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Published in:
AIP Conference Proceedings

DOI (link to publication from Publisher):
10.1063/5.0170903

Publication date:
2023

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

Link to publication from Aalborg University

Citation for published version (APA):
Casian, C., Berger, C., Mahdavi, A., Pont, U., & Schuss, M. (2023). Projected versus actual energy performance improvement due to thermal retrofit of buildings: A case study. *AIP Conference Proceedings*, *2918*(1), Article 020041. https://doi.org/10.1063/5.0170903

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RESEARCH ARTICLE | NOVEMBER 09 2023

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AIP Conf. Proc. 2918, 020041 (2023)
https://doi.org/10.1063/5.0170903

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Projected Versus Actual Energy Performance Improvement Due to Thermal Retrofit of Buildings: A Case Study

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Abstract. In recent years, the building regulations regarding buildings' thermal performance have been steadily tightened. Such regulations target primarily new buildings. However, construction of new and more energy-efficient buildings alone cannot bring about a significant reduction of the building sector's negative environmental impact. This implies the importance of thermally retrofitting the existing building stock. Thermal retrofit of buildings typically addresses building envelope as well as building systems for heating, cooling, and ventilation. Both normative calculations and dynamic simulation can be used to estimate the impact of retrofit measures on buildings' performance. However, past studies have revealed discrepancies between the computationally projected and the actually monitored post-retrofit energy performance of buildings. Such discrepancies, commonly referred to as energy performance gap, must be better understood, if the potential of thermal retrofit measures toward energy conservation and reduction of greenhouse gas emissions is to be more reliably realized. In this context, this paper compares the energy demand of a number of apartments in a multi-unit residential building in Vienna, Austria before and after thermal retrofit. In the course of the study multiple sources of information were considered, including original building plans, details of the retrofit measures, calculated post-retrofit energy demand, and energy bills over different years. Based on this data, the actual pre-retrofit energy performance of the selected units could be compared with the respective post-retrofit values. Moreover, the units' actual performance could be compared with computed values (obtained via energy certificates and dynamic simulation). The gap between expected and monitored energy performance was analyzed and potential contributors to this gap were discussed.

INTRODUCTION

Buildings (including both households and commercial spaces) account for approximately 40% of the total energy consumption in the European Union [1] and over one third of the final energy consumption globally. Buildings are also responsible for a major share of CO_2 emissions (36% in the EU). Hence, in order to limit the carbon footprint of buildings, efforts are needed to significantly reduce the energy required for space heating and cooling. Therefore, it is essential to convince the involved stakeholders to invest in improving the energy efficiency of buildings. In the capital city of Austria, Vienna, various institutions are involved at the municipal level in efforts to reduce the energy demand of residential buildings (Wohnfonds Wien, Wiener Wohnen). This is an important factor, as approximately 13 million square meters of social housing is home to 500,000 people (and thus over 25% of the city's population) [2]. In recent years, the municipality of Vienna and the government have intensified the efforts to improve the technical performance of its building stock via provision of subsidiary grants and harmonizing the applicable building regulations. A central part of the related efforts pertains to the thermal retrofit of the existing building stock. In this context, the present contribution addresses a specific building retrofit project in Vienna, which provided the opportunity to conduct

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5th Central European Symposium on Building Physics 2022 (CESBP 2022)
AIP Conf. Proc. 2918, 020041-1–020041-8; https://doi.org/10.1063/5.0170903
Published by AIP Publishing. 978-0-7354-4734-9/$30.00

a scientific study of the expectations associated with the thermal improvement measures and the actual post-retrofit energy performance of the building. Thereby, information on actual energy use was obtained in terms of energy bills before and after the renovation. This information was subsequently compared with the results of numeric simulations and energy certificate calculations.

Motivation

Although EU member states make investments in implementing strategies towards increasing buildings' energy efficiency, there is an existing gap of knowledge about the actual energy savings of renovation measures. This contention is corroborated, for instance, through a study regarding social housing carried out in the Netherlands [3], which suggests that more information is available regarding thermal retrofit measures than information on their effectiveness to achieve energy savings. Nonetheless, a comparative analysis of deep thermal retrofit in Denmark [4] (6.6 million € subsidized rehabilitation of a 5293 m² residential building in the year 1969 in the village of Hvalsø), implied an overall energy bill reduction of 31% (8,000 € annual savings in electricity and 22,280 € in heating) and high approval ratings (assessed via questionnaires) of the indoor air quality among the users but also a 12.9% increase in the rents. The city of Vienna continuously invests in renovation of existing buildings. Around 200 million € are made available annually from funds from Vienna's housing subsidy. There are currently (year 2021) 247 residential buildings in the city with more than 17,300 apartments under renovation. Another 185 residential buildings with around 13,600 residential units are being audited [2]. However, the determination of the actual technical, financial, and social impacts of the refurbishment measures remains a challenge. As such, it would be useful to routinely assess the extent of the so-called energy performance gap, that is the deviation of buildings' actual post-retrofit performance from the expectations (predictions prior to the execution of the retrofit projects). The present study thus intended to *i)* quantify the energy performance improvement in the course of a typical renovation project implemented by the municipality of Vienna (2015 – 2016); *ii)* deploy dynamic thermal simulation to assess the effect of the thermal improvements on the overall energy demand; *iii)* identify the extent of the performance gap observed in the retrofit project.

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Background

Various studies underline the importance of occupants' role in buildings' energy performance and its implications for energy simulation [5-7]. In the context of the present case study, the focus was on the simulation-based determination of the energy performance gap (EPG). However, no monitored data could be obtained regarding occupants' patterns of presence and behavior in the apartments. Therefore, the standard occupancy profiles from EnergyPlus were considered as basis. Moreover, some qualitative information could be obtained from some of the occupants concerning their behavioral tendencies. As far as the comparison of buildings' performance level before and after renovation is concerned, a number of studies are available. For instance, in case of a nZEB (nearly Zero Energy Building) renovation project in the city of Tallin (Estonia) [8], a rather impressive post-retrofit reduction of the measured heating energy demand (i.e., 76% reduction from 168 to 41) was documented. However, this performance still was 1.8 times higher than the projected heating energy use during the planning process via dynamic thermal simulation (23 $\mathrm{kWh.m^{-2}.a^{-1}}$). Some studies indicate that the projected energy demand of renovated buildings can be exceeded by a factor of 3 despite the endorsement of green building regulations and the incorporation of energy-efficient technologies [9].

A recent meta study [10] investigated the extent of the purported role of occupants' behavior in EPG, taking both the so-called prebound and rebound effects into account. Most of the identified EPG studies were located in Europe (78%), and 60% were residential buildings, indicating an interest in such purpose of buildings. An essential step in isolating the contribution of occupant-related factors to EPG is the normalization with regard to weather data. Almost one third of the studies (31%) included monitored outdoor weather conditions to normalize the measured energy use data. Normalization with regard not only to weather, but also regarding possible differences between buildings' as-designed and as-built states facilitated a proper isolation of occupants' role in EPG [10].

For the purpose of the present case study, dynamic thermal simulations were performed using the application EnergyPlus, which offers energy prediction capabilities with high temporal and spatial granularity. Thereby, each room was represented as a separate thermal zone to achieve a more detailed spatial granularity.

METHOD

The overall approach of the present case study included the following steps:

1. Collection, representation, and interpretation of the energy bills
2. Interviews with some building occupants
3. Identification of the exact alterations made to the building envelope in the course of the renovation (e.g., thermal properties of insulation materials and substituted windows)
4. Generation of hi-fidelity simulation models of the building for parametric studies to systematically explore the influence of modeling assumptions on computed performance, including: *a)* estimation of the fraction of demand hot water (DHW) in total thermal energy use, *b)* benchmarking the heating setpoint, internal gains, and schedules according to various standards [11,12], *c)* normalization with regard to weather information, *d)* consideration of the air change rates. The simulations were conducted for a standard reference year as well as based on weather station data from the years 2017 and 2018. Summary data for these three years are provided in Table 1.

As previously mentioned, in the EU in general and in Austria in particular, more information is available on thermal measures undertaken than their effectiveness in energy saving. The selection of the case study building was aided by a cooperation with the aforementioned organization, Wiener Wohnen, which possesses a sizeable database of retrofitted households, can initiate contact with the inhabitants of buildings, and provide technical and financial data pertaining to specific retrofit projects. In the course of this cooperation, a residential building comprising 27 apartments was selected. Built in 1951 as part of the public housing (Gemeinde Wohnbau) project, this building is located in the 22nd district of Vienna (Fig. 1). The building has a total floor area of 1349 m^2 over five floor levels.

During the years 2015-2016 the building was the object of a renovation project. The thermal retrofit component of this project included specifically the refurbishment of the building envelope. Table 2 provides an overview of the house renovation and maintenance works performed. Based on the information in the energy certificate of the building project, an ambitious energy labelling level was projected (see Table 2) and an 80% reduction in heating energy demand was targeted.

The building plans were obtained from a Viennese municipal department in charge of storing all the data in relation to new construction developments and renovations (MA37 Baupolizei). Further information regarding construction was obtained from the architecture office in charge. The energy bills for the period before and after renovation were collected on site in the course of interviews with participating tenants. Out of the 27 apartments in the building, 21 were inhabited at the time of data collection. The tenants in 6 apartments (roughly 30% of the overall occupancy) agreed to provide the energy bills before and after renovation. Note that energy bills data does separate shares of energy used for space heating and demand hot water (DHW).

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TABLE 1. Mean values and standard deviations of air temperature, horizontal global irradiance, and wind speed for the reference year as well as TU weather station data for the years 2017 and 2018

	Air temperature [°C]	Irradiance [$Wh.m^{-2}$]	Wind speed [$m.s^{-1}$]
Reference year	10.0 ± 8.7	128 ± 208	4.2 ± 2.7
Year 2017	11.1 ± 8.5	137 ± 213	3.4 ± 2.2
Year 2018	11.1 ± 8.5	136 ± 215	3.4 ± 2.2

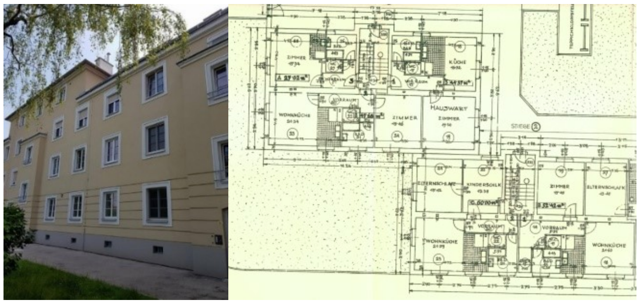

FIGURE 1. Case study building (left: view from the courtyard, right: original floor plan)

TABLE 2. Renovation and maintenance works done at the case study building

Thermal insulation of the facades	16 cm EPS-F
Thermal insulation of the firewall	16 cm Mineral wool
Thermal insulation of the roof	20 cm Mineral wool
Installation of thermal insulation windows	Wood-Alu, U-Value = 1.10 W.m^{-2}.K^{-1}
Projected post-retrofit heating energy demand	HWB = 37.6 kWh.m^{-2}.a^{-1}

As the energy simulation pertains to space heating demand only, the share of DHW must be estimated computationally. In other words, to assess the energy required for space heating, DHW-related share must be subtracted from the bills' total energy use data. Various approaches have been proposed for this purpose [11, 13, 14]. For the purpose of the present contribution, the findings of a previous study [13] were utilized. This study describes statistical methods to analyze hot water consumption profiles in different types of buildings based on several international standards.

To generate the simulation model, the available building plans were recreated in the SketchUp 3D-computer modelling application (see Fig. 2) and imported into EnergyPlus, using OpenStudio.

As alluded to before, the actual energy performance of buildings may significantly deviate from prior computational projections due to multiple factors (e.g., as-designed versus as-built details, weather conditions, occupants' behavior). To address some of these issues, 156 simulation runs were performed using EnergyPlus. Thereby, various options regarding occupant-related data, weather conditions, window operation, heating setpoint temperatures, and ventilation rates were considered. An exhaustive treatment of all the obtained results would not be possible within the limited scope of this contribution. Nevertheless, to provide examples of different simulation assumptions, a selection of these options (referred to as simulation scenarios) are presented in Table 3. Thereby, the sources of information for assumptions concerning occupant-related data, deployed weather files, window operation, heating setpoint temperatures, and ventilation rates are shown. All of these assumptions influence the simulation runs' outcome. Specifically in highly insulated buildings, air change rates (due to natural ventilation) can be responsible for a major share of space heating loads. The Austrian Standard ÖNORM B 8110-5:2019 stipulates an air change rate (ACH) of 0.4 h^{-1} for the calculations of energy certificates [15]. However, a previous study [16] implies that the assumed air change rates in calculations may have to be considerable larger if a more reliable prediction of the actual post-retrofit energy performance of buildings is to be expected. As a consequence, the present study also included multiple air change rate assumptions (i.e., 0.4, 0.6, and 0.8 h^{-1}). Note that in the following, results and discussion of EPG will focus only on those scenarios in Table 3, which involve the deployment of the local weather station of TU Wien for the relevant observation period (i.e., scenarios S.9, S.10, and S.11).

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RESULTS

Table 4 provides information on actual energy use of the selected apartments for space heating and DHW. As mentioned before, the available energy bills entail information on the total thermal energy use (space heating and DHW). Hence, the DHW share must be estimated. Figure 3 depicts the resulting space heating and DHW components separately. Figure 4 and Table 5 show the EPG magnitudes (percentual deviation of actual heating energy use from projected values) for the analyzed apartments according to three scenarios. Finally, Figure 5 offers a graphic comparison of actual heating energy demand for the selected apartments (observation years 2017 and 2018) with simulations (scenarios S.8, S.9, S.10, and S.11 as per Table 3).

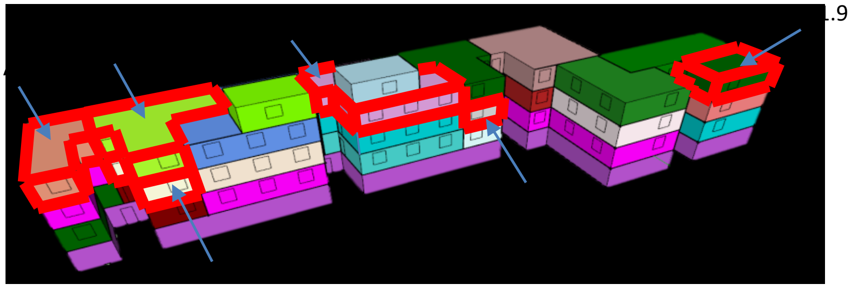

FIGURE 2. Illustration of the building complex with the location of the selected apartments

TABLE 3. Overview of selected simulation scenarios

Scenario	Occupant-related data	Weather data	Window operation	Heating setpoint [°C]	Air change rate [h^{-1}]
S.1	ASHRAE	Standard weather file (Vienna)	N/A	20	N/A
S.2					0.4
S.3	ASHRAE/ ÖNORM				
S.4			EnergyPlus ventilation regime (threshold temperature = 20°C)		
S.5				18	
S.6				19	
S.7				21	
S.8	ÖNORM		N/A	20	
S.9		TU Wien weather station (2017, 2018)			
S.10					0.6
S.11					0.8

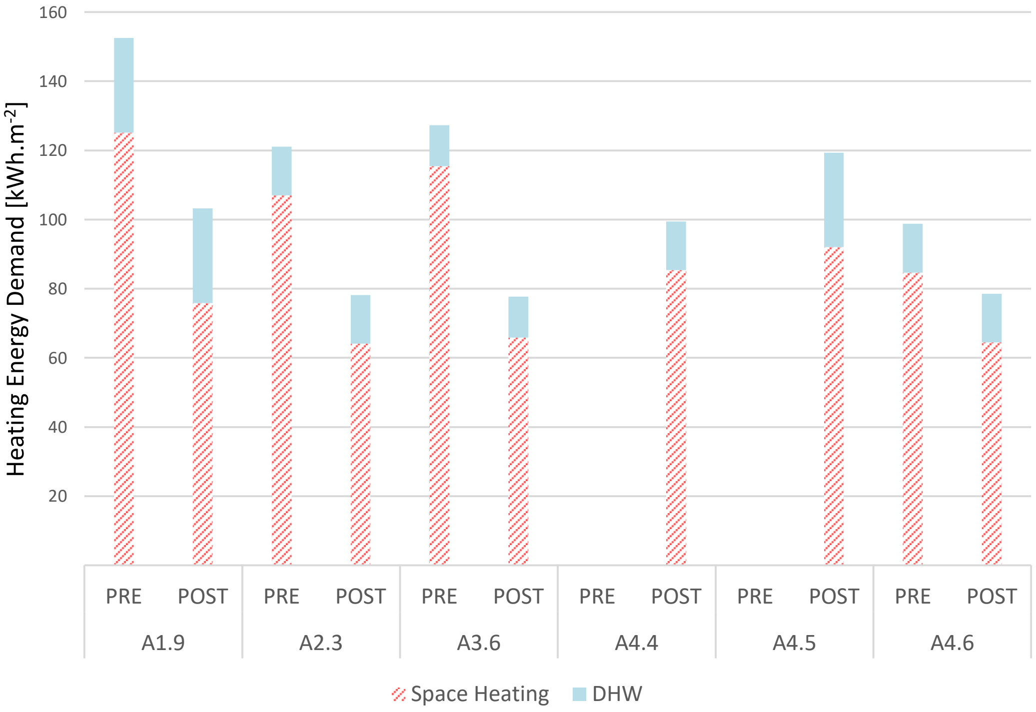

FIGURE 3. Thermal energy demand (for space heating and DHW)

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TABLE 4. Representation of the reduction of post-retrofit energy demand for heating and DHW

Apartment	Net Floor Area [m²]	Average energy use [kWh.m^{-2}]		Reduction of energy use [%]
		Pre-retrofit	Post-retrofit	
A1.9	28.0	153	103	32
A2.3	54.6	121	78	35
A3.6	64.7	127	78	39
A4.4	54.4	-	99	-
A4.5	28.2	-	119	-
A4.6	54.4	99	79	20

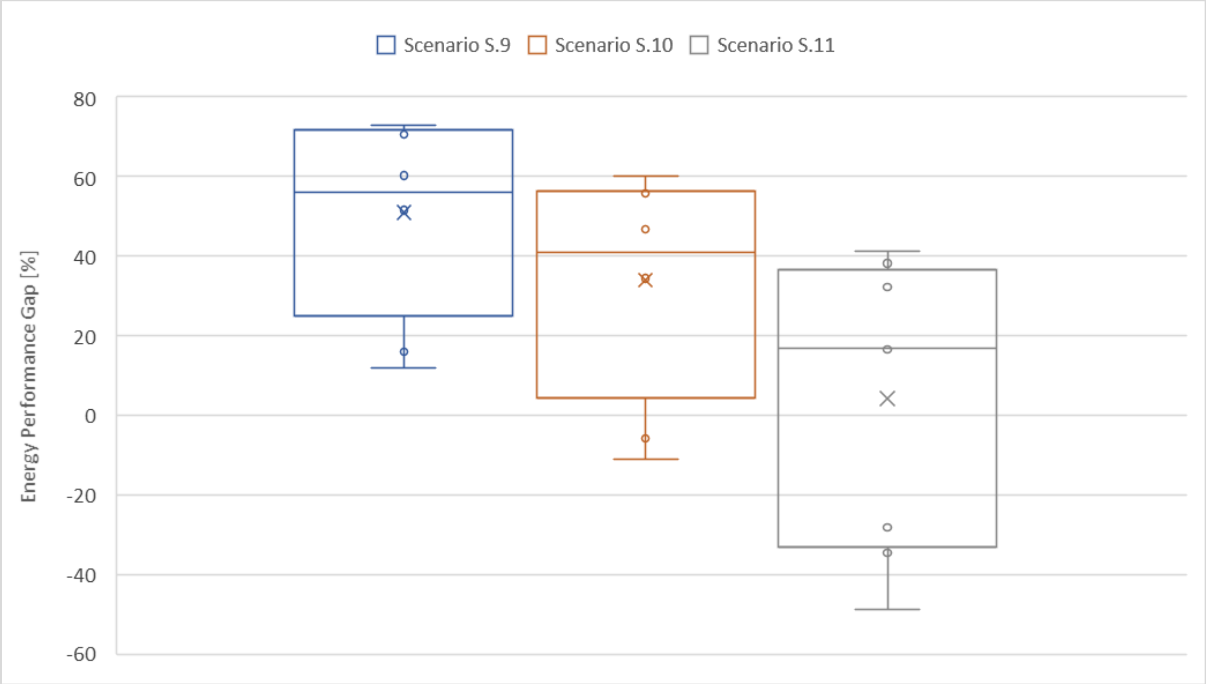

FIGURE 4. Distribution of the EPG [%] of the selected apartments for the years 2017 and 2018

TABLE 5. EPG Rate [%] according to three simulation scenarios for the years 2017 and 2018

Simulation period [Year]	Apartment	EPG [%]		
		Scenario S.9	Scenario S.10	Scenario S.11
2017	A1.9	52	35	17
	A2.3	72	56	38
	A3.6	12	–11	–34
	A4.4	73	60	–49
2018	A1.9	60	47	32
	A3.6	16	–6	–28
	A4.4	71	56	41
	A4.5	52	34	17

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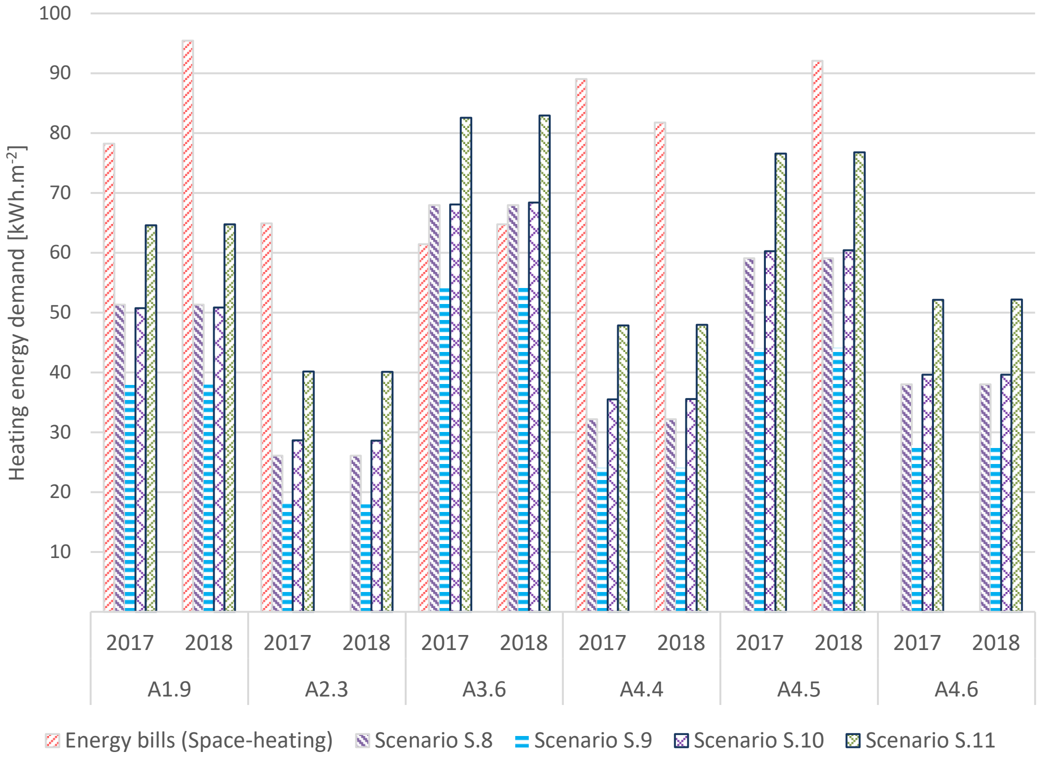

FIGURE 5. Comparison of space heating (derived from energy bills) with simulation results (Scenarios S.8, S.9, S.10, and S.11)

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DISCUSSION

As implied by the information in Table 4, the actual reduction of energy use (between 20% and 40%) subsequent to the execution of the retrofit project is by no means insignificant, but falls short of the prior expectations. As far as DHW is concerned, prior to the execution of the retrofit project, the energy use for DHW (estimated based on energy bills) amounted to 9% to 18% of the total thermal energy use. After the renovation, the estimated DHW energy use amounts to 14% to 27% of the total thermal energy use (see Fig. 3). These results appear plausible, as the thermal retrofit measures specifically target heating energy use and are less relevant to DHW. Consequently, the relative share of DHW in total thermal energy use increases after the retrofit.

The magnitude of energy performance gap is of course dependent on the model input assumptions (i.e., simulation scenarios). Generally speaking, both the calculation based on energy certificate and the simulations tend to overestimate the energy saving effect of the thermal retrofit measures. Consideration of the information entailed in Figs. 3–5 and Table 5 warrants certain observations. The energy gap median is roughly 20% to 60% for the three scenarios S.9, S.10, and S.11. The relatively lowest EPG magnitudes pertain to scenario S.11, which involves the highest assumed value for air change rate. This circumstance is consistent with the previously mentioned findings [16]. It is worth mentioning that, during the interpretation of the interview results with the occupants, the tenant in apartment A3.6 could be identified as a highly energy-conscious individual. Interestingly, the derived magnitude of EPG (12%) for this apartment was shown to be the lowest.

The results of the case study presented underline the challenges in the accurate a priori prediction of buildings' energy performance subsequent to thermal retrofit measures. Both simplified estimations based on calculation methods adopted in energy certification tools and dynamic numeric simulation display a tendency to overestimate the energy-efficiency effect of thermal retrofit projects. Whereas improvements in the fidelity of simulation models are arguably possible with regard to building geometry, construction, and systems, there may be certain limits of prediction accuracy due to the probabilistic patterns of both external weather conditions and internal occupancy-related processes. A more accurate determination of the energy performance gap in the present study would have required a detailed study of the tenants' actual patterns of presence and behavior. However, this could not be achieved due to both logistical challenges and privacy protection considerations. At any event, a more accurate derivation of the EPG magnitude would require more detailed and reliable information regarding weather conditions and occupant behavior in the post-retrofit operation phase.

To conclude with an observation of a more general nature, it seems it may be counterproductive to declare building occupants, in a sweeping manner, as the major contributors to EPG, even though occupants can be of course part of the complex set of factors involved. The more productive approach to occupants' role in improved energy-efficiency may be the provision of user-friendly interfaces to buildings' control components and systems as well as the communication of information to the occupants with regard to working of building systems and their proper operation. Such measures could be complemented by elevating occupants' environmental consciousness and provision of monetary incentives.

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