile, which is in the office space 21°C (69.8°F), and the "standby" profile, which is set at 18°C (64.4°F). To calibrate the model, the "in use" and "standby" temperature profiles for the office zone had to be reduced. Also, the hours per day in which the "in use" temperature profiles were assumed for the calculation had to be reduced.
- *Internal loads:* the assumptions for the internal heating loads had to be increased. They are considered to be 0.024 kWh/d (81.9 kBtu/d) and 2.3 W/m^2 (0.73 Btu/h·ft^2). The internal loads reduced the heating demand during the heating season; the heating season is considered to be 212 days per year for high-performance isolation scenarios and 365 days per year for the pre-refurbished building. The heating period of the well-insulated Passive House is much shorter than that of the less-insulated buildings. The internal gains are only taken into account in the heating period depending on the insulation level of the building.
- *Ventilation airflow:* assumed with 0.365 L/h (0.096 gal/h) for the renovated building.

- *Target indoor temperature:* 20°C (68°F) in office spaces and gang halls.
- *Indoor temperature in summer:* 25°C (77°F).
- *Internal heat gains by building users:* 1.26 W/m^2 (0.40 Btu/h·ft^2).
- The consumption of DHW was not separately metered in the pre-refurbished building and had to be estimated at 10 L (2.6 gal) per capita and day. With regard to the low DHW consumption, a detached DHW system has been installed.
- The usage of heating energy (site energy) and electricity (site energy) for different refurbishment scenarios takes into account the energy for space heating, ventilation, DHW, as well as all electricity (including lighting and appliances [plug loads]) and energy losses.

Economic Modeling

The drivers of a decision-making process on a building that has arrived at the end of its life cycle are mostly related to the future purpose of the building but do not consider the energy-related options in the first step. German building codes allow "maintenance refurbishments" if minor constructive measures are anticipated. A maintenance refurbishment is considered to be concrete refurbishments, partial replacement of HVAC components, and painting. In comparison to that, a major repurposing concept that requires major constructive measures at the building envelope and in the building floor space entails that the minimum energetic requirements of the German Energy Saving Ordinance (EnEV 2014) have to be considered (Scenario 1 in our modeling scenarios). However, a major repurposing concept has to be considered a once-in-a-life-cycle opportunity to enhance the energetic quality of the building beyond the minimum requirements. The decision-making process of this modeling project considers a decision between maintenance refurbishment and an energetic refurbishment in different scenarios.

Investment Cost Databases: The investment costs were taken from refurbishment cost databases and cost data collected from the accomplished refurbishment of this specific building (Scenario 4). The databases distinguish between different measures in construction and HVAC and consider the total specific costs per square meter (square foot), including costs for the equipment, labor, and the value-added tax of 19%. However, these data may only be considered as average values as the cost spread of the cost elements has to be considered with regard to the month and the region in which the project is to be implemented. The Scenario 3 investment costs were taken from a recently accomplished tendering process. In 2014, the refurbishment costs for projects carried out in the federal building stock were collected (BBSR 2014).

Within the German research project EDLIG (2014) (energy services for deep refurbishments) KEA collected and evaluated at least 15 different projects with regard to the investment costs (KEA 2014). In general, the availability of reliable investment data is costly in terms of labor, with only a few published evaluation reports available. In further research work, databases will have to be populated with estimated and verified investment costs for all crucial building types.

The investment costs are usually not available for measure bundles. In this case, the investment cost data for the Scenario 4 measure bundle was available. Obviously, the investment cost of a measure bundle seems to be significantly less costly than the total of each component.

Lifetime Period of Measure Bundles: The lifetime period was derived from the averaged individual lifetime periods given for each measure in the German industrial standard VDI 2067 (VDI 2014). To calculate the average lifetime periods for each scenario, the individual lifetime periods of the considered components are weighted by the investment costs of the measures in comparison to the total investment of each scenario. To simplify the comparison of the scenarios, an average lifetime period of 33 years is assumed for all scenarios. The economic balance considers the costs and savings in the average lifetime period of 33 years. Components with a shorter lifetime period, such as lighting and shading systems, are considered with end-of-life-cycle maintenance costs. A reinvestment of components with an average lifetime period <33 years are not considered; neither are residual values of installations with an average lifetime period >33 years. As these installations contain the major part of the investments (70%–80% in the scenarios), these assumptions disadvantage the scenarios with high-level insulation.

Capital Costs: The economic model assumes that the investment is 100% funded by bank loans with a loan period of 20 years with fixed interest rates. After 20 years, no further payments of loan payback or interest rates will take place and 100% of the investment, and the interest rates as well, are paid back. The market offers low interest rates for loans with 15–20 year payback periods (but not yet for 33 years). The interest rate was chosen to be 2.5% (20-year fixed).

Energy Savings: The calculated energy savings of each scenario are multiplied by the site energy heating price of 0.1 €/kWh (0.04 $/Btu) and electricity 0.29 €/kWh, including energy taxes and a value-added tax of 19% in year one. In the sensitivity analysis, the energy cost savings are calculated with price-increasing rates of 2% and 4%. The measure bundle still has a residual value after year 20 that generates value: the building is still in use until the year 33. Savings are considered from year 0 to 33.

Maintenance Cost Savings: The replacement of existing and worn-out installations and constructions is accounted for by the life-cycle cost analysis. In most of the cases, owners of small- and medium-sized buildings do not collect data about maintenance costs appropriately. In this modeling project, the maintenance costs are calculated on the basis of the industrial standard VDI 2067 (VDI 2014) (Table 4), which provides empirical data for maintenance costs for some of the major construction and HVAC equipment as a percentage of the investment costs of newly installed equipment. These percentage values are considered average values over the lifetime period (Table 4); at the start of the lifetime period the value is

Table 4. Lifetime Periods and Average Maintenance Costs According to VDI 2067 (VDI 2014)

Measure	Lifetime Period, Years	Average Annual Maintenance Costs in % of Investment Costs
Wall insulation	50	0.75%
Windows	30	0.75%
Ventilation systems (unit and ducts)	27	2.5%
Lighting systems	20	3%
Shadings	20	4%

assumed to be 0, in the middle of the lifetime period it equates to the average value given by the standard VDI 2067 (VDI 2014), and at the end of the lifetime period it is considered to be double this average value. In the case of this modeling approach, 0.5% of the new investment costs is accounted for by the avoided maintenance costs for the existing wall, roof, windows, and HVAC installation. An additional savings potential from the avoided maintenance that results from downsizing the HVAC equipment was not counted.

Other Potential Savings: Other potential savings such as avoided insurance and operation costs were not counted.

Cost-Benefits Analysis

The economic calculations are focused on a 33-year period of costs and savings, based on calculated investment costs (Scenarios 2, 3, and 5) for verified investment costs from the accomplished project (Scenario 4). These investment costs are transferred into annual costs by annuities that are based on a discount rate of 2.5% (fixed), no residual value, and a time period of 20 years. From years 20–33, only reinvestment-related costs appear and savings are still collected. Other additional costs, such as maintenance of new installations and operation, are not accounted for. The annual savings do include the energy cost savings and avoided maintenance.

The cost-benefit analysis in this study focused on the costs only; other value benefits such as increased building values and increased tenant rates are not assessed here. The assessment method should, in this case, only provide information on which of the measure bundles serves the best cost benefit. The price-increasing scenarios and interest rates should be considered. From the four optional methods (discounted cash-flow, annuity method, dynamic payback period, and the NPV) the NPV method was chosen: the NPVs of all annual costs and all cost savings are accounted on today's NPV by using the cumulated discount rates. The project is economically viable if the NPVs of savings and costs are positive.

Figure 7 shows the investment costs per square meter (square foot) of the total heated floor area, split into maintenance costs and the energy-related costs for the different measures. The same amount of maintenance investment costs is considered for all scenarios. The major differences can be found in the context of the wall and roof insulation, airtightness, and different air ventilation systems. As in Scenario 1, because no wall insulation is realized and the other measures are on a low level, it is the one with the lowest investment costs. The other scenarios are more expensive because of the more complex measures.

Table 5. Corner Points of the Economic Modeling of the German Case Study

Loan Payback Period, *n*	Years	20
Lifetime Period, ∅ *N*	Years	33
Interest Rate/Discount Rate, *i*	%	2.5
Avoided Maintenance Costs for Replaced Installations in % of New Investment Costs	% per year	0.5
Price-Increasing Rates	% per year	0, 2, 4
Energy Price, District Heating	€/kWh (€kBtu)	0.10 (0.029)
Energy Price, Electricity	€/kWh (€kBtu)	0.29 (0.001)

Description of the Modeling Scenarios

The plug loads were reduced significantly by replacing old computers and tube screens with energy-efficient installations, the installation of an energy-efficient server, and the reduction of private coffee machines, electric kettles, and refrigerators in the office rooms. In the modeling calculation, it is assumed that the plug loads in all scenarios are kept the same and only the electricity for lighting, ventilation, and warm-water supply and auxiliary electricity has been adjusted where needed. No cooling load is foreseen because in any scenario the minimum requirements for indoor climate conditions (air exchange rate per hour and square meter [square foot], and peak indoor temperatures) defined in the building code regulations were achieved. After the refurbishment, the building was connected to district heating (73% CHP and 27% oil peak load boiler).

Scenario 0—Baseline: Energy performances of four different energetic scenarios were compared to the buildings' pre-refurbishment state (energy consumption, U-factors, air

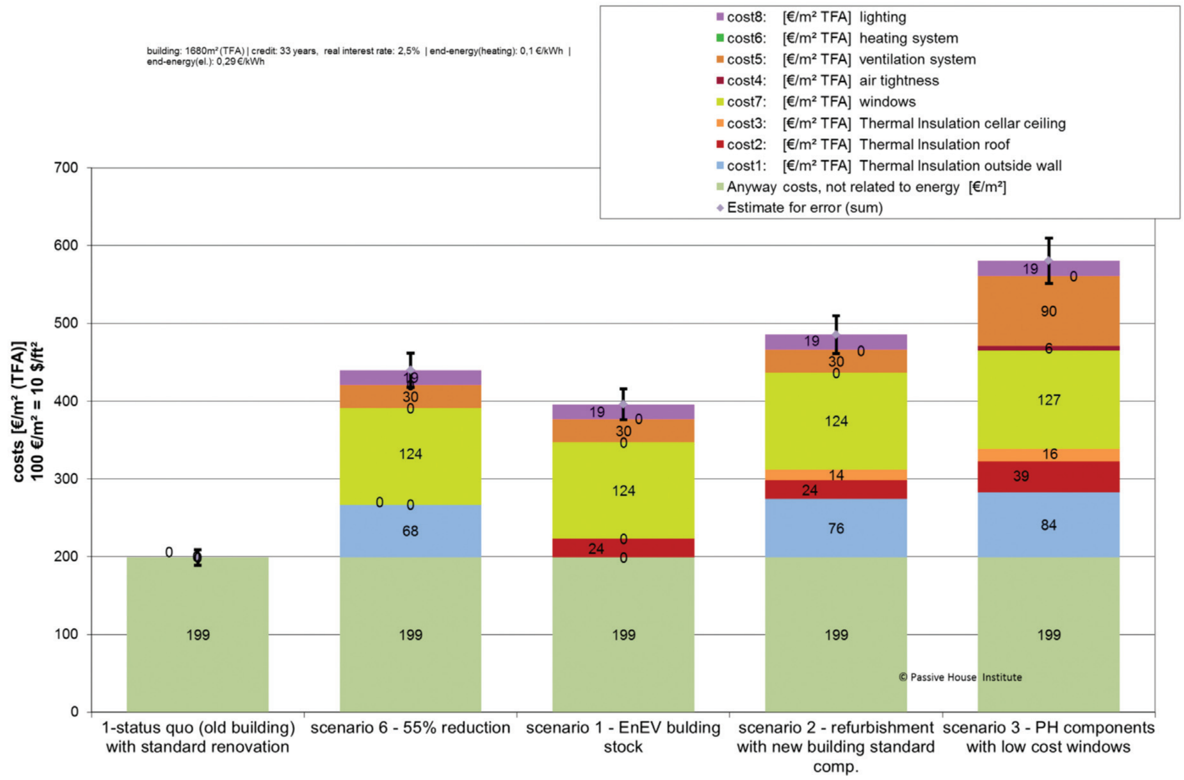


Figure 7 *Specific investment costs of measures and measure bundles for the German case study.*

leakage rate, and thermal bridges). In the first iterations of the modeling process, the modeled demand in the baseline scenario did not meet the monitored consumption (rebound effect). This has been adjusted by modifying the usage and ventilation parameters of the building before refurbishment. The calculated specific site energy consumption for heating is 236 kWh/m^{2}yr (75 kBtu/ft^{2}yr); the electricity consumption (including plug loads but excluding the IT server) equates to 20 kWh/m^{2}yr (6 kBtu/ft^{2}yr). In comparison to that, the measured and climate-adjusted consumption for heating was 216 kWh/m^{2}yr (69 kBtu/ft^{2}yr) and the electricity consumption (with plug loads) equated to 20 kWh/m^{2}yr (21 kBtu/ft^{2}yr).

Scenario 1—EnEV Building Stock—Minimum Requirement According to the German Energy Saving Ordinance: The EnEV (2014) (current German Energy Saving Ordinance) standard for refurbishments in the building stock permits U-factors of components to exceed 40% of the standards for new buildings. To design a modeling concept, the measures were focused on the insulation of the rooftop (160 mm/U = 0.2 W/m^2·K [6.3 in./ U = 0.035 Btu/h·ft^2·°F) and the replacement of windows (U_W= 1.3 W/m^2·K [0.229 Btu/h·ft^2 °F]), which leads to energy savings of nearly 40%. The ventilation of this building is redesigned as an exhaust air system in which the ventilation system transports the used air outside the building. The selection of window exchange without wall insulation may create thermal bridges at the window slab and should not be followed up by the thermal wall insulation (PHI 2013). Common to all scenarios is the replacement of the centralized, boiler-supported DHW supply by a decentralized, electric-flow-type heater.

Scenario 2—EnEV New Building Standard: This renovation scenario represents the U-factor criteria that are required for EnEV 2014 (German Energy Saving Ordinance) building code. The EnEV targets a low-energy standard for new buildings that is defined by minimum requirements for average U-factors U_m and target values for the source energy demand. To achieve these conditions, wall and basement insulation has to be applied. The application of the standard for new buildings has already lead to significant heating energy savings of 75% and total site-energy savings of 71%.

Scenario 3—Passive House with Low-Cost Windows: This renovation scenario represents the criteria for major renovation at the Passive House level, achieving savings of about 86% heating energy. This scenario does not account for new technical solutions but is the cost-optimized version of Scenario 4, the refurbished building in its current status. Scenario 3 takes into account that since 2011 the costs for triple-glazed and, specifically, insulated Passive House windows (U_W= 0.74 W/m^2·K (0.14Btu/h·ft^2·°F) has decreased significantly. In Scenarios 3 and 4, a two-duct ventilation system with separated fresh and exhaust air circuits, a heating heat exchanger, and a heating recovery system is implemented. In Scenarios 3 and 4 it is assumed that the ventilation system is dedicated to be used as a stand-alone installation for

Table 6. Technical Description of Scenarios of German Case Study

	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 6
	Old Building, as Built in 1962	**EnEV Building Stock**	**EnEV Standard for New Buildings**	**Passive House with Low-Cost PVC Window Frames**	**Passive House (as Refurbished)**	**55% Reduction**
Roof (λ = 0.035 W/m K) insulation thickness, mm (in.)/U-factor, W/m^2·K (Btu/h·ft^2·°F)	No improvement	160 (6.3)/ U = 0.2 (0.035)	160 (6.3)/ U = 0.2 (0.035)	400 (15.75)/ U = 0.085 (0.015)	400 (15.75)/ U = 0.085 (0.015)	No improvement
Wall (λ = 0.032 W/m K), insulation thickness, mm (in.)/U-factor, W/m^2·K (Btu/h·ft^2·°F)	0	—	140 (5.51)/ U = 0.24 (0.042)	300 (11.81)/ U = 0.11 (0.019)	300 (11.81)/ U = 0.11 (0.019)	60 (2.36)/ U = 0.5 (0.088)
Basement ceiling, insulation thickness, mm (in.)/U-factor, W/m^2·K (Btu/h·ft^2·°F)	—	—	85 (3.35)/ U = 0.3 (0.052)	120 (4.72)/ U = 0.23 (0.040)	120 (4.72)/ U = 0.23 (0.040)	—
Venetian blind cassette, mm (in.)	—	—	—	80 (3.15)	80 (3.15)	—
Windows						
U-factors for glass, W/m^2·K (Btu/h·ft^2·°F)	—	U_g = 1.3 (0.229)	U_g = 1.3 (0.229)	U_g = 0.64 (0.112)	U_g = 0.64 (0.112)	U_g = 1.3 (0.229)
U-factors for window (average of frame and glass), W/m^2·K (Btu/h·ft^2·°F)	—	U_W = 1.3 (0.229)	U_W = 1.3 (0.229)	U_W = 0.74 (0.130)	U_W = 0.74 (0.130)	U_W = 1.3 (0.229)
Ventilation						
	Exhaust air system only in rooms to the street	Exhaust air system	Exhaust air system	Ventilation with heat recovery	Ventilation with heat recovery	Exhaust air system
Generation of warm water	Heating boiler	—	—	—	—	—
Light System						
Lighting control	Manual	Presence detector	Presence detector	Presence detector	Presence detector	Presence detector
Natural night ventilation in summer for cooling	—	X	X	X	X	X
Cooling system for server	X	X	X	—	—	X
Sun protection	—	X	X	X	X	X

heating purposes and may replace the existing radiator-based heating distribution completely. The cost-saving effects of closing down the existing radiators and the distribution ductwork for heating hot water is, however, not considered in the economic modeling of Scenarios 3 and 4. In both Passive House scenarios, cooling is not needed to achieve the indoor climate conditions required by the building codes.

Scenario 4—Passive House (Current Situation): This renovation scenario represents the criteria for major renovation on the Passive House and is the same as the technical concept of Scenario 3: the calculation-predicted site energy heating savings of 86% and the actually measured energy savings was 78%.

Scenario 6—55% Reduction Relative to Baseline: This scenario represents the reduction of 55% which requires only a partial refurbishment with new triple-glazed windows, an exhaust ventilation system, a decentralized DHW and thin external wall insulation (6 cm/U = 0.5 W/m^2·K) [2.36 in./ U = 0.088 Btu/h·ft^2·°F]). This thin insulation does not adhere the EnEV building stock regulations where the minimum thickness is 10 cm (3.94 in.) of insulation (EnEV 2014). The same effect takes place if the bundle of measures chosen is to be new windows with a rooftop insulation.

Optimization of Bundles

Optimization of energy conservation measures means to find a minimum of total cost, which in this modeling approach is the sum of energy costs, capital costs, and maintenance costs. To find this minimum, the cost structures of the measures under consideration and their effects in terms of energy savings must be known. Of course, the result of any optimization calculation will depend on the underlying energy prices. To optimize the bundles, the single measures, their investment costs, and their impact on the energy performance are evaluated.

Considering energy conservation measures for buildings, the first issue is to find a cost-efficient combination of thermal insulation measures, which are windows, and measures in the thermal envelope on external walls, basements, and roof tops to reduce heat losses through the envelope.

The optimization process can be carried out using the modeling, which requires a rather arduous iteration process. In this Darmstadt case study, the first approach was carried out using an estimative U-factor-based method and in an one-step iteration of modeling results from different scenarios.

Estimative Method: The estimative method refers to a simplified method using the degree-days approach, considering that the heating degree-days are a function of the average U_m-factor of the building's envelopes: with lower U_m-factor, the number of heating degree-days is reduced linearly in a first approximation, which leads to a (slightly) nonlinear function of $q_h(U_m)$. Here, in addition to the transfer losses q_T, ventilation losses are also included, using a ventilation rate of nV = 0.6 h^{-1}.

The calculation of this estimative method is depicted for the example of the wall insulation. Here, the heat transfer loss is directly proportional to the U-factor. Figure 8 shows that the benefit of additional insulation (the decreasing U-factor) decreases with thickness, while the costs increase more or less linearly. The discrepancy between the decreasing impact (saved energy per floor area) and the steadily increasing investment costs creates a cost-benefit equation with a cost minimum at a performance maximum at a certain thickness d of the insulation. The specific heat transfer losses of the external wall, for example, as a function of its U-factor U_W are proportional to U_W times the temperature difference ΔT between indoor and outdoor temperatures. Over the heating period, with varying outdoor temperatures and fixed indoor temperature T_i = 20°C (68°F), the annual heat loss q_T, using the degree-days approach, is given by the following:

$$q_T = \frac{24}{1000} \cdot U_W \cdot H_{15} \quad \text{kWh/m}^2\text{yr (kBtu/ft}^2\text{yr)} \tag{1}$$

with the number of degree-days, H_{15} (K/d), depending on the climate in the given location, for a building with heating limit temperature T_h = 15°C (59°F). In the specific case study H_{15} = 2050 K/d is chosen. The benefit of an additional insulation of thickness d with resulting U-factor $U(d)$ is the amount $q_T(d)$ by which the heat losses (per 1 m^2 [1 ft^2]) are reduced.

$$\Delta q_T = \frac{24}{1000} \cdot (U_W - U(d)) \cdot H_{15} \quad \text{kWh/m}^2\text{yr (kBtu/ft}^2\text{ yr)} \tag{2}$$

Note: In this modeling case study the embedded energy e_e is not considered. If taken into account for large insulation thickness, the energy content of the insulation material, the

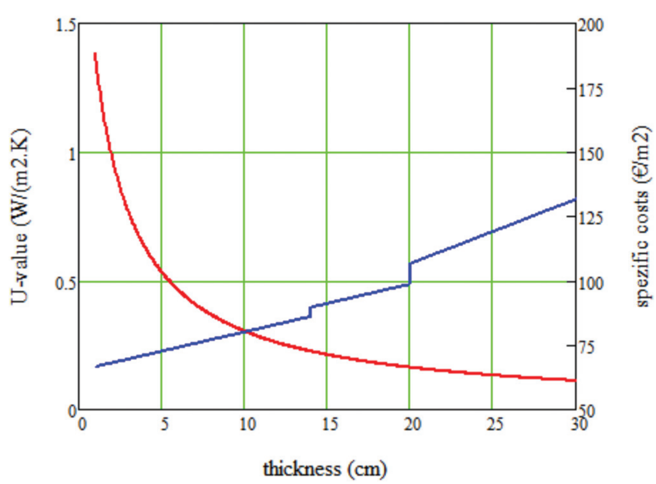


Figure 8 *U-factor of external wall (curve descending from left to right and left vertical scale) and insulation costs (right vertical scale) as function of thickness (heat transfer coefficient = 0.035 W/m·K [0.0019 Btu/h·ft^2°F]).*

embedded energy $e_e(d)$ (kWh/m^2) must be subtracted from the energy savings Δq_T of Equation 2.

Using the cost structures described above, a least-cost path of these measures can be derived. This least-cost path is achieved by a stepwise comparison of the capital, energy, and, in this case, maintenance costs of every possible savings measure.

As each of the data points for capital/energy and total costs represents one specific measure bundle, the quantitative result of this model is a list of measures that contribute to the combination of measures that are implemented to achieve the minimized total heating costs (capital costs plus energy costs) of the considered building or building type.

Iterative NPV Optimization: The iterative NPV considers the results of the energetic and economic modeling results for each scenario. By the assessment of the energetic contribution and the investment costs, the most cost-effective measures were identified. In the iterative method, a comparison of NPVs of the parts of life-cycle costs that are considered: energy, maintenance, and capital costs. In this modeling effort, the results were optimized by NPV optimization. The results are shown and discussed in Figures 10 and 11.

To prepare for the fine-tuning of the results, it has to be considered which measures contribute in which way to the energy efficiency and at which costs.

In a first approach, the impact of each measure is assessed by comparing specific energy savings to the U-factors of measures in different scenarios for this case study. Figure 9 shows the relation between U-factors and their induced energy savings. Increasing the U-factor of the wall by 0.1 induces energy savings of 9 kWh/m^{2}yr (2.85 kBtu/ft^{2}yr). A comparable ratio can be achieved by increasing the rooftop insulation by 0.1. In the case of the window, this value is at 7 kWh/m^{2}yr (2.2 kBtu/ft^{2}yr). In the case of the basement ceiling insulation, the ratio is at 5 kWh/m^{2}yr (1.6 kBtu/ft^{2}yr).

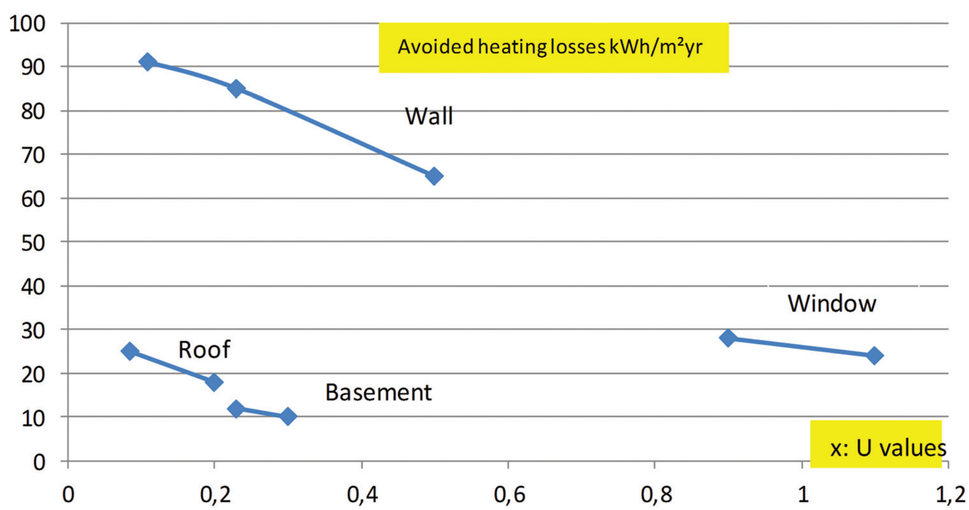
In a second step, the investment costs of thermal insulation measures and their impact on the energy balance of the specific building are assessed in Figure 10. It shows the investment costs per square meter (square foot) of heated floor space of different modeled measures and the energy savings per heated floor space, and delivers the ratio of annual energy saving per square meter (square foot) and € investment costs.

The highly cost-efficiency external wall insulation is responsible for the largest amount of savings. However, the impact per additional primary investment between the right side (Passive House) of the wall insulation curve and the left side (building code for new buildings) is comparably small: an additional 30 €/m^2 (2.9 €/ft^2) investment cost only contributes to 8 kWh/m^{2}yr (2.9 kBtu/ft^{2}yr) of energy savings. A comparable ratio is achieved with the roof insulation (flat roof).

The investment in a high-efficient ventilation system with heat recovery shows a minor additional investment compared to an exhaust air ventilation system.

Primary or Source Energy Calculation

Using the site energy balance, the fuel-specific source energy p_e is calculated with reference to national databases for p_e factors (IINAS 2015), which considers a global emissions model for integrated systems. The p_e of electricity refers to the German electricity mix. To single out the impact of the energy conservation measure bundle, the calculation has to be done for the first time after accomplishing the building concept with a reference



kWh/m^{2}yr	10	20	30	40	50	60	70	80	90
kBtu/ft^{2}yr	3.2	6.3	9.5	12.3	16.6	19.8	22.9	24.6	27.8

Figure 9 *Energy savings per U-factor improvement in the Darmstadt case study.*

energy supply. In this case study, the determined supply system was district heating.

Results of the German Modeling Approach

With regard to the implementation of the case study results in a practical decision-making process, two NPVs have to be considered.

The first NPV considers not only the energy-related investment and capital costs but also energy and maintenance cost savings in the NPVs; this is to determine the energetic level and assumes, as in this case study, that the maintenance-related investment costs are given and have to be financed anyway to keep the building functional. This perspective is relevant, for example, if a government provides funding for a repurposing (seed money) and the energy-related measures have to be funded in an energy performance contract.

The second NPV considers that the global investment and capital costs have to be accounted for and out-balanced by the energy and maintenance cost savings.

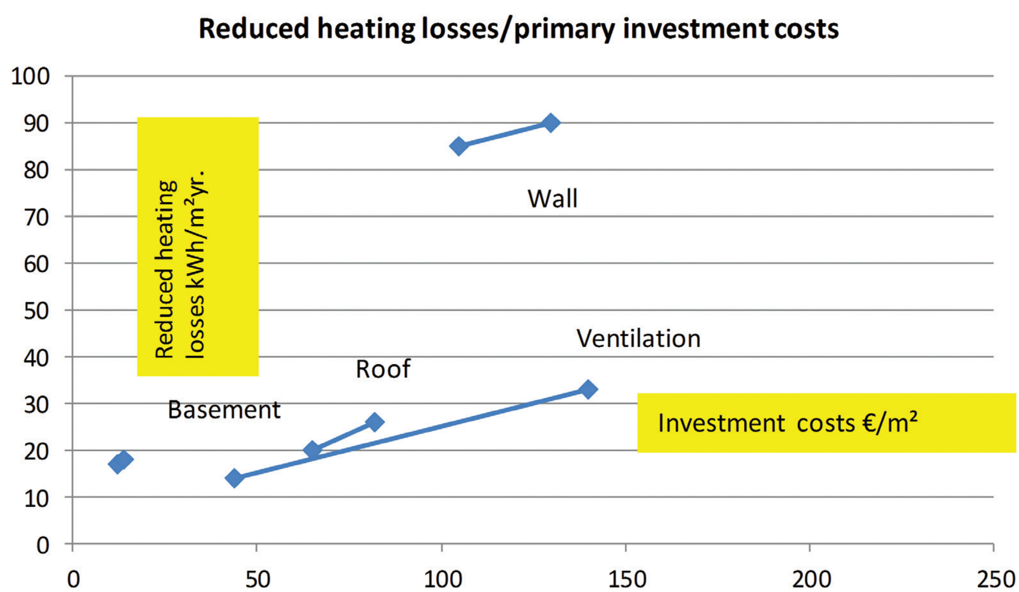
For this study, capital costs are considered to be a funding of 100% of the investment costs by loans with an interest rate of 2.5% and a payoff period of 20 years.

Comparison of NPVs of Energy-Related Investments, Costs, and Benefits: This scenario supports the decision-making processes between different energetic scenarios.

- All NPVs are positive—for all scenarios, the NPVs of savings are larger than the NPVs of costs, which means all of the scenarios are cost-effective within 33 years of the calculation term.

Table 7. Fuel-Specific pe and CO_2 Equivalent Factors (Including all Greenhouse Gas Emissions) Used in Germany (Jank and Kuklinski 2015)

Fuels	Primary Energy Factors kWh p_e/kWh e_e
Lignite	1.21
Hard coal	1.08
Natural gas	1.12
Heating oil	1.11
Wood chips	0.06
Wood pellets	0.14
Thermal solar	0.15
Photovoltaics	0.61
Wind	0.06
Electricity mix 2014	2.13



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kWh/m²yr	10	20	30	40	50	60	70	80	90
kBtu/ft²yr	3.2	6.3	9.5	12.3	16.6	19.8	22.9	24.6	27.8

Figure 10 *Investment costs and heating loss reduction in the German case study (1960 office building, 1680 m² (18,0083 ft²), compactness A/V: 0.38. Before refurbishment, see Table 6.*

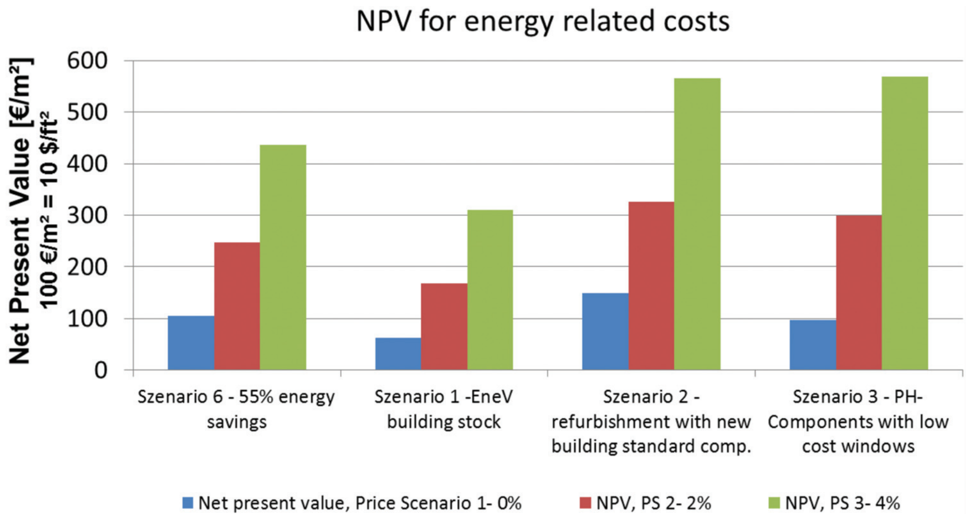

Figure 11 *NPVs of different scenarios of energy-related investment costs per square meter (square foot) of the German case study.*

Table 8. Site and Source Energy EUIs

	(Scenario 0) Baseline ΔE*, %		(Scenario 1) Minimum Standard ΔE, %		(Scenario 6) DER (50%) ΔE,%		(Scenarios 3 and 4) Passive House ΔE,%	
Energy	Site	Source	Site	Source	Site	Source	Site	Source
Calculated energy savings, %	0	0	40%	39%	55%	53%	81%	76%
Calculated energy savings, kWh/m^{2}yr (kBtu/ft^{2}yr)	0	0	103 (33)	119 (38)	142 (45	163 (52)	208 (66)	235 (75)
Energy use intensity (EUI), kWh/m^{2}yr (kBtu/ft^{2}yr)	256 (80)	307 (97)	153 (49)	188 (60)	114 (36)	145 (46)	48 (15)	72 (23)

* Energy savings

- The best NPV is generated by the EnEV building code for new buildings (EnEV 2014) (Scenario 2), followed by the cost-optimized Passive House scenario (Scenario 3).

The following three main parameters of the economic modeling are influencing the positive NPV results:

1. The long time period of the economic model in which the costs and savings are collected
2. The over-average price for heating energy—actually 0.1 €/kWh (0.029 €/Btu)
3. The fixed interest/discount rate over the full 20-year financing period

The sensitivity analysis was carried out with a lower price for heating energy (0.06 €/kWh [0.0032 €/Btu]); the NPV of all scenarios and price scenarios is still positive. The time period of 33 years is still long and will not be attractive for short- and medium-term capital.

Figure 11 shows the NPVs for the refurbishment of the buildings in Scenarios 1, 2, 3, and 6. It is the sum of the savings of energy and maintenance costs, deducting the energy-related cost for the refurbishment, in 33 years. The different shades of the columns show the NPV for different energy price increase scenarios (left column = 0% energy price increase, middle column = 2%, right column = 4%).

Figure 12 shows the NPVs for the refurbishment of the buildings in Scenarios 1, 2, 3, and 6. It is the sum of the savings of energy and maintenance costs, deducting the global cost for the refurbishment, in 33 years. The different shades of the columns show the NPV for different energy price increase scenarios (left column= 0% energy price increase, middle column= 2%, right column = 4%).

Comparison of Global Cost NPV: In this scenario the total investment costs—energy-related and basic costs together—are accounted for in decision making. This is the case in most of the business and funding models, as it assumes

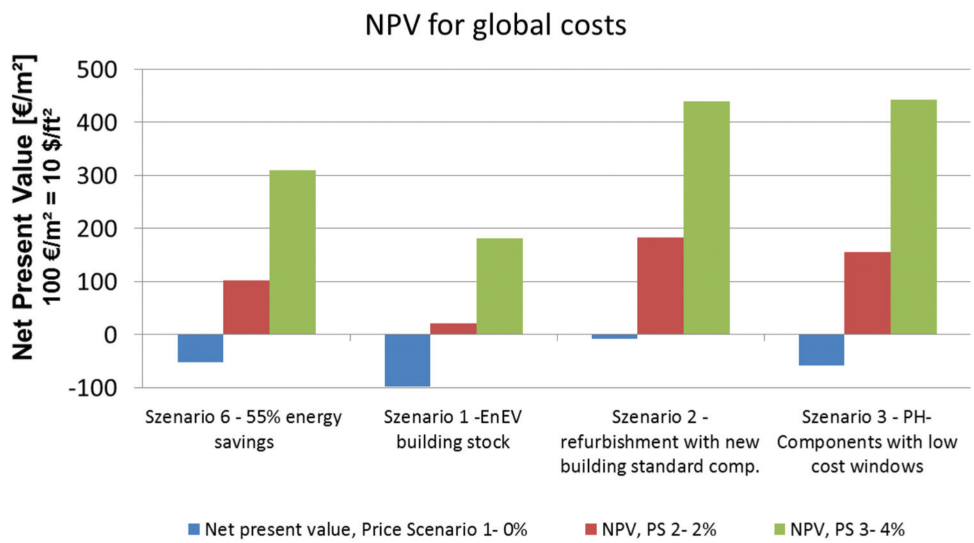

Figure 12 *NPVs of different scenarios of global investment costs per square meter (square foot) of the German case study.*

that all costs are funded and will have to be paid back completely to an investor, bank, funds, or energy service company.

- Except for Scenario 1, without an energy price increase, all NPVs are positive—for all scenarios the NPVs of savings are larger than the NPVs of costs.
- The best NPV is generated by the EnEV building code for new buildings (Scenario 2), followed by the cost-optimized Passive House scenario (Scenario 3).

If the calculation considers a heating energy price of 0.06 €/kWh (0.0031 €/Btu) and no price increase rate, the NPV is negative for all scenarios. When calculating a 2% price increase, most scenarios (except for Scenario 1) turn positive. The payback period of the best scenarios is in a range of 33–37 years.

Summary and Conclusions for German Case Study

This research work was done under IEA EBC Annex 61, Business and Technical Models for DER (IEA 2015), which targets the identification of high-efficient measure bundles for deep retrofit project. KEA collected some 20 well-documented building refurbishment projects and picked an office building from the 1960s that was refurbished in 2011–12 into a Passive House standard building (KEA 2014). For this building, a modeling case study was set up to calculate at least three different scenarios (minimum requirements by German building code, –55% to the baseline, and a Passive House scenario). An additional scenario was created by optimizing the cost-effectiveness of the DER measure bundle using the NPV. The NPV was calculated from the capital, energy, and maintenance costs of each scenario. The economic model focuses the average life time period of the measure bundles of 33 years. It is assumed that, due to national use, the loan payback period will be not more than 20 years, in which the investment loan including interest rates is completely paid back.

The technical and economic assessment of the scenarios shows the following results:

- The standard scenario fulfills the requirement given by the national building code EnEV (2014). In our case, to show a technical suboptimal solution, a refurbishment of windows and the roof would be sufficient. With energy savings of 40%, this scenario is also not economically competitive against more ambitious measure bundles.
- For the –55% (Scenario 6) the results are more competitive. To comply with –55%, a partial refurbishment that considers the window and a shallow layer of insulation on either the roof or the wall will be sufficient. In our case, the thin wall insulation in Scenario 6 would save 55% of heating but would not comply with the national building code and should not be considered.
- The EnEV (2014) building code for new buildings (Scenario 2) and the cost-optimized Passive House standard (Scenario 3) both lead to deep refurbishments (>70% of energy savings) and lead to competitive economical results. These two scenarios would pay back the total investment as well as the energy-related part of the investment.
- This economic equation does not show the benefits of the higher comfort of the air ventilation system with heat recovery, with almost room temperature of the fresh incoming air and a reliable air exchange.

However, from these results a general conclusion cannot be derived: premises, U-factors, building usage, etc. have to be considered on the level of the individual building. For this building type, the EnEV (2014) building code for new buildings and the cost-optimized Passive House standard would be economically competitive solutions in which the total costs of the energetic refurbishment would be paid back from energy cost and maintenance cost savings in 25–35 years. Both solutions would comply with the European Union strategy to accelerate the energy efficiency in buildings by deep retrofit projects with savings >70%. Also, these two solutions could be used for energy performance contract-related deep retrofit business models.

COMPARISON AND DISCUSSION OF AUSTRIAN AND GERMAN MODELING RESULTS

Both countries share the same ASHRAE Climate Zone 5. The modeling in Austria was carried out in a building with high usage (a housing building) and in Germany in an office building. Both buildings exist and allow for evaluation of the actual post-refurbishment performance and calibration of the modeling. The modeling was carried out with the PHPT (PHI 2015b), which uses monthly data for modeling.

The modeling assumptions show 1°C (1.8°F) higher indoor temperature in the Austrian housing building with approximately 30% higher gains from lighting and machinery. The airflow in the dream scenario (Austrian Scenario 4) is on a comparable level.

Although both buildings were built in the 1960s in Climate Zone 5, the initial situations were remarkably different in the EUI heating and the U-factors for walls and windows.

Economic framework conditions show a difference of 20% for the district heating price. The heating price given here is an average value of consumption (kWh [Btu/h]) and load price (kW_{peak}). In the Austrian building, a better heating load ratio may result in a lower heating price. The Austrian electricity price is almost one-third of the German value but does not have much impact on the cost-benefit calculation.

The comparison of specific investment cost, energy savings, and the achieved U-factors shows the following (see also Table 9):

- *Windows energy impact:* The energy savings is comparable in Austria and Germany at 20 kWh/m^{2}yr (62.8 kBtu/ft^{2}yr), which is 13% of the Austrian and 9% of the German baseline.
- *Windows investment costs:* Investment costs are 2.4 times lower in Austria than in Germany in a comparable standard (triple-glazing, comparable U-factors); this can only refer to different assumption of investment costs which were considered and higher fire safety requirements in the office building.
- *Roof energy impact:* The energy savings of the insulation top ceiling insulation (internal) captured 17–23 kWh/m^{2}yr (55–76 kBtu/ft^{2}yr), 11%–15% of baseline in Austria, with U-factors of 0.159 and 0.093 W/m^2·K (0.0308 and 0.017 Btu/h°Fft^2) compared to external flat-rooftop in Germany with 18–25 kWh/m^{2}yr (56–78 kBtu/ft^{2}yr), 9–11% of baseline with a U-factor between 0.2 and 0.085 W/m^2·K (0.38 and 0.0164 Btu/h°Fft^2).
- *Roof investment costs:* The specific investment costs are €9–30/m^2 (€0.88–2.9/ft^2) in Austria and €60–80/m^2 (€6.2–7.9/ft^2)in Germany. The difference is explained by the less cost-intensive material and labor costs for internal roof insulation of the Austrian building.
- *Wall energy impact:* Wall insulation has the largest impact at the best cost-savings ratio in both cases. In Austria, with an initial U-factor of 0.847 W/m^2·K (0.1628 Btu/h·ft^2°F), the improvement to new U-factors 0.315–0.115 W/m^2·K (0.060–0.022 Btu/h·ft^2°F) initiated energy savings of 45–55 kWh/m^{2}yr (142–172 kBtu/ft^{2}yr), or 29%–35%. In the German case, savings are 80–90 kWh/m^{2}yr (251–282 kBtu/ft^{2}yr), which is 35–40% of baseline with U-factors 0.24 and 0.11 W/m^2·K (0.046 and 0.0217 Btu/h°Fft^2) with an initial U-factor of 1.36 W/m^2·K (0.26 Btu/h°Fft^2). The impact in percent is comparable.
- *Wall investment costs:* In Austria, €30–70/m^2 (€2.9–6.8 ft^2) has to be compared to €82–88/m^2 in Germany. At the top level of insulation, the considerable amount of investment cost is almost 20% more expensive than in Austria.

Table 9. Comparison of Initial Situation of Both Case Studies

Measure	Austria	Germany
Usage	Housing	Office building
EUI heating, kWh/m^{2}yr (kBtu/ft^{2}yr)	151 (474)	216 (678)
EUI electricity, kWh/m^{2}yr (kBtu/ft^{2}yr)	58 (182)	20 (63)
Net floor area, m^2 (ft^2)	2098 (22,583)	1680 (18,084)
A/V	0.38	0.38
U-factor, wall, W/m^2·K (Btu/h·ft^2·°F)	0.847 (0.16)	1.36 (0.264)
U-factor, roof, W/m^2·K (Btu/h·ft^2·°F)	0.769 (0.148)	0.7 (0.135)
U-factor, window, W/m^2·K (Btu/h·ft^2·°F)	2.57 (0.497)	3.3 (0.64)
U-factor, basement, W/m^2·K (Btu/h·ft^2·°F)	0.415 (0.08)	0.51 (0.1)

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